A Study of Two Aspects of Medium Density Fibreboard Manufacture

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Chemical and Process Engineering to the University of Canterbury

by

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Summary

This thesis covers two aspects of MDF panel manufacture.

In Part A of the thesis the development and application of a plant-based model of the blowline resin blending process used in the manufacture of Medium Density Fibreboard (MDF) is described. Experience quoted in the literature, operating experience in plants and data from specific plant trials have provided a number of insights into the process, but it was not until a calculation of the blowline steam flow became available that these disparate observations could be integrated into the comprehensive model of the blowline blending process that is described in this thesis.

The steam flow in the blowline is calculated from a combined mass-energy balance over the refiner, allowing the steam velocity profile in the blowline to be established. In addition to the perspective that this data provides in understanding the various observations of the blowline blending process, it also shows a linkage between blowline velocities and nozzle atomisation that prevents the use of high pressure atomising nozzles to create small resin droplets unless blowline velocities are high. It is concluded that this relationship is largely responsible for the higher resin contents that blowline resin addition requires when compared with MDF made using the dry blending process that is used for other wood-based composites.

The refiner mass-energy balance shows that blowline conditions are sensitive to the refiner conditions, with relatively small changes in some parameters used to control the refiner operation changing the blowline steam flow significantly. This raises the possibility that changes in blowline conditions contribute to significant variability in the bonded fibre network that makes up MDF.

Once the steam flow is known for a particular case, the blowline design can be optimised to provide the blending conditions that have been found to give a good blending result. This has been now been done in 25 MDF plants around the world; in 24 cases the blowline diameter was greater than the optimum for good blending. In the remaining case the diameter had been reduced, to the point where the choke flow limit was exceeded, leading to a fibre buildup on the dryer wall.

The significance of resin droplet size, in terms of its effect on the strength properties of the panel and on the outcome of the blending process is discussed. The relationship between the mass of resin in each droplet and the mass of the fibre is significant in the blending process, particularly in the formation of resin spots. There
are indications both from panel studies and from the resin performance in blowlines that have been optimised, that resin droplets should be smaller rather than larger.

Resin atomisation, both in pressure and steam atomised nozzles and through interaction with the blowline steam flow is examined. This results in a wide range of resin droplet sizes, with the smallest from an effective atomising nozzle and the largest created by the interaction of the resin stream with a low steam velocity in the blowline. This wide range of conditions explains much of the variability in the blending outcome, ranging from good resin efficiency where resin droplets are small and poor resin efficiency where resin droplets are larger. The development of a steam-atomised resin injection nozzle is described. The nozzle is in commercial production with a number of units in service. Good resin efficiencies have been achieved, while the design has been successful in overcoming resin blocking problems that have occurred with other nozzle types.

The blowline blending model has proved to be both robust and reliable. It was originally developed to reduce resin usage, with reductions of up to 25% of resin previously added having been achieved. In addition the model also provides solutions to a number of problems which have been shown to originate in the blowline.

This thesis develops and extends the concepts used in the model to validate the approach and to provide insights into its further development.

In Part B of the thesis the influence of temperature, moisture and fibre type on the stress response of a fibre mat to an applied strain was investigated to determine the impact of these variables on the development of the Vertical Density Profile (VDP) in MDF panels.

There are a number of models of the in the literature that predict the development of VDP from the condition of the material in the press and the press conditions. While these models, developed for particleboard, claim to be sufficiently general to be extended to cover the case of MDF, there are features of the MDF profile that suggest that this might not be the case. This investigation was set up to determine the stress-strain response of MDF fibre under the conditions encountered in the hot pressing operation.

A small circular press was designed so that it could be mounted in a compression testing machine, allowing the stress-strain data to be recorded. The press was
constructed so that heated and humidified air could be passed through the mat so that uniform temperature and moisture conditions could be established through the mat prior to the stress-strain measurements being made. The press was then closed to determine the stress-strain response of the fibre. After the press was closed it was held in that position and the relaxation response of the fibre mat measured under conditions where the compliance of the press imposed a small continuing strain on the mat as the relaxation of the fibre reduced its compressive resistance.

The fibre response at moisture levels of 0% - 20% and at temperatures up to 100°C was measured although limitations of the conditioning limited the moisture content that could be reached at the higher temperature ranges. Two fibre types, prepared from high and low density *P. Radiata* wood, showed a very similar stress-strain response.

The density-stress response for the fibre mat appears to follow that for a foam compression model where the resistance to compression at constant temperature and moisture is proportional to the square of the density ratio. An extension to the cellular foam theory to the situation of a discrete fibre mat is proposed.

The temperature and moisture effect on the compressive resistance of the fibre mat appears to follow established relationships for solid wood, although the inability to reach the high temperature-high moisture condition excludes this important area from the analysis.

A modified stress relaxation response is characterised by an increase in density that, at constant moisture content, appears to be independent of the density of the mat, over the range encountered in the development of the density profile. The moisture effect on the stress relaxation response appears to be more significant than that due to temperature.

It is concluded that temperature and moisture content gradients established early in the press are the most significant factors in determining the vertical density profile through the MDF panel. The squared relationship with density implies that these gradients are particularly important in the generation of the high density of the faces of the VDP. The stress relaxation effect provides a uniform increase in density through the mat, modified only by a moisture response which increases this effect where moisture contents are high.

The data provide insights into the relative effects of temperature, moisture and density as these change in the pressing of MDF fibre, in a form that can be
incorporated in a model of the pressing process and also used by MDF press operators to aid in their understanding of the processes that lead to generation of the VDP in commercial MDF operations.
Introduction

Medium Density Fibreboard or MDF is a composite panel made from a fibre prepared from wood or other plant-based material. After the fibre is separated, it is dried and mixed with an adhesive, formed into a mat and pressed in a heated platen press where the adhesive is cured to form the panel. The use of fibres instead of the particles used in other wood-based panels gives a fine structure that allows the MDF composite to perform as closely as possible to solid wood in surface finishing and machining characteristics. These characteristics, together with its uniformity, have led to it being used as the preferred material for automated processing lines producing furniture and other cabinetry components.

The first MDF was made in a particleboard plant in Deposit, New York in 1965. Fibre prepared for the manufacture of wet process panels was dried and used to make a panel on a particleboard line instead of the wood particles usually used. This resulted in a panel that not only had improved strength properties, but also could be successfully machined to a smooth edge. These advantages meant that MDF could be used as an alternative to solid wood and resulted in rapid growth of the new product. Initially this growth was in USA, but by 1975 there were plants in Japan, Germany and what was then Yugoslavia, in addition to 9 plants in USA. The Canterbury Timber Products Ltd. plant at Rangiora started up in 1976, the 13th plant in the world and the first in the southern hemisphere.

MDF capacity has grown rapidly. From the first production in 1965, world capacity is now estimated at $36 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$ (Wadsworth, 2002) while in New Zealand capacity is some 900,000 m$^3$ yr$^{-1}$ (MDF Yearbook, 2002).

The MDF process shown diagrammatically in Figure A1 was developed from two existing technologies. The fibre manufacturing process was based on technology developed for paper and panel board manufacture, while the adhesive and pressing technology has come from particleboard manufacture. While both these sources are significant, the MDF process has been developed to have some distinctive features and is now regarded as a separate technology which can be used to produce a range of products with different properties, both as flat panels and as moulded shapes.
This thesis is in two parts.

**Part A** is an investigation of the blowline resin blending process, where the resin is mixed with the prepared fibre.

**Part B** is an experimental investigation of the stress-strain response of the fibre under the conditions encountered in the hot press that is of significance in determining the vertical density profile through the MDF panel.

The fibre for MDF is prepared in a thermomechanical pulping process. It differs from that used to make a fibre for papermaking in that the material is heated in steam at a pressure of approximately 8 bar prior to mechanical separation of the fibres. The objective is to reach a temperature where the lignin rich material between the fibre softens, allowing the largely cellulose fibres to be separated with minimum damage.

---

**Figure 1 – MDF Process Diagram.**

*The Blowline Blending process (Part A of the thesis) focuses on the hatched elements. The hot press where the density profile (Part B of the thesis) is created is shown as solid.*

A range of thermosetting adhesive systems has been used for MDF. Phenol formaldehyde is used in the production of fibreboard sidings, but urea formaldehyde
(UF) has become the dominant system for MDF. It requires lower temperatures in the hot press to reach resin cure and is now used for the majority of commercial MDF production. The resin is water-based with soluble and colloidal components. Typically the resin is manufactured with a solids level (resin / (resin + water) between 60 and 68% and may be diluted further with water before being mixed with the fibre.

The preparation and delivery of MDF fibre at an elevated pressure has permitted the addition of resin ahead of the dryer, the so-called blowline resin injection process. This is the major point of difference from processes used for other wood-based composite panels, where the prepared wood particles are dried before being mixed with the resin.

The fibre, with the resin already distributed over it, is dried in a flash-tube dryer and formed into a mat which is then pressed in a heated platen press to form an MDF panel with the required thickness and density.

The operation of the press has been developed to the point where the distribution of material within the thickness of the pressed panel can be controlled, to allow the balance of properties within the panel to be determined. The vertical density profile (VDP) is regularly used as one of the quality control parameters for the MDF panel and equipment is now available to measure the VDP continuously as the panel leaves the press.

![Figure 2 - Density Profile through 18 mm MDF Panel](image)

Figure 2 shows a typical vertical density profile for an 18 mm thick MDF panel with face densities over 1000 kg m\(^{-3}\) providing bending strength and a surface that takes
paint and lacquer finishes well. There is a uniform density within the centre of the thickness of the panel which ensures a uniform machining response on the edge of the panel.

This investigation comes at the culmination of a career in the wood industry, the larger part of which has been spent in the MDF industry. The two parts of this thesis are an attempt to bring a disciplined approach to these two areas of the MDF process that was not possible in the midst of a busy operation.

Subsequently, the need for progress in understanding these areas of the MDF process has become apparent to the author in consultancy assignments and the opportunity to develop new approaches in these areas has become possible. The blowline optimisation approach has been widely accepted, having been applied in 25 plants around the world.

The data used in this thesis comes from three sources. The literature has been consulted, and experimental work is described. However much of the information shaping this investigation is based on operational experience that is not reported, but which has become part of the skill base or culture of the industry. Data from this source is used carefully, and only in areas where there is general acceptance of the concept.

Other data, particularly in the blowline blending area, comes from reports prepared for clients which must remain confidential. Where this material is used in the thesis the plants are identified by a coded letter.
Publications by the Author Contributing to or Arising from this Investigation


## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>IB</td>
<td>Internal Bond</td>
</tr>
<tr>
<td>MDF</td>
<td>Medium Density Fibreboard</td>
</tr>
<tr>
<td>NB</td>
<td>Nominal bore (as a pipe classification)</td>
</tr>
<tr>
<td>NPA</td>
<td>National Particleboard Association</td>
</tr>
<tr>
<td>ODF</td>
<td>Oven dry fibre</td>
</tr>
<tr>
<td>PF</td>
<td>Phenol Formaldehyde</td>
</tr>
<tr>
<td>precure</td>
<td>Resin curing at a point before the hot press</td>
</tr>
<tr>
<td>resin efficiency</td>
<td>The inverse of the resin: fibre mass ratio necessary to achieve particular MDF panel properties</td>
</tr>
<tr>
<td>Sch</td>
<td>Schedule (as a pipe pressure classification)</td>
</tr>
<tr>
<td>UF</td>
<td>Urea Formaldehyde</td>
</tr>
<tr>
<td>VDP</td>
<td>Vertical Density Profile through the thickness of a composite panel</td>
</tr>
</tbody>
</table>
Part A: Chapter 1
Introduction

1.1 Blowline Blending – An Historical Review

The synthetic adhesives used to make wood-based composites are thermoset resins. These require a low moisture content material, typically below 15%, to perform satisfactorily. The first wood-based panel to use these adhesives was particleboard, where the wood portion of the composite is made of carefully sized wood particles, which are dried and cooled before being mixed with resin in a mechanical paddle mixer.

This approach was used in early MDF manufacture, but resulted in the formation of aggregations of fibre with a high resin content. These “resin balls” as they became known, formed dark spots in the panel, which affected surface overlays and finishes and also created difficulties in machining. The high resin content aggregates sometimes broke out from the panel, or in some cases, were strong enough to damage the machining cutters.

Various solutions to the resin spot problem were tried. In some plants attrition mills were used after the paddle mixers to break up the resin-rich lumps, but with limited success (Frashour, 1990). The solution to this problem finally adopted was to add the resin to the fibre as it left the refiner, before the dryer, as shown in Figure A1.

![Resin Blending Options - Blowline (top) and Post dryer blending](image)

This largely solved the resin spot problem, but it became clear that higher levels of resin were needed to achieve given panel properties. At the time blowline blending was being used with phenolic resin systems, in products such as sidings, where the
resin spots were covered with a factory applied paint system. Blowline blending was tested with the much faster curing urea formaldehyde resin used for MDF in the Sundsvall laboratory of Sunds Defibrator AB by Dr O. F. Haylock who was one of the investors in the Canterbury Timber Products Ltd. plant (Haylock 1977). Subsequent trials in a USA plant showed that the approach could be used commercially and it became the standard method of resin addition for MDF. Post-dryer blending capability was maintained in some plants (Smith, 1998), sometimes used in conjunction with blowline blending for a portion of the resin, or for the fibre used in the core of the panel, where the resin spots were less visible.

In addition to reducing resin spots in the panel, blowline blending had other benefits in the operation. As shown in Table A1, the moisture content of the fibre leaving the dryer is significantly different for the two cases.

- For post dryer resin addition the moisture after the dryer is 2% – 4%. This, with the moisture added with the resin, gives the desired moisture content into the press. In the example in Table A1, the resin is sprayed at 45% resin solids; the balance being water. At a resin addition rate of 8% resin solids on oven dry fibre (or ODF) the water in the resin is 7.3% on fibre. With 4% moisture in the fibre after the dryer, the total moisture into the press is 11.3%.

- When the resin is added at the blowline, the moisture in the resin is part of the moisture load into the dryer, so the moisture level after the dryer is controlled to that needed in the press.

Typically the moisture content of the material entering the hot press is in the range 9% – 12% on oven dry fibre.

*Table A1 – Moisture level comparison, Post-dryer and blowline resin addition*

<table>
<thead>
<tr>
<th>Resin Addition Point</th>
<th>Post Dryer</th>
<th>Blowline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin Addition rate</td>
<td>% resin solids/ODF</td>
<td>6</td>
</tr>
<tr>
<td>Resin Solids level</td>
<td>% resin solids/wet resin</td>
<td>45</td>
</tr>
<tr>
<td>Water in resin</td>
<td>% Total mass (resin + fibre)</td>
<td>7.3</td>
</tr>
<tr>
<td>Moisture into dryer</td>
<td>% Total mass into dryer</td>
<td>72</td>
</tr>
<tr>
<td>Moisture in fibre after dryer</td>
<td>% Total mass (resin + fibre)</td>
<td>4.0</td>
</tr>
<tr>
<td>Total Moisture into press</td>
<td>% Total mass (resin + fibre)</td>
<td>11.3</td>
</tr>
<tr>
<td>Dryer evaporation</td>
<td>kg kg⁻¹ ODF</td>
<td>68</td>
</tr>
</tbody>
</table>
While the dryer load is similar for both cases, the lower moisture in the fibre leaving the dryer for the post-dryer resin addition case requires higher exit temperatures, increasing the energy required and the fire risk.

However there was a consensus from the earliest reports (Gran 1982, Bucking 1982, Hammock 1982) that blowline blending required higher resin addition rates to achieve given properties in the panel. This view continued in later reports with Frashour (1990) quoting incremental resin addition rates (resin solids on dry fibre) of 0.5% – 2.0% for blowline addition, with panels using 7% – 8% resin addition rates for post dryer blending requiring 9 – 10% when the resin was added at the blowline. Smith (1998) in his survey suggests that the difference is even greater.

The cost increment is significant. A Canadian study (Poliquin, 1998) places the adhesive cost for MDF at $C36.0 m^{-3}$, for blowline resin addition. This comprises 26% of the total variable cost, made up of wood, adhesive and other additives, labour and purchased energy. If the resin penalty for blowline blending is 10 – 20% of total resin the additional cost of blowline resin addition is $C3.6 – 7.2 m^{-3}$ or $C720,000 – $C1,440,000 yr^{-1}$ for a typical 200,000 m^{3} yr^{-1} plant.

The benefits of blowline blending outweighed this cost and this process became the dominant method in the MDF industry. With a growing market, the focus for the plants was to increase output. While resin cost has always been a major issue, the investigation of alternatives that might reduce the additional resin did not have the highest priority, particularly as there was no clear direction as to how this might be achieved.
1.2 Blowline Blending - Plant Experience

The literature provides some insights into the blowline resin blending issue. The reference material on blowline resin blending is almost exclusively from industry forums, with very little appearing in the refereed journals covering wood and wood products.

On the other hand, while equipment suppliers have focused considerable effort on the development of the mechanical blenders used for particleboard, very few of the improvements in MDF blowline blending have come from this source. It could be assumed that there is little potential revenue in selling a new pipe.

At yet another level, most plants have been trying different approaches to solving the problems associated with blowline blending. Very little of this has been reported, but there are some significant pointers in this experience that have helped shape the current investigation.

Haylock (1977) reported the use of Phenol Formaldehyde (PF) resins added at the blowline to produce fibreboard siding, with the Rangiora plant being set up with this capability. Initially this plant did make such a PF bonded product. PF resins require higher temperatures to cure in the press, resulting in longer press times than the much more reactive urea formaldehyde (UF) resins used for MDF. This difference in curing conditions led to the assumption that the elevated temperatures in the blowline and in the dryer could start to cure the UF resin, leading to a loss of resin bonding capability in the press.

Haylock also reported that trials adding UF resins to the blowline were carried out in the CTP plant at Rangiora, New Zealand in November 1976. Similar trials were underway at the Medite MDF plant in Oregon, but no date is given (Hammock, 1982). The Medite plant had post dryer blending capability, so a direct comparison of usage levels was possible in this plant, but data on this was not included in the paper.

The first analysis of blowline blending appeared in the 1982 proceedings of the Washington State University Particleboard Symposium, when three papers covered the topic.

Hammock (1982) described the blowline resin addition system used at the Medite plant in Oregon and compared this with the blenders also installed at the plant.
While the improved product from blowline blending offset the increased resin cost, there is little analysis of the blowline blending process. The solution to the higher resin consumption was seen in terms of optimising the resin formulation.

In a general paper, Gran (1982) discussed the early experience with blowline blending. While supporting resin addition at the blowline, the paper acknowledged that other approaches could also be successful. Gran also estimated fibre and resin volumes in the blowline. The problem of higher resin usage was seen as a resin rather than a process problem.

Bucking (1982) reported on pilot plant comparisons between MDF made with blowline blending and post-dryer resin blending. The formation of fibre - resin balls in the post dryer blenders was attributed to the greater specific area of fibres. Turbulence in the blowline was identified as important in achieving a good result, but the advancement of the resin curing process at the temperatures encountered in the blowline and in the subsequent dryer was considered to be the reason for the higher resin requirement for blowline resin addition.

A major pilot plant study (Maxwell et al. 1984) examined the effect of a number of plant and material factors on MDF panels, comparing those prepared with resin added at the blowline with panels made with resin added to the fibre after drying. In line with the perception that the resin cure is advanced as it passes through the blowline and dryer, this study focused on resin - fibre interactions and how these might be modified through the use of catalysts or retarders. It also discussed how the press closing could be controlled to improve panel strength properties. Neither the blowline configuration nor conditions was discussed.

Two papers presented at the 1990 NPA Resin and Blending Seminar examined blowline blending. Waters (1990) examined theories relevant to the "black box" of the blowline and dryer and concluded that precuring of the resin before the press remained the most likely reason for the increased resin requirement. Frashour (1990) lifted the lid on this box a little and, in a comprehensive review of MDF resin blending, addressed the reason for the increased resin requirement when the resin was added to the blowline. The times in the blowline and the dryer were estimated and it was concluded that if advancement of the resin cure is the reason for the increased resin requirement, then this must occur very quickly. Blowline configurations were reviewed, but it was concluded that there was no clear direction for improving blowline blending performance.
Robson (1991) discussed blowline flow conditions for the Bangor pilot MDF plant and concluded that velocities could exceed the speed of sound. The laws governing flow of compressible fluids in pipes do not support this conclusion. These predict that the pressure will remain at a point where the specific volume of the compressible fluid is such that the velocity stays below the sonic level.

Robson also calculated resin drop sizes resulting from the interaction between the resin jet and the steam flow in the blowline and compared this with the size of the fibre. He also calculated the number of collisions between fibres in the blowline and raised the possibility that these may contribute to distributing the resin between the fibres.

In a further paper (Robson et al. 1998) this approach was developed and improvements in panel properties were attributed to a revised blowline configuration which was not described. Their conclusion that the blowline steam flow is determined by the blowline configuration is not supported by the current investigation.

Cooper (1992) investigated the reasons for resin spotting in the Carter Holt Harvey (CHH) MDF plant in Rangiora. Resin spots in the panel were identified as having two to five times the average resin content of the surrounding panel. Buildup from both the wall of the blowline and the dryer tube was found to have similar elevated resin to fibre ratios. Several different nozzle arrangements were tried, without influencing the resin spot frequency in the production over the trial periods. Similarly a trial based on heating the resin from 20°C to 60°C showed no change in the resin spot incidence. Cooper was able to measure the velocity of the fibre in the blowline using short duration flash photography. This provides a validation point for the calculation of the steam flow in the blowline developed in the current investigation.

Cooper concluded that the best method of eliminating the resin spots was to separate this material from the good fibre before the press line. It is interesting to note that such separators have become commonplace in MDF plants, particularly ahead of continuous press lines making thin panel, where the presence of hard lumps in the fibre can damage the steel belts used to convey the mat through the press.
With some sense of déjá vu, this development has led to recent promotion of post-dryer blending for MDF manufacture, on the basis of its claimed lower resin requirement.

Smith (1998) surveyed resin blending in North American MDF plants. This revealed that both blowline and post-dryer were being used with 75% of the plants using blowline resin addition, 11% having both blowline and post-dryer resin blending capability and 14% with post-dryer blending, this last group all being older plants. Smith commented that the newer plants used blowline blending exclusively. His data indicated a significant increase in resin requirement for blowline blending, quoting average resin to fibre ratios (as % on ODF) of 7% for post-dryer blending and 11% for blowline blending. The study also reported that resin efficiency was better in plants with a higher steam to fibre ratio (based on total steam flow to the refiner). While the additional resin requirement for blowline blending was accepted, few individual plants were able to determine the real cost of this for their particular operation and product range and it was accepted as the cost of producing a marketable MDF panel.

The survey also reported a ranking of the problems associated with blowline blending systems identified in the survey, with the top four by frequency being:

- Buildup on the blowline and dryer walls
- Plugged resin nozzles and lines
- High resin usage
- Spots in the panel.

This suggests that blowline resin injection systems in the plants covered by the survey did not have the desired reliability, nor had they eliminated the resin spot incidence.

There are two other areas of broader interest to the MDF resin blending issue. Although these do not address the resin blending issue directly they provide additional insights into the fibre - resin relationship in MDF.
1.3 Identification of Resin on the Fibre Surface

There have been several attempts to establish a method that would allow the location of the resin on the fibre to be studied at different points in the process. One approach was to identify the resin on the fibre so as to define the resin distribution on the fibre that gave the best resin performance. However UF resins are transparent when cured and not easily identified on the fibre surface. Gran (1982) compared photographs of fibre with resin added at the blowline and after drying and claimed that these showed very little difference between the two approaches. It is this difficulty in identifying the resin that makes this approach problematical. Various tracers have been used to allow the resin to be identified, but in the absence of a clear relationship between resin distribution on the fibre and the expensive tracer, a plant trial has not been justified. Chapman (1979) reported on a trial that used radioactive tracers to identify the uniformity of resin distribution on a macro scale.

Kamke et al. (2000) reviewed previous work on resin distribution and discussed an optical approach to measuring phenolic resin distribution using digital image processing. Phenolic resins have a distinctive red colour and could thus be distinguished against the background of the wood or fibres of the composite. To observe UF resins on fibre, an acid-dye mix was sprayed onto fibre that had wet resin on its surface. The acid cured the resin in situ and the dye allowed the resin to be distinguished when viewed under UV light. A plant trial using this technique was not conclusive.

Feng & Hutter (2001) reviewed previous attempts to incorporate a tracer to make the UF resin visible and described a patented method of visualising these resins by incorporating Cu$^{2+}$ ions in the resin, thereby allowing them to be identified by Energy Dispersive Analysis of X-rays (EDAX), or by X-ray fluorescence. The ability to quantitatively map the resin on an MDF surface was seen as a significant advance, but the relationship between resin distribution and panel performance was not established.

Loxton et al. (2003) described a fluorescent label that is chemically bound to a UF resin, thus ensuring that the label does not move independently of the resin in any of the processing stages after resin mixing and identified a change in resin distribution in the hot press. The label was visualised using confocal microscopy.
1.4 Fracture Mode Studies

A study of the failure mode in the Internal Bond (IB) test (Butterfield et al. 1992) provided data suggesting that the size of the resin bond was significant in the strength of the MDF composite. This work showed that the most common failure mode in the IB test occurred not in the resin bridge or its attachment to the fibre, but within the S2 layer of the fibre wall. The S2 layer is the main structural layer of the fibre and this failure mode suggested a weakness at this point in the fibre, probably close to the S1 - S2 interface. It is not known whether this weakness is inherent in the fibre, or induced by the forces generated in separating the fibres in the refiner. No other references to this failure mode have been found, but fibres are not normally subjected to such a tensile stress in the radial direction of the fibre, or to the comparable shear force acting tangentially.

The consequence of this failure mode is that resin performance, as measured by the IB test, will improve as the resin bonds become smaller and for a given resin content, are therefore present in greater numbers. The increased number of smaller bonds allows a higher load to be transferred through the weakness between the S1 and S2 layers before the intra-wall failure occurs by distributing this over a greater area of the intrawall layer, both that beneath the resin bond and adjacent to its perimeter. This hypothesis suggests that it is the number of the resin bonds formed rather than the adhesive performance which determines the strength properties of the composite, at least as far as these are measured by the IB test.

However this test is regularly used to determine the required resin addition rate. The test is described in most panel product standards (EN319:1993) and involves attaching loading blocks with an adhesive to both faces of a 50 mm square sample of the panel. The assembly is loaded into a tensile testing machine and a strain applied until the sample fails in tension. The failure will occur at the weakest point in the thickness of the composite. Most of the strength properties of composites are dependent to some extent on the density of the panel, with the correlation being significant but not strong. For the IB test, the expected failure point will be at the lowest density point in the thickness of the panel, emphasising the importance of density profile in panel performance.
1.5 Conclusions

There are several conclusions that can be drawn from the published material covering blowline blending.

- There is an increased resin requirement when the resin is added at the blowline. (Smith, 1998)

- Initially this was thought to be caused by the resin being affected by the temperatures in the blowline and the dryer and it was suggested that resin formulations needed to be changed to overcome the problem. (Gran, 1982, Bucking, 1982, Maxwell et al. 1984, Waters, 1990).

- Despite this there appears to have been little progress through development of resin technology.

- The failure mode in the IB test suggests that improved strength will result from a greater number of smaller resin bonds. This suggests that resin atomisation is important.

- Increasingly it is the blowline and perhaps more importantly the flow conditions in the blowline that has become the focus for improving fibre-resin mixing in making MDF (Frashour 1990, Robson 1991, Robson et al. 1997).
2.1 Scope

This part of the thesis covers a model of the MDF blowline blending process that, until this work, has not been fully described. Literature on the blowline blending process is limited; with reports on pilot plant work inconclusive (Robson 1991). Most MDF plants have addressed the issues of high resin usage and resin spots in the panel with little reported success (Cooper 1992, Smith 1998). The model of the blowline blending process that is the subject of this thesis arose from plant trials designed to address these specific issues. Development of the model has been carried out in plant investigations that have continued to shape the model and also reinforce its validity.

The blowline transfers fibre from the refiner to the dryer, both also shaded. The resin mixes with the fibre in the turbulent flow in the blowline as the pressure drops from 8 bar(G) in the refiner to atmospheric in the dryer. Mass and energy flows in the refiner determine the flow in the blowline; the outcome of the resin blending affects some aspects of the dryer operation, but the blending result is monitored in the measurement of the strength of the panel after the press in the internal bond test.

The blowline blending model has been applied in 25 MDF plants worldwide. It has been successful in identifying the factors that determine the outcome of the blowline blending process and in showing how these can be optimised to improve the blending result. Specific outcomes from these investigations include:

- Resin savings, with the same panel properties being achieved with 25% less resin in one case.

- Identification of the cause of buildup in the blowline and on the dryer wall, allowing these to be controlled, reducing downtime requirements for cleaning as well as reducing formaldehyde content in the dryer exhaust.

- A design approach that allows a blowline to be optimised to maximise fibre capacity within available steam supply or dryer capacities.
The model is presented in this thesis and its rationale and development examined. As a plant-based model it covers a broad area. It focuses on the refiner conditions and how these determine the blowline flow and on the size of the resin droplets entering the blowline. The ability to calculate the steam flow in the blowline, while not in itself a complex calculation, was critical in linking the diverse observations on blowline blending into a comprehensive model.

The size of the resin droplets as they enter the blowline is significant in the blending outcome, with both plant experience and fracture mode studies (Butterfield et al. 1992) suggesting that the droplets should be as small as possible. There are however links between the blowline steam flow and the droplet size that may limit the nozzle performance where steam velocities are below the optimum level. Nozzle performance is examined and the development of a steam-atomised nozzle described. This nozzle is produced commercially. It is in use in a number of plants as part of blowline optimisation process and has been used in a plant to successfully solve a difficult problem of blockages with the previous nozzle design.

2.2 Objective

The objective of this thesis is to critically review the development of the model, to validate the approach used and to determine limits for further development of the model. The breadth of the model precludes an in-depth investigation in this thesis of all the areas covered and this aspect is left to others.

The thesis addresses two main areas.

- The method for determining the blowline flow and its characteristics is examined, with the implications of this on the resin blending process and on the design of the blowline considered.

- Equations for determining the resin droplet size under blowline conditions are reviewed. The resin droplet size given by these equations is considered in relation to the effect of this variable on both the resin-fibre mixing process in the blowline and on the resulting MDF panel discussed.

The model indicates that the blending outcome will improve if both blowline velocity increases and resin droplets become smaller, with no suggestion that present designs have reached a limit from this perspective. However there are other limits to
both increasing blowline velocities within the available pressure drop in the blowline and in achieving atomising performance closer to that calculated from existing nozzle designs that will need to be overcome to allow continued development of the blowline blending process.
Chapman (1998) presented a comprehensive blowline blending model that is the subject of the current investigation. This model was based on a combined mass-energy balance over the refiner that was used to calculate the steam flow in the blowline. Once the steam flow was established the blowline diameter could be selected to give the steam velocities that have been found to give good blowline blending results. This also defined the requirements for resin injection. The refiner calculation showed how blowline conditions could be maintained over the full range of refiner production rates necessary to meet the fibre demands of the press.

This model has been presented in other Symposia (Chapman 1999), (Chapman and Jordan, 2003) and as an invited presentation to three Composite Panel Seminars in USA and in Canada in 2002 (Chapman and Jordan, 2002). It is also the basis for a paper on refiner operation (Chapman, 2001). Over this period the model has been used to optimise blowline blending performance in 25 MDF plants throughout the world, in New Zealand, Australia, Malaysia, Europe, Chile, USA and Canada. Much of the data used in this thesis comes from the reports prepared as part of these investigations. The basic model has proved to be particularly robust; its application under a variety of different conditions has contributed much of the material discussed in this thesis. It has also facilitated explanation of other aspects of the blowline and dryer operation.

### 3.1 Blowline Conditions

The blowline flow comprises steam, water and fibre. The steam carries the fibre and the water, which may be absorbed within the fibre or present as discrete liquid droplets, from the refiner exit through the blowvalue to the dryer. The flow is the outflow from the refiner, representing the accumulated wood and water flows into and out of the refiner system. The balance between steam and water is determined by energy considerations.
The resin enters the blowline through an opening that may be a nozzle of varying degrees of sophistication, or just a pipe. The resin and the fibre interact in the turbulent flow in the blowline and the resin becomes attached to the fibres. The blowline discharges the flow from the refiner into the dryer air stream, providing a significant reduction in the fibre concentration that reduces the possibility of further interactions between the fibres and the attached resin droplets. It also means that the mixing of the fibre and resin must be completed in the blowline before the flow mixes with the much larger volume of the dryer air.

The blowline blending process is not easy to study, not least because the blowline conditions are difficult to replicate in a laboratory situation. Some of the difficulties in establishing a meaningful intermediate point that would allow the processes to be separated for individual study have been discussed above. There are laboratory refiners with blowline blending capabilities and while these have provided some insight into the process, the scale difference between the laboratory and industrial plants creates difficulties. Robson (1991) reported significant differences in the resin droplet size and in other blowline parameters, between the laboratory and full-scale blowlines, but it is not clear that these differences are reflected in the properties of the respective panels.

The model described in this thesis is developed largely from plant experience and takes a broad view of the process. The internal bond (IB) test is used as the primary indicator of the strength of the panel and the resin addition rate is changed in response to the results from this test. The IB test samples are taken from the panel after the hot press. Fibre moisture content and conditions within the hot press can influence the results. However the importance of these variables is well established and they are well controlled in most plants. It may be assumed that any process change affecting resin blending that leads to a change in the internal bond test value with other plant conditions remaining constant would have to be explained by the model. The difficulty with this approach is that the model must be a complete and comprehensive representation of the process, with a very small window for error.
3.2 Plant Experience

3.2.1 Resin Dilution

The consensus in the literature is that the reason for the increased resin requirement with blowline blending is the effect of the temperature in the blowline and in the dryer on the resin as it passes through these stages. Despite extensive work on this aspect, as described by Maxwell et al. (1984) and with individual plants making changes to their resin formulations to minimise this effect, no significant gains have been reported through this approach.

At the same time, most plants were experimenting with different blowline and resin injection configurations in an effort to overcome problems such as buildup in the blowline and on the walls of the dryer, as well as to reduce resin cost. One factor that appeared to be beneficial was to reduce the solids content of the resin by adding additional water prior to injecting the resin into the blowline.

This shows in the resin solids contents in some of the plants where the blowline-blending model has been applied. Figure A3 shows the resin solids level as it is added to the blowline. The UF resin is received into the plant at 60% or 65% resin solids and five plants (U, M, L, G, and F) are using resin without dilution. The three plants (H, E, N) adding resin at 60% are also probably using resin without further dilution. The other plants are adding water to the resin, presumably because this has been found to be beneficial.

![Figure A3](image-url)  
*Figure A3 – Resin Solids Content for Blowline Resin Blending.*
The additional water added to the resin increases the dryer load and the dilution limit may be determined by dryer capacity. The ultimate limit for dilution water flow is determined by resin stability. Depending on the formulation, the resin becomes unstable at 30 – 35% resin solids.

3.2.2 Resin Atomisation

Significant insights into the development of the model that is the subject of this investigation came from work in several plants where resin performance was an issue.

One significant trial involved a plant (Plant T) with two fibre preparation lines, one preparing fibre for both top and bottom faces of the panel, the other preparing material for the inner core of the panel. This arrangement was designed to allow material with different fibre quality or resin contents to be used in these two areas of the panel.

In this case the same resin content was used in both fibre preparation lines. The trial set out to optimise nozzle configuration on the core fibre line, with the resin level being reduced to maintain internal bond values as the nozzle configuration was changed to improve atomisation performance. The nozzle configuration on the face fibre line initially remained unchanged, but the resin flow was reduced in line with that being used in the core fibre line. As the resin flow was reduced, resin spots began to appear in the surface of the panel. This was corrected by changing the nozzle configuration on this line. The refiner conditions were stable during the trial, but as this trial predated the development of the refiner mass - energy balance, the blowline conditions cannot be calculated.

There were several significant aspects to this trial.

- It demonstrated that resin spots were formed as a consequence of changes in the size of the resin droplets. This occurred when the flow through the pressure - atomised nozzle was reduced, with no change in the configuration of the nozzle in the blowline from the refiner which fed fibre to the outer faces of the panel. As a consequence of the reduced flow the pressure drop across the nozzle fell, leading to larger resin droplets. These eventually reached the point where they were of sufficient size to form resin - rich aggregates that showed as resin spots in the panel. Changing the nozzle configuration to increase the pressure drop
across the nozzle reversed this process. It is unlikely that the resin droplets became large enough to form the resin spots, suggesting that some aggregation process was occurring following the injection of the resin. The refiner and dryer conditions were not changed during the trial.

- Increasing the pressure drop across the nozzle in the core fibre line by changing its configuration reduced the resin droplet size, leading to an increase in the strength of the panel as measured in the IB test. Continuing this process allowed the internal bond strength to be maintained with a 25% reduction in resin addition rate.

- This trial suggests that there is a continuum of performance in blowline blending, with an aggregation process at one end, leading to resin spots when resin atomisation is poor, while at the other end, resin efficiency is improved when the resin droplets become smaller.

- The trial also demonstrates the importance of good resin atomisation in resin performance.

This plant had relatively long blowlines, with the resin injection point close to the refiner. It may be that this provided a longer time for the aggregation effect to become dominant.

Experience in another plant (Plant D) demonstrated the importance of resin atomization. The blowline diameter had been reduced to increase steam velocities in the resin blending section, with the three original resin injection nozzles being used. Resin efficiency improved, but resin spots remained. This was traced to the resin piping to the nozzles, with one nozzle having a much greater pressure drop in the supply line. This reduced the resin flow to this nozzle, resulting in a lower pressure drop across the nozzle, with larger resin droplets. When this situation was corrected the resin spots disappeared.
3.2.3 Blowline Conditions

A third trial of significance (Plant X) showed the importance of blowline conditions. In this trial, IB levels improved significantly when the steam flow in the blowline was increased. This was achieved by increasing the steam flow into the refiner housing, so that refiner conditions, as far as fibre preparation was concerned, were not changed. The effect of this was to increase the steam velocity in the blowline. With resin injection and refiner conditions held constant and no change in the press settings, this showed that increasing the steam velocity in the blowline lead to increased IB levels in the panel, indicating improved resin efficiency.

Following this trial the blowline diameter, initially 150 Schedule (Sch) 40 pipe was reduced to 100 Sch. 40 pipe in the resin blending section following the optimising of the blowline configuration. The cross sectional area of the smaller pipe is 50.3% of the original, resulting in a doubling of the steam velocity calculated at the same pressure. A significant improvement in resin consumption was achieved. The pressure drop in the reduced diameter section of the blowline increased, but this was accommodated by opening the blowvalve further, so that the overall pressure drop between the refiner and the dryer did not change.

This effect is consistent with general experience in plants where the resin content necessary to achieve required panel property levels increases as panel thickness increases. It is difficult to explain this purely in terms of a thickness effect, or the conditions reached in the press, which will have been determined to ensure that the resin has been adequately cured. However in a plant where capacity is limited by the press, the fibre rate will fall as panel thickness increases and unless the blowline steam flow is deliberately increased, the blowline velocities will fall.

While a relationship between blowline steam flow and resin blending performance would be expected and is indicated in the conclusion that resin contents were lower in plants where the steam flow to the refiner was higher (Smith, 1998), this by itself does not fully describe the situation. The conclusion from the IB fracture mode study (Butterfield et al. 1992) is that smaller resin bonds in greater numbers improve resin performance. However this study does not quantify this relationship.
3.2.4 Fibre – Resin Interactions in the Blowline

In view of these two observations, the suggestion by Robson (1991) that the collisions between the fibres and resin droplets may be significant in the blowline blending outcome is helpful, particularly when the fibre to steam volume ratio is calculated, as shown in Figure A4. The steam to fibre mass ratios calculated for the blowlines of the plants studied ranges from 0.25 to 1.0. In the case discussed in Chapter 4, this ratio is shown in Figure A13 (page 41) as 0.4212 kg kg⁻¹ ODF at the entry to the blowline and 0.5177 kg kg⁻¹ ODF at the discharge to the dryer. Calculating the steam volume as saturated steam at a range of pressures and the fibre volume at a density of 400 kg m⁻³ gives the fibre volume fraction as between 1% and 3.2% at 5 bar pressure over the range of steam to fibre mass ratios encountered, this falling as the pressure reduces along the blowline.

![Figure A4. - Fibre to Steam Volume ratio in Blowline](image)

This relatively low fibre concentration implies that the resin is not being sprayed into a dense fibre mass, rather the resin droplets are carried along with the fibre by the steam flow and interact with the fibre in the collisions caused by the turbulence created by the steam flow in the blowline.

The trial discussed in Section 3.2.2 on page 17 (Plant T) demonstrating that resin spots could be created by increasing the resin droplet size, provides an important insight. It is unlikely in this case that the reduced flow through the nozzle resulted in
resin droplets of the size necessary to produce the visible resin spots in the panel and this suggests that a subsequent aggregation process becomes dominant as the resin droplet size increases. The resin droplet sizes are examined in Chapter 8.

This fibre to steam volume ratio becomes significant in the three-phase flow existing in the blowline after the resin is injected. The conditions suggest that the interaction between the resin droplets and the fibres will not necessarily be instantaneous, but will continue as long as these phases coexist within the blowline. The formation of resin spots can be explained by the formation of liquid resin bridges between the fibres that are of sufficient strength to persist in the flow conditions in the blowline. As these become larger they attract further resin droplets until the material is discharged into the dryer air stream. Once this process becomes established, the larger particles will shield resin droplets from the turbulence in the blowline flow, allowing the growth process to proceed at an accelerating rate.

It is also unlikely that the fibre is uniformly distributed over the blowline cross section at any point, with the aggregation of the particles into "ropes" being common where solid particles are carried in a gas flow. This effect is not considered in the fibre-droplet interactions and it is assumed that each fibre is able to respond independently of any adjacent fibres.

It is possible that impacts between resin, either as a discrete droplet, or attached to a fibre and the blowline wall also play a part in the aggregation process, particularly in the accumulation of resin in quantities well above the overall average for the fibres as reported by Cooper (1992).

The flow in the blowline is highly turbulent, with Reynolds numbers typically in the range of $1.2 - 2.3 \times 10^6$, creating force gradients in the flow. Reynolds numbers are calculated in Section 6.2.1 on page 66. These forces will act on any particles or assemblies in the flow. If the forces acting on an assembly are weaker than the resin bonds holding the assembly together, it will survive and may continue to grow as other fibres and resin droplets attach themselves to it.

The converse of this situation is particularly significant in the blowline blending model. The flow leaving the refiner comprises fibres, which may be individual fibres, fibre fragments, or particles comprising several fibres, in a flow of steam. At some point along the blowline resin droplets are introduced into this flow. The volume ratio
of the fibre in the steam, shown in Figure A4 on page 40 is such that the resin droplets will not necessarily contact the fibre immediately. However the turbulent flow in the blowline leads to impacts between the entities. The collisions between two fibres are not significant in the resin mixing process. Collisions between two resin droplets will cause aggregation. Those collisions involving a resin droplet and a fibre are significant in determining the outcome of the resin blending process, shown diagrammatically in Figure A5.

![Diagram of fibre and resin droplet interactions in the blowline]

**Figure A5 – Fibre - Resin Droplet Interactions in the Blowline.**

The primary collision is defined as the first contact between a resin droplet and a fibre, in which the resin droplet attaches itself to the fibre.

The secondary collision is defined as one in which the resin droplet attached to a fibre is involved in a collision with a second fibre. A liquid resin bridge develops between the fibres. The outcome of the first of the secondary collisions determines the overall blending result.

If this resin bridge survives it has the potential to continue to grow through further collisions, eventually becoming a resin spot.

If the resin bond is broken the original resin droplet is split into two, reducing the quantity of resin on the original fibre and creating another potential bonding point in the resin now attached to the second fibre. As the original resin droplet is now split
between the two fibres, the quantity on each fibre is now smaller. This makes the separation outcome more likely in subsequent collisions.

If the resin bond is not broken the assembly survives and will continue to grow. As further fibres attach themselves to the assembly it becomes larger and its size may shield further fibres or resin droplets from the shear forces in the blowline flow.

The evidence for the aggregation outcome is strong, based on the trial discussed in Section 3.2.2 (page 17). The separation outcome is less easy to prove, but it is a logical extension of the aggregation model, which is supported by the conclusion of the IB fracture mode study (Butterfield et al. 1992), that resin performance as measured by the IB test will improve if resin bonds are smaller. From a resin efficiency perspective, the survival of a liquid resin bond between two fibres represents a lost opportunity to create two smaller resin entities by splitting the original resin droplet. The resin droplet size is examined further in Chapter 5 (page 44).

There is no indication of the lower limit for resin droplet size. Robson (1991) postulates several possibilities for distribution of the resin over the surface of the fibre but the question of the most effective arrangement is not clear. There are several requirements to be met before a bond is formed that will contribute to the strength of the composite. As well as the size of the resin droplet, factors such as the arrangement of adjacent fibres and the extent of contact between them will determine how a particular bond may contribute to the strength of the composite. These factors are dependent on processes other than the fibre blending stage. For the present study it would appear that the lower limit has not been reached in commercial plants and that efforts should continue to improve resin atomisation so that smaller resin droplets can be produced.

In practice the resin droplets will have a particular size distribution and blowline conditions may not be uniform. Large resin droplets in an overall population of much smaller ones may lead to resin spots even where resin efficiency is good. However the collision model does suggest the conditions which will favour either of the two outcomes of the collisions between fibres and resin droplets in the blowline.
3.3 Resin Spots.

In this analysis, resin spots are seen as the ultimate end of the aggregation process in the blowline. While the final outcome of the aggregation is a visible resin spot in the panel, there are intermediate steps in this process.

1. The results of the aggregation process may not be visible in the panel.

2. A brown fleck is sometimes apparent in the panel, as shown in Figure A6 on page 25. Initially this was thought to be associated with the fibre, but analysis of these showed the increased resin content that is characteristic of the products of the aggregation process. This condition probably appears when blowline conditions move slightly in the direction where the aggregation outcome becomes more significant.

3. Larger resin spots shown in Figures A7 and A8 on page 25 can occur, but these are generally much lower in incidence in the panels. Panels with spots of this size would normally be downgraded.

3.4 Summary

In summary, the separation outcome will be more likely if:

- The resin droplets entering the blowline are as small as possible.

- The turbulence in the blowline is as high as possible, creating the highest shear force gradients within the flow. This will be achieved if the blowline steam flow is as high as possible. Velocities calculated at 4.5 bar of 80 m s⁻¹ and above are found in plants with good resin efficiency.

- The fibres are undamaged and uniform in size so that the force gradient has a greater distance over which to generate the force necessary to cause separation. Small fibre fragments will be shielded by the larger ones and thus be more difficult to separate.
Figure A6 - Resin Flecks in MDF panel. scale is mm

Figure A7 - Resin Spot - actual size, scale is in mm

Figure A8 - Resin Spot - actual size, scale is in mm
The observations and studies discussed in Chapter 3 have been integrated in the model of the blowline blending process shown in Figure A9.

The one factor that links these independent observations is the steam flow in the blowline. It is this data that allows the separate and distinct observations in this area to be brought together into the comprehensive blowline blending model that is presented in this thesis.

The primary inputs to the model are:

- The refiner conditions, particularly the steam flows, refining energy and differential pressure across the refiner plates determine the blowline steam flow and also impact on fibre quality are discussed in this Chapter.

- For a given steam mass the steam velocity at any given point is determined by the diameter of the blowline and the pressure. One important consideration is that the collisions significant in the resin blending outcome continue to occur over
the length of the blowline from the point where the resin is injected until the fibre is discharged into the dryer. The application of the blowline steam flow data to blowline design is discussed in Chapter 6 (page 61).

- The resin properties and the injection nozzle determine the resin droplet size. This may also be influenced by interaction with the steam flow in the blowline. This aspect is discussed in Chapter 5 (page 44).

**4.1 Implementing the Model**

The calculation of the steam flow in the blowline is an important part of the blowline blending model as it provides a basis for bringing the various observations and experiences with blowline blending together and provides the starting point for its implementation. The application of the model to optimise a particular blowline is summarised below.

The blowline carries the fibre and water from the refiner to the dryer and as such represents the accumulation of all mass and energy flows in or out of the refiner system. The steps involved in analyzing a particular blowline are listed in summary form below. The mass - energy balance calculation is implemented as an Excel spreadsheet and discussed in Section 4.1.2.

1. The mass - energy balance programme is set up for any particular or non-standard operation of the refiner

2. A set of data representing normal operation of the refiner system is collected to complete a trial mass - energy balance. Ideally this is close to the maximum fibre flow condition.

3. The trial mass - energy balance identifies data points which may not be correct. Steam and water ratios at various points in the system are checked against values for similar refiners.

4. When a satisfactory mass - energy balance has been achieved this is extrapolated to the maximum fibre flow - maximum refining energy condition for the refiner.
5. The blowline steam flow at the maximum fibre flow is used to determine the blowline diameter for the resin blending section. Velocities in this section, calculated at 4.5 bar pressure, should be above 80 m s\(^{-1}\) and below the choke flow limit of 474 m s\(^{-1}\) at atmospheric pressure at the dryer entry.

6. The resin nozzles are located in the reduced diameter section. The blending length is normally at least 50% of the blowline length.

7. For long blowlines the section upstream of the resin blending section can be designed to minimise pressure drop, with velocities calculated to transport the fibre.

8. The mass-energy balance is then used to determine the best way to maintain blowline velocities at the minimum fibre production rate. Usually the housing steam flow is increased to maintain blowline steam flow as the steam coming from the refiner operation falls.

4.1.1 The Refiner

The refiner is an important part of the MDF process, separating the feed material into individual fibres.

The first stage in this process is heating the material to the point where the lignin, present in greatest concentration in the material between the individual fibres, becomes plastic, at a temperature generally taken as 140°C. The heating occurs firstly in an atmospheric steaming bin and then in a pressure vessel maintained at a pressure of some 8 bar by injecting steam.

This prepared material is transferred from the preheating vessel into the refiner where the fibres are separated by the mechanical forces between radial bars on two closely spaced discs, one rotating at 1500 rpm (50 Hz) or 1800 rpm (60 Hz) and one stationary. The housing in which the discs operate is also pressurised, with the pressure differential across the refiner plates important in controlling the fibre flow through the refining zone. The fibre is discharged from the refiner at the pressure in the refiner housing, typically about 8 - 9 bar, in a flow of steam.
The blowline carries this stream of wet fibre in steam from the refiner to the dryer, with the pressure dropping from that in the refiner housing to the essentially atmospheric pressure at the dryer. This pressure drop occurs across the blowvalve, which can be adjusted to provide a variable pressure drop and the line losses in the blowline.

The refiner also has a significant effect on the quality of the fibre. The blending model predicts that the best result will be achieved where the fibres are uniform in size. In particular the presence of fines or fibre fragments is significant in the blending process, increasing the possibility that the aggregation outcome will dominate. This is because greater shear force gradients are necessary to separate the fibres as these become smaller.

Some fibres are damaged in the size reduction processes in the preparation of the feed material to the refiner. For a chip prepared from wood with an average fibre length of 3 mm by cutting across the grain of the wood every 25 mm, statistically one in every 9 fibres will be cut into two pieces by this operation. These fines will generally be portions of fibres with a length determined by where the cut has occurred in relation to the fibre position. For fibre prepared from waste streams from sawmills, such as sawdust and shavings the proportion of damaged fibres is much greater. In the case of planer shavings, some fibre fragments resulting from splitting of fibres will also be present.

In the refiner the impact of the bars on the refiner plates will cause a failure in the weakest zone adjacent to the impact point. If the material has reached the temperature necessary to plasticise the lignin, this failure will happen in the weakened zone between the fibres, leaving the cellulose intact. If this point has not been reached, the failure will occur at the point of greatest stress. This may lead to the fracture occurring within the cellulose part of the fibre, resulting in additional fibre fragments, or fines being produced.

The refiner conditions have a very significant effect on the outcome of the blowline blending process, both in determining the flow conditions in the blowline and the effect on the generation of fines. For this reason its operation is discussed in some detail.
The refiner and its associated processing equipment are shown schematically in Figure A10 and consist of the following stages:

1. Prior to the refiner the chips may be washed to remove stones and dirt. If wastewater from the feed screw (item 4 page 30) is returned to the chip wash, then the chip wash will operate at a temperature above ambient.

2. After the washer, (not shown) the chips are drained of surface water and transferred to a chip bin. If a chip washer is not used, the conditions at the entry to the chip bin are used as the starting point for the analysis.

3. Steam is added in the chip bin to start the heating process. Some steam may be lost to atmosphere. The quantity can be calculated as the difference between the steam supplied and the steam necessary to provide the heat required to increase the temperature from that of the incoming material to that as it leaves the bin.

4. A screw press generates a solid plug of feed material that provides a seal between the atmospheric conditions in the chip bin and the steam pressure in the preheater vessel, while providing a continuous feed of material into the preheater. In forming the plug, water is squeezed out of the material. For fresh
chips this waste-water stream contains much of the sap from the wood, it will also contain some wood fragments. If the plant uses a chip wash, the waste-water stream may be directed to the chip wash.

5. The moisture level in the material leaving the feed screw is required to solve the mass balance. This value can be calculated if a reliable measurement of the waste water flow is available. If this is not available, a value of 0.85 kg kg\(^{-1}\) ODF is assumed, on the basis of one personal measurement made of material after the screw and confirmation that this figure is used by refiner suppliers. If necessary the impact of uncertainty in this figure can be checked by varying it in the analysis and determining the effect on the subsequent conditions.

6. The material level in the preheater vessel is monitored continuously and adjusts the speed of the screw press to maintain the desired level. The level is set at the height that provides the desired retention time in the preheater for the current fibre production rate. The pressure in the preheater is controlled by the admission of live steam.

7. Preheater pressure is typically 7 - 8 bar, although both higher and lower pressures are used. While the condensation temperature of steam at these pressures is 171\(^{\circ}\)C - 176\(^{\circ}\)C a temperature differential is necessary to ensure that the centre of the chip reaches the required temperature of 140 \(^{\circ}\)C (Roffael et al. 2001). Residence time in the preheater is typically 3 to 5 minutes. In addition to the desired reduction in lignin strength, heating wood to this temperature causes other changes. The acid buffering capacity of the wood becomes greater and colour changes occur, with the wood becoming darker (Murton, 1998).

8. The material is discharged from the bottom of the preheater vessel. A rotating scraper arm removes material uniformly from the bottom of the descending column of material, transferring this to a screw conveyor traversing the diameter of the preheater across the bottom of the vessel. The speed of this screw is controlled to determine the fibre production rate.

9. Water may be added to this screw, particularly for low moisture content feed materials. The temperature of this water can have a significant effect on the refiner conditions. It can chill the surface of the particles coming from the
preheater to the point where the lignin softening is reversed. This leads to increased levels of fines as the fracture point returns to the impact point rather than occurring in the softened lignin between the fibres.

10. In early refiners, this screw delivered the preheated material directly into the refiner. In current designs the metering screw delivers the material into a high-speed ribbon screw feeder. This conveys the material into the refiner around the periphery of the screw, while allowing steam to flow back from the refiner into the preheater. This return steam flow can also have a significant effect on the energy flows in the system and requires particular treatment in the mass - energy balance.

11. The refiner consists of a pressurised housing containing two discs, one fixed and one rotating, with a positioning system that allows the distance between the plates to be maintained in the face of varying loads from the material passing through. Each disc carries a series of refiner plates with raised bars in a generally radial configuration and channels between. The prepared material enters the space between the bars through a central opening in the stationary plate and is subjected to the impacts of the bars as those on the rotating disc cross those on the stator. It is these impacts which cause the fibres to separate. If the preheating has been satisfactory then the fracture will occur in the lignin rich middle lamella layer, minimising the damage to the cellulose fibres.

12. The design of refiner plates is the subject of considerable development. This does not impact on the mass - energy balance through the refiner, but can affect the flow characteristics of the material through the plates.

13. The rotating disc, with a diameter between 1.1 and 1.7 m, rotating at a speed of 1500 rpm (for 50 Hz supply) creates a pumping action which moves the fibre towards the periphery of the plates. Dams link the radial refining bars at several points; these force the material from the flow channels into the area between the bars where the impacts which cause the fibre separation occur. The fibre discharges from the plate periphery into a pressurised housing surrounding the plates.
14. The pressure in the housing space outside the plates is determined by the pressure drop across the blowvalve and in the blowline for the flow of steam coming from the refiner. Initially the blowvalve (see 15 below) was used to control the pressure change across the refiner plates, but the characteristics of this valve provide very poor control. As refiner discs have increased in diameter, (to 1.7 m in recent high capacity units) and as unidirectional plates which reduce refining energy have been adopted, control of the housing pressure by the blowvalve has been superseded by admitting a controlled flow of steam to maintain the housing pressure. If this pressure is higher than the preheater pressure, the fibre flow through the plates will slow and some of the steam generated in the refiner plates will flow back through the ribbon feeder into the preheater. Effectively this steam replaces a portion of the fresh steam needed to heat the incoming material to the conditions within the preheater and is calculated as the difference between that necessary to heat the incoming material to the preheater conditions less the fresh steam supplied.

15. The fibre is discharged from the refiner through a blowvalve that provides a variable pressure drop and then into the blowline which carries the fibre from the refiner to the dryer. As noted above, the blowvalve does not provide good control of the pressure change across the refiner plates and, as will be discussed later, the pressure drop across the blowvalve has negative implications for both fibre quality and resin blending effectiveness.

The importance of good control of the refiner has been recognised and modern refiners at least are fully instrumented, with pressure controls on the preheater and the differential pressure between the preheater and the refiner housing. Flow meters are installed on the steam flows to the chip bin, the preheater and the dilution water flow. The refining energy is also closely monitored. This provides the main input data for the calculation of the blowline steam flow.

The other significant flow is the fibre production rate. This must be measured continuously to calculate the resin addition rate, which is generally expressed as a percentage of the dry fibre rate. For plants using chip, the refiner feed screw can be calibrated to provide a feed rate measurement. For cases where the feed is more variable, such as plants using a blended feed of chip, sawdust and shavings, it is more usual to have a weigh-scale after the dryer, measuring the mass flow rate at
this point. The measured mass comprises fibre, resin and wax and the moisture content after the dryer and requires a calculation to establish the fibre production rate.

In addition to the flow and pressure controls, automatic controls can be used to:

- Maintain retention time in the preheater by adjusting the level in the preheater vessel in response to changing production rates.
- Maintain refining energy level (as kWh te\(^{-1}\) ODF) at a specified value by controlling the distance between the refiner plates.

Primarily the controls are directed at providing effective control of fibre quality and of refining energy, which is a significant cost.

4.1.2 Calculation of Blowline Steam Flow

The blowline steam flow is calculated from mass and energy balances over the refiner. A boundary is drawn around the system and mass and energy values are assigned to all but one of the flows crossing that boundary. Equations for the conservation of mass and energy are then used to determine the mass flow and energy content of the remaining flow. Once a flow is established, this can be used with new boundaries to determine other flows.

The calculations are relatively simple, providing there is no change in the quantity of material in the process. This is a reasonable assumption for the MDF refiner operating under steady state conditions, as the preheater, which provides the only storage vessel in the system, is usually maintained at a constant level. The mass and energy balances have been implemented as a single calculation using an Excel spreadsheet and are collectively referred to as the "mass - energy balance."

Pressures are expressed in bar (gauge), with 1 bar = 10\(^{5}\) N m\(^{2}\).

- The mass - energy balance uses the following approach:
• Enthalpies are calculated from applicable temperatures and pressures, using regression equations derived from steam tables (Rogers & Mayhew, 1995) for an appropriate pressure range.

• Calculations use normalised mass and energy flows expressed as kg or kJ kg\(^{-1}\) oven-dry fibre (ODF).

• All moisture contents are expressed as dry basis.

• The resin solids content is expressed as resin/ (resin + water).

• The calculation is based on a steady state condition, with no change in the quantity of material within the process. This assumes that the quantity of material in the preheater remains the same.

• Heat loss from equipment is ignored.

• It is assumed that thermal equilibrium is reached at each stage, with the evaporation of water to vapour occurring instantaneously.

• As long as both steam and liquid water are present, the temperature will be the condensation temperature for the pressure at that point.

• The proportion of water as steam at each point is calculated from the energy beyond that necessary to heat the dry fibre and the water to the condensation temperature at the applicable pressure at that point of the process.

• Latent heat of vaporisation is not adjusted to reflect the increased energy necessary to evaporate bound water from wood. For the refiner process, moisture levels encountered are above the fibre saturation point unless the feed material is very dry.

• Electrical energy flows included in the mass - energy balance calculation are converted into heat at 100% efficiency.

• The blowline is assumed to be adiabatic, with steam flashing from water in the fibre as pressure falls. The steam velocity at a point is determined from the steam mass flow and the specific steam volume calculated from the pressure at that point.
The spreadsheet calculates the steam velocity in the blowline at two points.

- The resin entry point (defined by a particular pressure, generally taken as 4.5 bar).
- The pressure at the point where the blowline discharges into the dryer is taken as ambient unless the calculated velocity at ambient pressure exceeds the sonic velocity.

The operation of the model is shown in the validation example discussed in the next Section.
4.2 Validation of the Mass-energy balance

Cooper (1992) measured the velocity of fibre in the blowline on Line 1 at the Canterbury Timber Products plant, now CHH Pine Panels (CHH), using short duration flash photography. The actual refiner conditions (production rate, steam flows and refining energy level) when these measurements were made are not recorded. The extrapolation of these fibre velocities to the velocity of the mass as a whole is justified for the highly turbulent conditions applying in the blowline. With this assumption this data provides a validation point for the mass-energy balance, providing the refiner conditions at the time can be determined.

The lack of refiner operating data in Cooper’s thesis is perhaps understandable. Very little work had been reported on blowline conditions up to that point. Frashour (1990) had only just suggested that the refiner conditions could be significant in the blending outcome and Cooper’s study precedes the first report of the Bangor blowline study (Robson, 1991). The incomplete data makes the use of Cooper’s results as a validation for the refiner model more difficult.

The Line 1 fibre preparation system at the CHH plant consists of two refiners in series, with the primary refiner discharging directly to the secondary unit. In this case the blowvalve, a slide valve on the outlet of the refiner, was installed on the primary refiner while the secondary refiner discharged directly to the blowline.

The actual refiner conditions were not given, but the panel production rates for the measured blowline velocities were in Appendix A9 of Cooper’s thesis. These have been converted into fibre production rates assuming 18 mm thick panels, using typical factors for this thickness to relate the fibre requirement to the finished panel volume shown in Table A2.

<table>
<thead>
<tr>
<th>Resin solids</th>
<th>R</th>
<th>9</th>
<th>% on oven dry fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wax-solids</td>
<td>W</td>
<td>0.7</td>
<td>% on oven dry fibre</td>
</tr>
<tr>
<td>Trim and sander losses</td>
<td>T</td>
<td>15</td>
<td>% incoming material</td>
</tr>
<tr>
<td>Panel density</td>
<td>D</td>
<td>725</td>
<td>kg m$^{-3}$ on ex-press panel</td>
</tr>
<tr>
<td>Panel moisture after press</td>
<td>M</td>
<td>8</td>
<td>% of dry panel</td>
</tr>
</tbody>
</table>
From these factors:

Total material into press = \((1 + (T + M)/100)\)\(D\)

or \(891.8\) oven dry kg (into press) \(\text{m}^3\) (finished panel)

This material comprises fibre, resin and wax in the proportions in Table A2, so that if \(F\) is the fibre required, the material into the press is

\(F \times (1 + (R + W)/100)\) or \(1.097\) \(F\),

and the fibre required is \(812.9\) kg oven dry fibre. \(\text{m}^3\) (finished panel)

This factor is used to convert Cooper’s panel production rates into fibre production rates through the refiner.

**Table A3 - Calculated Fibre Production Rates from Cooper (1992, Appendix 9)**

<table>
<thead>
<tr>
<th>Panel Prod. (\text{m}^3) h(^{-1})</th>
<th>Fibre Rate OD (\text{te h}^{-1})</th>
<th>Blownode</th>
<th>Housing press. bar</th>
<th>Blowline Vel. m s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.4</td>
<td>10.9</td>
<td>100</td>
<td>5.5</td>
<td>93</td>
</tr>
<tr>
<td>13.4</td>
<td>10.9</td>
<td>100</td>
<td>5.5</td>
<td>91</td>
</tr>
<tr>
<td>12.8</td>
<td>10.4</td>
<td>80</td>
<td>5.4</td>
<td>78</td>
</tr>
<tr>
<td>13.2</td>
<td>10.7</td>
<td>80</td>
<td>5.4</td>
<td>78</td>
</tr>
<tr>
<td>14.8</td>
<td>12.0</td>
<td>100</td>
<td>5.7</td>
<td>103</td>
</tr>
<tr>
<td>14.2</td>
<td>11.5</td>
<td>100</td>
<td>5.6</td>
<td>86</td>
</tr>
</tbody>
</table>

A plot of these data against fibre production rate in Figure A11 shows that there is reasonable consistency in the velocities measured, with a tendency for these to increase with increasing fibre flow. However the blowline velocity is clearly influenced by factors other than production rate.

*Figure A11 - Blowline Velocity against Fibre Production Rate for Cooper’s data.*
4.2.1 Pressure at the Velocity measurement point.

In this fibre production line, the blowvalve is installed on the primary refiner, so that the pressure at the entry to the blowline is that for the housing of the secondary refiner less the entry losses.

Neglecting the tangential velocity component, the entry losses at 5 bar pressure, (calculated as $k V^2/2g$ with $k = 1$) were less than 0.2 bar. The pressure at the point where the fibre velocity was measured was some 2 m downstream from the refiner outlet. The pressure at the velocity measurement point is taken as 0.5 bar less than the housing pressures given in Appendix A9 of Coopers' thesis, or 5 bar. This pressure is used in the mass - energy balance calculations of the blowline steam flow for the refiner line shown in Table A4 on page 40.

4.2.2 Current Operating Conditions – CHH Line 1

The mass - energy balance for CHH Line 1 was recalculated during a recent visit as a result of a focus on resin spotting in the plant. These data, calculated at a fibre production rate of 12 te h⁻¹, are shown as an example of the mass - energy balance. The data are used by arrangement with CHH Pine Panels Ltd. The data input table for the mass - energy balance is shown in Table A4.

From this data two graphs are prepared. The first of these (Figure A12, page 41) shows the magnitude of the individual mass and energy flows into and out of the system and allows an assessment of the significance of each in the overall refiner operation.

The second graph (Figure A13, page 41) shows the accumulated mass and energy flows at a number of points in the system. In this view the energy is allocated initially to that necessary to heat the wood and the water to the condensation temperature at the applicable pressure. Any energy beyond this will appear as latent heat, allowing the quantity of steam at each point to be calculated.
### Table A4 - Mass - Energy Balance Input Data Table

<table>
<thead>
<tr>
<th>MASS-ENERGY BALANCE</th>
<th>CHH Line 1 7/7/03</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wood to bin</strong></td>
<td>OD te hr⁻¹</td>
</tr>
<tr>
<td><strong>Steam to chip hopper</strong></td>
<td>kg hr⁻¹</td>
</tr>
<tr>
<td><strong>Steam Loss</strong></td>
<td>kg hr⁻¹</td>
</tr>
<tr>
<td><strong>Waste water</strong></td>
<td>l min⁻¹</td>
</tr>
<tr>
<td><strong>Plug screw</strong></td>
<td>kW</td>
</tr>
<tr>
<td><strong>Preheat steam</strong></td>
<td>kg h⁻¹</td>
</tr>
<tr>
<td><strong>Preheat Press</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Ref 1 dilution</strong></td>
<td>l min⁻¹</td>
</tr>
<tr>
<td><strong>Ref 1 Energy</strong></td>
<td>kWhr te⁻¹</td>
</tr>
<tr>
<td><strong>Energy to preheat % ref energy.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Ref 2 dilution</strong></td>
<td>l min⁻¹</td>
</tr>
<tr>
<td><strong>Ref 2 Energy</strong></td>
<td>kWhr te⁻¹</td>
</tr>
<tr>
<td><strong>Ref 1 Hous. Steam</strong></td>
<td>kg hr⁻¹</td>
</tr>
<tr>
<td><strong>Ref. Hous Press</strong></td>
<td>bar</td>
</tr>
<tr>
<td><strong>Ref 1 Blowvalve % open</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Press at resin entry</strong></td>
<td>bar</td>
</tr>
<tr>
<td><strong>Resin solids % on ODF</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Resin % solids</strong></td>
<td></td>
</tr>
<tr>
<td><strong>SG</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Blowline dia</strong></td>
<td>mm</td>
</tr>
<tr>
<td><strong>Blowline length</strong></td>
<td>m</td>
</tr>
<tr>
<td><strong>Total Steam</strong></td>
<td>kg/hr</td>
</tr>
<tr>
<td><strong>Resin Flow</strong></td>
<td>l/min</td>
</tr>
</tbody>
</table>
Figure A12 - Individual Mass and Energy Flows for data in Table A4

Figure A13 - Water and Steam Flows through System for data in Table A4

The blowline steam flow is calculated from these data and is shown in Table A5
Table A5 - Calculated Blowline conditions for CHH Line 1 Mass - energy balance

<table>
<thead>
<tr>
<th>Blowline Conditions</th>
<th>diameter</th>
<th>Pressure</th>
<th>Steam flow</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin entry</td>
<td>102.262</td>
<td>5.0</td>
<td>1.40</td>
<td>53.8</td>
</tr>
<tr>
<td>Dryer Entry</td>
<td>102.262</td>
<td>0.0</td>
<td>1.73</td>
<td>357.3</td>
</tr>
</tbody>
</table>

The calculated velocity at 5 bar pressure is 53.8 m.s\(^{-1}\) significantly below the 100 m.s\(^{-1}\) measured experimentally by Cooper (1998, Table A3, page 38). However it is consistent with blowline velocities (calculated at 4.5 bar) that are found in plants where resin spotting in the panel is a problem.

Resolution of the difference between these two figures requires a re-examination of the refiner conditions that might have applied when Cooper's measurements were made.

The refiner plates used in the primary refiner are now designed to operate in one direction only (unidirectional plates). These facilitate the flow through the refining zone, reducing refining energy consumption. This in itself reduces the quantity of steam leaving the refiner, but more importantly, requires that the pressure in the housing be increased to maintain the fibre in the refining zone. The effect of this is to reduce the steam coming forward into the refiner with the preheated feed material. This shows in Figure A13 on page 41 where the steam coming forward to the L44 (the primary refiner) is 0.0642 kg kg\(^{-1}\) ODF.

In refiners with reversible refining plates, with less efficient fibre flow through the plates, this ratio is usually much higher; in fact values of up to 0.50 kg kg\(^{-1}\) ODF have been observed where the housing pressure is below the preheater pressure. These plates were used at the time of Cooper's measurements and it is likely that this ratio was significantly higher for these plates than that in Figure A13. The value of this forward flow ratio necessary to give a blowline velocity equal to that measured by Cooper can be calculated from the mass - energy balance.

Increasing the steam flow to the preheater, so that 0.46 kg kg\(^{-1}\) ODF steam comes forward with the material from the preheater increases the blowline steam flow to the point where the steam velocity in the blowline at 5 bar pressure is 100 m s\(^{-1}\). This value is consistent with other refiners operating in conditions typical of those applying
during Cooper's investigation, particularly where the refiner is operating at maximum fibre capacity as is the case.

On this basis it is concluded that the mass-energy balance does give a valid view of the refiner as it was operating when Cooper was doing his measurements. If this is the case, then there must be some other factor which is responsible for the resin spotting in the plant. Cooper reports that the incidence of resin spots at the plant is intermittent and it is likely that variation in refiner conditions is the reason for this. Resin spots would be produced when the steam flow coming forward to the refiner with the fibre was low.

One further validation point has been established at a plant in Canada where this model gave a blowline steam flow which agreed with that calculated by another refiner model prepared by another consultant operating in the field (unpublished) which is used in that plant (Plant L).

This analysis of the refiner operation conditions illustrates the effect that these can have on the blowline conditions. In the case studied, the blowline steam flow varies almost over a 2:1 ratio between the conditions applying when Cooper measured the fibre velocity and those which would be achieved with effective control of the housing steam pressure. With the blowvalve the only means of controlling the flow from the refiner it is understandable that the blowline conditions would vary significantly.

It is concluded that this is the likely reason that the blowline was not considered in the early investigations into blowline blending. It is also likely that the blowlines were much bigger than necessary, leading to reduced blending efficiency, particularly when new plants were yet to reach design capacity.
One of the early trials (Section 3.2.2 on page 17) in this investigation showed that resin efficiency improved when the pressure drop across the injection nozzle was increased and conversely, that resin spots were produced when the resin flow through an unchanged nozzle was reduced. For the pressure-atomised nozzle involved, this would have resulted in a change in the resin droplet size.

The importance of the size of the resin entities in the blowline is also demonstrated by the consistent conclusion in many plants that the benefits resulting from dilution of the resin were greater than the increased drying cost resulting from this change, as discussed in Section 3.2.1 (page 16). These observations demonstrate that resin droplet size is significant in the blending outcome, as these conclusions are based on plant experience where refiner and blowline conditions were not changed.

The model of the blending process shows that the interaction between the resin droplets and the fibres in the blowline can, through cleaving the liquid resin bridges between two fibres, result in a reduction in the size of the resin droplets attached to the fibres. This outcome will be more likely if the resin droplets are small to start with, as this reduces the force holding the fibres together.

The plant experience is very clear. Just what sizes of resin droplets can be created in the blowline environment and how these will affect the blending outcome are less certain.

5.1 MDF as a Bonded Fibre Network

Another way of looking at the effect of resin bond size is to consider the properties of the fibre network that makes up MDF. In the panel the fibres lie substantially in the plane of the panel. This is largely because of the compression occurring between the formation of the fibre mat at a density of some 30 kg m\(^{-3}\) and the density of the final product, typically ranging from 500 – 800 kg m\(^{-3}\). Even if the formation of the
mat results in a random orientation of the fibres as it is formed, the subsequent compression results in the fibres moving to this orientation over most of their length. The appearance of the fibres in the panel, as observed in the fracture surface after the IB test (Figure A14) confirms this.

Figure A14 - MDF Fracture surface after IB test (from Butterfield et al, 1992)

The consequence of this provides some insights as to how the location and size of the resin bonds influences the strength of the composite, as measured in the IB test. This measures the strength of the panel in a direction perpendicular to the plane of the panel and, consequently, as discussed above, to the plane of the fibres. In this situation, a fibre can only contribute to the strength of the panel if it has a minimum of two bonds to adjacent fibres, one to transfer the force into the fibre and one to transfer the load out to an adjacent fibre. It may be that a fibre is in a position where it can transfer load to an adjacent fibre purely by contact. This situation places additional loads on adjacent resin bonds which will reach the failure load sooner than if this situation did not apply.

Not every resin location will form a bond. From Figure A14 it is clear that there is considerable free space with the fibre network at the density at the centre of the panel. Adhesive bonds can only form where resin is present to form the bond and the distance between the fibres is small enough for the resin to bridge the distance between them.
The drying process results in some collapse of the lumen structure, with fibres appearing much more tape-like after drying (Figure A15). This makes the calculation of the voids volume (excluding the lumen volume) somewhat problematic. The bulk density of the fibres, assuming they are in the same form as in the wood, can be taken as that for the wood, or approximately 400 kg m$^{-3}$. The density of the cell wall is close to 1500 kg m$^{-3}$, this would be the density of the fibre if both void and lumen volume were zero.

This is probably the case where a part of the compression load in the press is concentrated at a point where two fibres cross. At these points the good contact between the two fibres would allow a bond to form with minimum resin thickness.

![MDF Fibres after drying](image-url)

*Figure A15 – MDF Fibres after drying (from Butterfield et al. 1992).*

There is limited data on just how the resin is distributed over the fibre surface as it leaves the blowline and again as it leaves the dryer. As noted earlier (Section 1.3 on page 8), the difficulty of visually identifying the resin on the surface of the fibre limits this as an investigation tool. Although progress has been made in this area, there is as yet no published data relating an observed resin distribution to the properties of the panel. The photograph (Figure A16 on page 47) from Butterfield et al. (1992), taken from the failure surface of an IB test block, clearly shows a smooth bond between two fibres which is likely to be resin. If this is the case, it suggests that the resin has been present in a mass at the point where the fibres crossed and has flowed to fill the area between the two fibres.
The mechanism which leads to such a flow from a resin which has been dried prior to this point in the process has not been elucidated.

Figure A16 – Resin Bond between Two MDF Fibres (from Butterfield et al. 1992).

This analysis of MDF as a fibre network provides some insights into the size of the resin entities on the fibre that will give the best strength to the composite.

- Within the network the tension forces will normally be transferred through the resin bonds, although it is possible that individual fibres might be restrained mechanically by adjacent fibres. Apart from this possibility, which ultimately depends on adjacent resin bonds to transfer the tensile forces within the network, two bonds are the minimum necessary to transfer these forces generated in the IB test into a particular fibre and then to an adjacent fibre. One resin droplet per fibre is the minimum that will provide these two bonds for each fibre but only if the resin is able to form bonds between the fibre and adjacent ones.

With the fibres lying largely in the plane of the panel and with a degree of void space around each fibre, other responses to the strain are possible if the two bonds are situated some distance apart on the length of the fibre. In this case it is possible that the fibre could deflect by bending, resulting in forces usually
carried by this component of the network transferring to adjacent fibres and the bonds associated with them.

This could explain the two distinct failure modes in the IB test. Some blocks fail with a pronounced bang, while others, with a similar failing load, fail much more quietly. This could be due to misalignment of the assembly so that the load is concentrated in one area of the test piece, leading to a progressive failure of the block. However if these 'quiet' breaks result from fibres being able to deform under the applied load before breakage occurs then a measurement of the stress-strain curve in the IB test could provide useful data on the distribution of bonds along the length of the fibres.

- It is not possible to determine where the resin lies on the fibre, nor whether this will be in a location where a bond will develop in the fibre network. This suggests that the resin should be distributed as widely over the surface of the fibre as possible, so that bond formation is possible at any point in the fibre network.

The conclusion from the above analysis of the network in MDF reinforces the earlier conclusion from the IB fracture mode study (Butterfield et al. 1992), that increasing the number of resin droplets on the fibre, with a consequent reduction in size, improves the strength of the MDF composite.

5.2 The Relationship between Resin Droplet and Fibre Size

With this in mind, the relationship between the size of a resin droplet and a typical fibre can be examined for the typical resin loadings used in MDF manufacture, to see what resin droplet size is necessary to meet this condition. In Table A6 a typical *P. Radiata* fibre is characterized and the resin droplet size necessary to provide one resin droplet per fibre is calculated. The approach is further extended in Figure A17 to the resin droplet size to achieve a specified number of resin droplets per fibre for these conditions.
This calculation shows that the resin droplet diameter to provide 1 resin droplet per standard fibre is 0.058 mm.

Table A6 – Resin Droplet Calculations for a Typical P. Radiata Fibre

<table>
<thead>
<tr>
<th>Fibre length</th>
<th>mm</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>0.03</td>
</tr>
<tr>
<td>Wood Density</td>
<td>Kg m$^{-3}$</td>
<td>400</td>
</tr>
<tr>
<td>Fibre volume</td>
<td>mm$^3$</td>
<td>0.00212</td>
</tr>
<tr>
<td>Weight</td>
<td>mg</td>
<td>0.00085</td>
</tr>
<tr>
<td>Resin solids</td>
<td>% on fibre</td>
<td>10</td>
</tr>
<tr>
<td>Resin/fibre</td>
<td>mg</td>
<td>8.48E-05</td>
</tr>
<tr>
<td>Resin solids</td>
<td>% solids</td>
<td>65</td>
</tr>
<tr>
<td>Wet Resin/fibre</td>
<td>mg</td>
<td>0.00013</td>
</tr>
<tr>
<td>Resin Density</td>
<td>kg m$^{-3}$</td>
<td>1260</td>
</tr>
<tr>
<td>Droplet Volume</td>
<td>mm$^3$</td>
<td>0.00010</td>
</tr>
<tr>
<td>No drops/fibre</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Sphere diameter</td>
<td>mm</td>
<td>0.058</td>
</tr>
</tbody>
</table>

Figure A17 – Calculated droplet size for a given number of resin droplets per standard fibre

A significant part of the fibre – resin droplet interaction model developed in this thesis is that the separation of fibres which have been linked by a liquid resin bond in the biowline is a critical outcome if good resin performance is to be achieved. Development of this approach provides some insights into the size of resin droplets that might be required to develop the maximum liquid bond strength between two fibres, assuming that the strength of the bond is proportional to the cross-sectional area of resin.
If two parallel circular fibres of diameter $D$ are joined over their full length by resin which is assumed to fill the space between the fibres which touch and the tangent line between the two fibres, (Figure 18a) the cross sectional area $a$ of the resin is:

$$a = D^2 \left(1 - \frac{\pi}{4}\right)$$  \hspace{1cm} \text{A5.1}$$

or

$$0.2146D^2$$

and the resin volume, assuming that the ends of the resin bond are planes at right angles to the axis of the fibres, for a bond length of $L$ is

$$0.2146D^2L$$

For a bond the full length of the standard fibre described in Table A6, the equivalent resin droplet diameter is 0.103 mm. Assigning this resin volume to the two fibres it joins gives an effective resin content of 28%, or 2.8 times the 10% average resin content assumed in Table A9.

![Diagram of resin between two fibres](image)

(a) Two parallel fibres  \hspace{1cm} (b) Two fibres at right angles

*Figure A18 – Resin volume between two fibres*

If the fibre was straight, parallel and in contact over their full length, and sufficient resin was present, the bond could be up to the length of the shortest fibre, or as calculated above, with two standard fibres aligned in both length and axes for the maximum case.

The resin spots in the panel often initially appear as dark coloured fibre bundles of generally aligned fibres, as discussed earlier and shown in Figure A6 on page 25. Analysis of these has confirmed the increased resin level that shows that they are a result of the aggregation process in the blowline. In one sense this example supports the separation-aggregation component of the model, where such fibres held together by a liquid resin bond over much of their common length are better able to survive
the blowline conditions and would thus be the first visible effect when blowline conditions change so that the aggregation outcome increases. This situation, where relatively few fibres are joined in a resin rich assembly, would be more likely if the resin drops were large compared with the fibres.

These calculations give some idea of the relationship between the size of the resin droplets and of the fibre. This data can be compared with the droplet size of the resin generated as it is injected into the blowline either through an atomising nozzle or by interaction with the blowline steam flow.

### 5.3 Droplet Size Equations

Nozzles used for blowline resin injection range from simple 15 mm or 20 mm pipes introducing resin to the blowline to increasingly sophisticated nozzles designed specifically to achieve small resin droplets with the reliability necessary to operate within the blowline environment.

The fact that blowline resin blending works when there is no attempt to break the resin into droplets as it is introduced demonstrates that the steam velocity in the blowline is sufficient to break the resin into smaller entities that are distributed over the fibres. There are indications that relying on this method leads to resin spots in the panel and to an increased resin requirement, but the low blowline velocities often associated with blowlines using this form of resin injection may also be a factor. It is not clear whether the atomisation process in this case is purely a result of the interaction between the steam and the resin film on the wall of the pipe. More realistically the fibre collisions with the resin film on the blowline wall play a significant part in the distribution of the resin over the fibres. What is clear is that the resin efficiency when resin is introduced in this way is well below that which can be achieved when the resin is atomised at entry.

Both Cooper (1992) and Robson (1991) have calculated resin droplet sizes based on the interaction between the blowline steam flow and a jet of resin entering the blowline. As noted above, this is a valid approach where the resin enters as a jet or a film, with the atomisation occurring as a result of interaction with the high velocity flow in the blowline.
Cooper uses the equation developed by Nukiyama and Tanasawa (1939) which is also discussed in a paper analysing single and twin fluid atomisers (Deysson & Karian, 1979).

\[
D_{sw} = \frac{585}{U_r} \sqrt{\sigma_i} + 597 \left[ \frac{\mu_i}{\sigma_i \rho_i} \right]^{0.45} \left[ \frac{1000 Q_i}{Q_g} \right]^{1.5}
\]  

(A5.2)

Symbols are listed in Table A7 on page 52 along with values in SI units and equivalent values in other units where these are used. Subscripts \( i \) and \( g \) refer to liquid and gas respectively. For equation A5.2 the units are SI except that:

- \( \rho_i \) is in g cm\(^{-3}\)
- \( \sigma_i \) is in dyne cm\(^{-1}\)
- \( \mu_i \) is in poise (Ns m\(^{-2}\))

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable</th>
<th>Units</th>
<th>SI unit</th>
<th>Value SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Fitting factor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Nozzle area</td>
<td>0</td>
<td>m(^2)</td>
<td>1.96E-05</td>
</tr>
<tr>
<td>b</td>
<td>Fitting factor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>D(_i)</td>
<td>Liquid path dia</td>
<td>mm</td>
<td>m</td>
<td>0.005</td>
</tr>
<tr>
<td>D(_m)</td>
<td>Mass median diameter</td>
<td></td>
<td>µm</td>
<td></td>
</tr>
<tr>
<td>D(_vs)</td>
<td>Volume-surface mean dia</td>
<td></td>
<td>µm</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Liquid path length</td>
<td>5</td>
<td>m</td>
<td>0.005</td>
</tr>
<tr>
<td>M(_g)</td>
<td>Gas flow rate</td>
<td>kg m(^{-1})</td>
<td>kg s(^{-1})</td>
<td>2.333</td>
</tr>
<tr>
<td>M(_l)</td>
<td>Liquid Flow rate</td>
<td>l \min(^{-1})</td>
<td>kg s(^{-1})</td>
<td>0.521</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>bar</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Q(_g)</td>
<td>Gas volumetric flow</td>
<td></td>
<td>m(^3) s(^{-1})</td>
<td>0.735</td>
</tr>
<tr>
<td>Q(_l)</td>
<td>Liquid volumetric flow</td>
<td></td>
<td>m(^3) s(^{-1})</td>
<td>0.00042</td>
</tr>
<tr>
<td>U(_r)</td>
<td>Relative velocity – gas - liquid</td>
<td></td>
<td>m s(^{-1})</td>
<td>58.8</td>
</tr>
<tr>
<td>V(_l)</td>
<td>Liquid velocity</td>
<td>0</td>
<td>m s(^{-1})</td>
<td>21.22</td>
</tr>
<tr>
<td>V(_r)</td>
<td>Gas velocity</td>
<td>0</td>
<td>m s(^{-1})</td>
<td>80</td>
</tr>
<tr>
<td>(\mu_i)</td>
<td>liquid viscosity</td>
<td>poise</td>
<td>1.25</td>
<td>N s m(^{-2})</td>
</tr>
<tr>
<td>(\rho_g)</td>
<td>Steam Density</td>
<td></td>
<td>0</td>
<td>kg m(^{-3})</td>
</tr>
<tr>
<td>(\rho_l)</td>
<td>liquid density</td>
<td>g cm(^{-3})</td>
<td>1.25 kg m(^{-3})</td>
<td>1250</td>
</tr>
<tr>
<td>(\sigma_i)</td>
<td>surface tension</td>
<td>dynes cm(^{-1})</td>
<td>25 N m(^{-1})</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Robson (1991) uses an equation (A5.3) where symbols and typical values for a UF resin system are listed in Table A7 on page 52 along with values for these from the blowline conditions in Tables A4 on page 40 and A5 on page 42.
\[ D_{vs} = \left[ 0.95 \frac{(\sigma_i M_i)^{0.33}}{U_i \rho_i^{0.37} \rho_g^{0.3}} + 0.13 \mu_i \left( \frac{D_i}{\sigma_i \rho_i} \right)^{0.5} \left[ 1 + \frac{M_i}{M_g} \right] \right]^{1.7} \]  

(A5.3)

Evaluating both these equations for the standard blowline conditions used in this work gives very different results for the resulting droplet size.

The mean volume/surface diameters \( D_{vs} \) calculated for the two equations using the same input data are:

- \( D_{vs} = 506 \mu m \) for equation A5.2
- \( D_{vs} = 256 \mu m \) for equation A5.3

The values are of the same order as those given in both Robson (1991) and Cooper (1992), but the difference between these two estimates requires further exploration. Both equations are evaluated at a constant 4.5 bar pressure for changes of + 25% and − 25% of one selected variable at a time. This range is clearly excessive for variables such as liquid density, but is considered to be typical of the flow variables encountered in actual blowline conditions, particularly the blowline steam flow where the range may be double this.

Results for this sensitivity analysis on both equations are shown in Figure A19 on page 54. The response is quite different for the two equations, with the flow conditions exerting a greater effect on the droplet size than the liquid properties in equation A5.3. This is consistent with the experience in blowline blending, where the response to changes in blowline conditions is generally more significant than changes in resin, particularly viscosity.

The one operational area where a change in resin properties does improve resin response is with increasing dilution of the resin. In terms of this droplet size analysis, this results from the reduced quantity of resin in each droplet rather than any change in viscosity or surface tension, both of which show a very small response for equation A5.2 in the sensitivity analysis.
Figure A19 – Droplet Size Prediction – Sensitivity to Variables at 4.5 bar pressure

The two source papers for the equations used (Lefebvre, 1981; Deysson and Karian, 1979) reviewed experience with two-fluid atomisation systems and presented correlations that reconciled the diverse equations that have been developed to predict performance of these nozzles.

Deysson and Karian comment on the small influence of liquid viscosity for this type of nozzle, which also shows in the sensitivity analysis in Figure A19, at least for equation A5.2. However the correlation presented suggests that the droplet size calculated for several equations generally similar in form to equation A5.3 lie within a ±20% range.

The two equations give droplet size estimates are well outside this range. Most of the development work in developing these equations is done at ambient pressure, whereas the droplet size calculations for the blowline are at a pressure of 5 bar. To test the sensitivity to the pressure the droplet size is calculated from both equations as the pressure is reduced from the 5 bar used in the initial estimate, to atmospheric pressure. The gas mass flow stays the same, with the gas velocity increasing as the gas phase density decreases. The result is shown in Figure A20.
This shows that the two estimates converge at lower pressures and demonstrates the importance of remaining within the range of variables covered in the initial investigation. For equation A5.2 (Nukiyama and Tanasawa, 1939) the density of the gas phase is not used. This investigation was done using air as the gas stream, with the liquid discharge at essentially atmospheric pressure. Equation A5.3 does include a gas phase density term and covers a pressure range up to 8.5 bar (g) (Lefebvre 1981).

Lefebvre, in his comprehensive review of the gas atomisation nozzles concludes that the equation subsequently used by Robson (1991) and presented here as equation A5.3, has "most to commend it".

The measurement of actual droplet sizes in the blowline conditions is almost impossible to achieve and the prediction of equation A5.3 is used. There cannot be a lot of confidence in the predicted size, particularly as the approach has been extended from the interaction of a liquid jet with a gas stream within the close confines of a nozzle to the much broader interaction between a resin jet and the flow of steam in a pipe. Nevertheless it does provide a way of assessing how changes in blowline and resin conditions affect the resin droplet size.

Figure A20 gives one further insight into the conditions in the blowline. As it is largely the velocity of the gas flow (as opposed to a momentum term) that determines the droplet size, better results would be achieved if the resin was injected where the steam pressure in the blowline was lower, at a point much closer to the discharge.

![Figure A20 – Droplet Size Predictions for varying pressures.](image-url)
end of the blowline. In most cases the resin injection point is closer to the refiner end of the blowline.

The conditions in Table A7 on page 52 used a gas velocity of 80 m s\(^{-1}\) for the calculation of the resin droplet size. Reducing the gas velocity to 50 m s\(^{-1}\) increases the droplet size to 408 \(\mu\)m. Using the calculations for the fibre described in Table A6 (page 49) it can be shown that the quantity of resin in droplets of this size is several times the mass of one fibre, as shown in Table A8.

<table>
<thead>
<tr>
<th>Blowline velocity at 4.5 bar - m s(^{-1})</th>
<th>Resin droplet size - Equation 5.3 (\mu)m</th>
<th>Mass Ratio Resin solids to fibre for this droplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>256</td>
<td>8.4</td>
</tr>
<tr>
<td>50</td>
<td>408</td>
<td>34.3</td>
</tr>
</tbody>
</table>

These data provide some new insights into the collision model. Assuming that these droplet sizes are reasonable, they are much bigger than the fibres, so there several fibres for each resin droplet immediately after the resin injection into the blowline. In this case the separation outcome must be responsible for distributing the resin over all the fibres if the requirement for one resin droplet on each fibre is to be met.

This data also provides a mechanism for the formation of resin spots with a resin content above the overall average for the fibres. The primary collision in this case is between a fibre and a very much larger resin droplet. The resin is progressively removed by collisions with other fibres, reducing the quantity remaining on the original fibre in a process which may not be completed by the time the assembly reaches the end of the blowline, leaving a resin rich assembly which becomes a resin spot, with a consequent reduction in the resin available in other parts of the composite.

### 5.4 Nozzle Atomisation

The previous analysis considers the resin droplet size achieved through interaction between the resin jet and the steam flow in the blowline. While this effect may be significant, most plants use some form of nozzle, with pressure atomised being most
common. The equations for this type of nozzle are less forbidding than those for the steam atomised type, but caveats similar to those discussed above apply.

Bakker (1988) uses an equation from Lefebvre (1981) to calculate the droplet size in an air atomised nozzle.

\[
\frac{D_{sv}}{L} = \left[ a \left( \frac{\sigma_i}{\rho_g U_r^2 D_i} \right)^{0.5} + b \left( \frac{\mu_i}{\sigma_i \rho_i D_i} \right)^{0.5} \left[ 1 + \frac{M_i}{M_g} \right] \right]. \tag{A5.4}
\]

The symbols and data used in the equation are those in Table A7 on page 52.

Deysson and Karian (1978) present a correlation for the droplet size in a pressure-atomised nozzle.

\[
\frac{D_m}{D_i} = \frac{k}{Re V_i} h(V_i) \tag{A5.5}
\]

where

\[
k = \frac{Q_i}{\sigma_i} \sqrt{\frac{\rho_i}{2 \Delta P}}
\]

\(h(V_i)\) is a function of \(V_i\)

and \(\Delta P\) is the pressure drop across the nozzle in bar.

The droplet diameter definition used in these equations is different. Lefebvre (1981) quotes work showing that \(D_{m}\), the mass median diameter, is 1.2 times the volume-surface diameter \(D_{sv}\) for the same droplet population, so that equation A5.5 can be rewritten as:

\[
\frac{D_{sv}}{D_i} = \frac{1}{1.2 \ Re V_i} h(V_i) \tag{A5.5a}
\]

Equation A5.4 includes the effect of gas phase density and on the basis of the earlier discussion can be used at the 5 bar pressure in the blowline.

Evaluating these equations for the standard conditions gives:

\(D_{sv} = 52\) \(\mu m\) for the pressure atomised case in equation A5.5a,

\(D_{sv} = 32\) \(\mu m\) for the steam atomised twin fluid nozzle in equation A5.4.
The droplet sizes are much smaller than those resulting when the atomisation is achieved by interaction between the resin flow and the blowline steam. This is consistent with the significance of the mass ratio term in the steam-atomised nozzle where the liquid flow is larger than the gas flow, as in this case. Deysson and Karian (1978) present a correlation showing linear relationship between the gas/liquid mass flow ratio and the droplet size where the ratio $M_g/M_l$ (the inverse of that used in equation A5.4) is below 2, as it is in the case of the steam atomised blowline nozzle developed as part of this project and discussed in Chapter 7 on page 83.

5.5 Resin Droplet Size Summary

Several indications of resin droplet size have been developed, both from the atomisation of the resin in both pressure atomised and gas atomised nozzles and from a consideration of the relationship between the resin and the fibre in the MDF composite. These are summarized in Table A9 (page 58). In these cases the calculations are based on the standard fibre in Table A6, (page 49) and for the demonstration blowline and resin properties in Table A7 (page 52).

The steam velocity in the blowline is estimated at the standard blowline steam velocity of 80 m·s$^{-1}$, (calculated at 4.5 bar pressure) which has been found to give a good blending result and also at a velocity of 50 m·s$^{-1}$ (calculated at 4.5 bar pressure), which is typical of blowlines prior to optimisation.

In view of the uncertainty in the nozzle equations it is difficult to draw precise conclusions from this data, but some general points can be made, with the help of a diagrammatic view of this data as shown in Figure A21 on page 59.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Droplet dia. - $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond size estimates</td>
<td></td>
</tr>
<tr>
<td>1 droplet per standard fibre</td>
<td>58</td>
</tr>
<tr>
<td>32 droplets per standard fibre</td>
<td>18</td>
</tr>
<tr>
<td>Circular bond between two non parallel fibres</td>
<td>18</td>
</tr>
<tr>
<td>Droplet size calculations</td>
<td></td>
</tr>
<tr>
<td>Droplet size Eqn A5.3 $V_g = 80$ m·s$^{-1}$</td>
<td>256</td>
</tr>
<tr>
<td>Droplet size Eqn A5.3 $V_g = 50$ m·s$^{-1}$</td>
<td>408</td>
</tr>
<tr>
<td>Droplet size Eqn A5.4 gas flow atomisation</td>
<td>32</td>
</tr>
<tr>
<td>Droplet size Eqn A5.5 pressure atomisation</td>
<td>52</td>
</tr>
</tbody>
</table>
Figure A21 – Resin Droplet Size Summary

This shows that:

- There are distinctly different resin droplet size ranges between the atomisation produced by a nozzle designed to do this and the effect of achieving this solely by the interaction between the resin jet or film and the blowline steam flow.

- The droplet size range produced by atomisation solely within the blowline steam flow is significantly larger than any estimate of the resin droplet necessary to provide at least one resin droplet per fibre.

- The resin droplet size range produced by an atomising nozzle is comparable with that needed to give at least one and possibly up to 6 resin droplets per standard fibre.

- The analysis confirms the separation outcome of the blowline collision process. This is the only way that the large resin droplets which result from the interaction between the resin jet and the blowline steam flow can be distributed over the fibres to develop the strength of the fibre network.

The overall picture from the droplet size analysis shows that an effective atomising nozzle gives a resin droplet size very much smaller than that resulting from interaction with the blowline steam flow. In terms of the fibre – resin droplet collision
model discussed in Section 3.2.4 (page 20) this size difference makes the separation outcome from the secondary collisions much easier to achieve when an atomising nozzle is used.

As the size of the fibre falls, either because the fibre source has smaller fibres, or because fibres are broken up in preparation, the initial resin droplet size becomes more critical.
Applying the Blowline Blending Model

The blending model has evolved from plant trials showing that steam velocity in the blowline and the size of the resin droplets were the major factors determining the blending outcome and hence the resin usage necessary to provide the required strength properties in the panel. It provides a mechanism for the blowline blending process and together with standard process calculations, provides a means for optimising existing blowlines and for designing blowlines for new plants.

The model explains a number of other observations in MDF plants, some of which have not previously been identified as originating in the blowline. In all the cases studied, the blending model has been able to explain the observed behaviour, giving confidence that the model is both reliable and comprehensive.

The blowline blending model is offered as a commercial product, with almost all the development work having been done in plants. Some of the specific plant experiences and trials which have shaped the model are discussed earlier in this thesis; however the broad parameters for improved blowline blending were apparent from the early applications. This enabled significant improvements in blending outcomes to be achieved while the method continued to develop. Subsequent plant experience has reinforced the original model and extended the understanding of the impact of blowline conditions on other aspects of the MDF process. It has also enabled the range of allowable blending conditions to be extended and methods developed to control these.

The blowline optimisation project has been carried out during a visit to the plant site. Early attempts to do this remotely, with data supplied by plant personnel showed that this was susceptible to misunderstanding and error, leading to delays and frustration. During the visit the refiner conditions are established using the mass - energy balance. Expressing the steam and water flows as ratios to 1 kg of oven dry fibre as shown in figure A12 has proved to be very useful in establishing these conditions, by allowing these ratios to be compared with those for refiners operating under similar
conditions. This analysis has been able to identify flow meters which were giving incorrect readings.

Once a valid picture of the refiner is obtained, this is then extended to the maximum fibre flow condition and it is this which is used to size the blowline. As the precision of the prediction has improved and the blowline design moving closer to limiting conditions, the operational aspects have become more important.

There are difficulties in doing research in an operating plant. The commercial aspect of the investigation limits the time available at the plant. This means in particular that it is rarely possible to get the level of confirmation of results which can be achieved in controlled laboratory experiments. One particular difficulty is getting accurate indications of the results which have been achieved. A much more general assessment of the success (or otherwise) of the project is usually all that is available.

### 6.1 Blowline Conditions

To achieve the best blending result, the blowline velocity should be as high as possible, to maximise the shear force gradients within the flow. The blowline steam flow is determined by the refiner conditions and will be highest for the maximum fibre flow - specific refining energy combination for the particular refiner. The blowline can then be sized so that the velocities in the blowline are maximised within the constraints of the available pressure drop between the refiner housing and the dryer.

It is necessary to maintain optimum blending conditions within the blowline as the fibre flow changes and at the lower energy levels that are achieved with new refiner plates. This can be done by introducing additional steam through the housing steam entry, with the required flow calculated from the mass-energy balance. Effectively the maximum blowline flow is achieved with the blowvalve as far open as possible.

The steam mass flow is determined by the mass and energy balances over the refiner and by extending this to include the enthalpy changes as the pressure falls along the length of the blowline, changes in the steam flow are calculated. In this analysis, the velocity is calculated at two points, each defined by a pressure:
1. The pressure at the resin injection point, taken as 4.5 bar
2. The discharge of the blowline stream into the dryer, at a pressure generally close to atmospheric.

From an analysis of the blowlines worked on, it would appear that a velocity of at least 80 m s\(^{-1}\) is needed at 4.5 bar pressure to achieve a good blending result. As there is always both steam and water in the blowline and as a result of the enthalpy changes as the pressure falls, the steam mass flow changes along the blowline. These enthalpy changes and the balance between steam and water in the flow from the refiner are used to calculate the increase in steam mass flow as the pressure falls. The increase ranges between 10% and 30%. In the case illustrated in Figure A13 (page 41), the steam mass flow in the blowline increases from 0.4212 kg kg\(^{-1}\) ODF at 4.5 bar to 0.5177 kg kg\(^{-1}\) ODF at the dryer, an increase of 23%.

The increase is significant because of the choke flow condition that limits the velocity in a compressible fluid within an enclosed space to the velocity of sound at the applicable temperature and pressure. If the calculated velocity at the applicable pressure exceeds this limit, the pressure will remain at a point above this, where the specific volume of the steam is such that the local velocity does not exceed the sonic limit for the steam mass flow. The velocity of sound in steam at atmospheric pressure and 100 °C is 473 m s\(^{-1}\) (Haar et al, 1984).

The pressure in the jet prior to entry can be calculated for this condition by increasing the pressure in the mass - energy balance at the dryer entry until the velocity falls below the velocity of sound. The consequence of this for the flow entering the dryer can be significant. The flow from the blowline enters the dryer with an internal pressure, causing it to expand rapidly as it moves beyond the constraint of the blowline. If this expansion is too great the expansion of the jet will cause wet fibre to reach the walls of the dryer tube where it will stick and build up, as in the case of Plant. The material may subsequently break away from the wall as a lump and travel with the fibre to the press where it can cause damage to the steel belts of a continuous press, or appear as a spot in the MDF panel.

For the case considered in Table A4, the current blowline is 100 NB Sch 40 pipe, with an internal diameter of 102.26 mm. The calculated velocities at 4.5 bar and...
atmospheric pressure are shown in Table A10 on page 64. In this case the recommended blowline size is 80 NB Sch 40 pipe with an internal diameter of 77.93 mm. This gives a calculated velocity of 92.7 m s\(^{-1}\) at 4.5 bar pressure and a velocity above the sonic limit of 473 m s\(^{-1}\) at the dryer entry. This condition will lead to an increase of pressure in the jet as it enters the dryer of 0.32 bar. Some expansion of the fibre stream will occur in the dryer as a result of this pressure and some contact with the dryer wall could be expected. The expansion can be eliminated with a short section of larger diameter pipe at the end of the blowline, just ahead of the dryer entry point. This drops the velocity below the sonic limit, but needs to be long enough to allow smooth flow to be re-established prior to the dryer entry. The length to establish this is generally taken as 10 – 12 pipe diameters. A 900-mm length of 90 NB Sch 40 pipe would achieve this.

**Table A10 - Blowline Velocities for Data from Table A4 (page 40)**

<table>
<thead>
<tr>
<th>Nominal pipe size</th>
<th>100</th>
<th>100</th>
<th>90</th>
<th>90</th>
<th>80</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Schedule</td>
<td>Sch40</td>
<td>Sch80</td>
<td>Sch40</td>
<td>Sch80</td>
<td>Sch40</td>
<td>Sch80</td>
</tr>
<tr>
<td>Inside diameter, mm</td>
<td>102.262</td>
<td>97.182</td>
<td>90.120</td>
<td>85.446</td>
<td>77.928</td>
<td>73.660</td>
</tr>
<tr>
<td>Velocity at 4.5 bar, m s(^{-1})</td>
<td>58.4</td>
<td>64.7</td>
<td>75.2</td>
<td>83.7</td>
<td>100.6</td>
<td>112.6</td>
</tr>
<tr>
<td>Velocity at 0.0 bar, m s(^{-1})</td>
<td>357.3</td>
<td>321.5</td>
<td>373.9</td>
<td>511.7</td>
<td>615.3</td>
<td>688.6</td>
</tr>
<tr>
<td>Internal pressure to maintain sonic velocity, bar</td>
<td>0.09</td>
<td>0.32</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The choke flow condition has provided another validation point for the calculation. In a recent installation (Plant D) a pressure tapping was installed 50 mm upstream from the end of the blowline. The calculated choke pressure at the blowline exit for the refiner operating condition was 0.19 bar, while the measured pressure was 0.19 bar.

The example used in Table A4 is for a system using fresh softwood chip, with a total specific refining energy in the two refiners in this case of 145 kWh t\(^{-1}\). A plant in North America using sawdust and shavings will use a much higher specific energy level ranging up to 450 kWh t\(^{-1}\) (Plant X and others).

Theoretical steam and water profiles for refiners operating with different raw material moisture contents and for high and low specific refining energies have been developed using the mass-energy balance (Chapman, 2001). This calculation, done by changing the refining energy in Table A4 (page 40) by 100 kWh t\(^{-1}\) shows that each 100 kWh t\(^{-1}\) refining energy generates 0.158 kg steam kg\(^{-1}\) ODF. Even for the low energy case in Table A4 the refining energy is the largest energy flow inflow.
For the high refining energy case the steam generated in the refiner determines the blowline steam flow, to the extent that a system operating with high specific energy and a low moisture feed requires very little drying, as the refining energy is sufficient to turn most of the water into steam.

### 6.2 Characterising the Blowline Flow

The flow in the blowline is a three-phase system, with 4 components.

- Steam carries the fibre from the refiner to the dryer.

- The fibre concentration is between in the blowline is 0.5 and 4.0 % by volume. The steam to fibre mass ratio ranges from 0.25 – 1.0, while the fibre to steam volume ratio falls as the specific volume of the steam rises with the falling pressure in the blowline.

- Water is present with the moisture content in the fibre generally well above the fibre saturation point.

- At some point along the blowline the liquid resin is injected into the blowline through a nozzle that will produce droplets of a defined size range. The resin droplets also contain water, in a water to resin solids mass ratio ranging from 2:1 to 0.5:1

The blowline carries the fibre from the refiner, at a typical pressure of 8 bar, to the dryer, where the pressure is substantially atmospheric. This pressure drop occurs over a variable orifice valve at the refiner outlet and as a line loss in the blowline itself. As a result of this pressure change, velocities in the blowline are high and as discussed earlier, may reach the speed of sound as the pressure becomes close to atmospheric, where the blowline discharges into the dryer airflow.

The flow may be considered to be adiabatic. The blowline is generally not insulated, so there will be some heat loss, but this will be small when compared with the total energy in the stream leaving the refiner; in the case considered in Table A4, the energy in the blowline flow (referenced to 0 °C) of 5.9 MJ s⁻¹.
The availability of water in the system is also significant in that the enthalpy changes as the pressure falls are accommodated by water becoming steam, making superheating insignificant and keeping conditions close to saturated at all times.

A simple model of the flow is used. The total energy of the blowline flow remains unchanged, while the falling solid and liquid enthalpies result in an increase in the proportion of energy available as latent heat, leading in an increase in the steam mass flow as the pressure drops along the blowline.

This approach is sufficient to characterise the blowline flow for the blowline optimisation project, but a more comprehensive approach would be needed to study the fibre-resin interactions identified in this work as significant in the blending outcome.

However the flow cannot be considered to be isentropic, which would require that the flow be essentially frictionless (Oosthuizen, 1997 p 37). The system is close to or at saturation at all points, so that conditions are not ideal, also a requirement for isentropic behaviour. This is not significant in terms of the flow calculations used in this analysis, but this should be reviewed in future analyses where isentropicity is often a requirement for more detailed flow models.

6.2.1 Reynolds Number.

The Reynolds number for the blowline flow in the demonstration case (Table A4 on page 40) is calculated for the blowline conditions and the range of possible blowline sizes in Table 10.

The Reynolds number is calculated as:

\[
Re = \frac{Vd\rho}{\mu} = \frac{4G}{\pi d \mu}
\]  \hspace{1cm} (A6.1)

Where \( Re \) is the Reynolds number

- \( V \) is the gas velocity \( \text{m s}^{-1} \)
- \( G \) is the mass flow \( \text{kg s}^{-1} \)
- \( d \) is the diameter in \( \text{m} \)
\[ \rho \text{ is the gas density kg m}^{-3} \]
\[ \mu \text{ is the viscosity kg m}^{-1} \text{s}^{-1} \]

Table A11 – Reynolds number for blowlines in Table A10 (page 64)

<table>
<thead>
<tr>
<th>Nominal pipe size</th>
<th>100</th>
<th>100</th>
<th>90</th>
<th>90</th>
<th>80</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Schedule</td>
<td>Sch40</td>
<td>Sch80</td>
<td>Sch40</td>
<td>Sch80</td>
<td>Sch40</td>
<td>Sch80</td>
</tr>
<tr>
<td>Inside diameter, mm</td>
<td>102.262</td>
<td>97.182</td>
<td>90.120</td>
<td>85.446</td>
<td>77.928</td>
<td>73.660</td>
</tr>
<tr>
<td>Velocity at 4.5 bar m s(^{-1})</td>
<td>58.4</td>
<td>64.7</td>
<td>75.2</td>
<td>83.7</td>
<td>100.6</td>
<td>112.6</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>1.167E6</td>
<td>1.228E6</td>
<td>1.324E6</td>
<td>1.397E6</td>
<td>1.531E6</td>
<td>1.620E6</td>
</tr>
<tr>
<td>Velocity m s(^{-1}) at dryer entry</td>
<td>357</td>
<td>396</td>
<td>460</td>
<td>473</td>
<td>473</td>
<td>473</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>1.756E6</td>
<td>1.848E6</td>
<td>1.993E6</td>
<td>2.079E6</td>
<td>2.223E6</td>
<td>2.317E6</td>
</tr>
</tbody>
</table>

This places the flow conditions at the limits of most of the published work on high Reynolds number multiphase flow. Crowe et al. (1998) comment that "the prediction of particle motion in turbulent flow fields is not straight-forward because there are few detailed models for turbulence in single-phase flows, let alone multiphase flows". One could add "at high Reynolds numbers" to this comment for the blowline case. Analysis of the blowline situation is further complicated by the fibres, which with a slenderness ratio of 80:1 - 100:1 cannot legitimately be treated as spheres and by the significance of the interaction between the fibres and the resin droplets which is identified in this study as important in the outcome of the blending process.

The development of a detailed model of the blowline flow characterising the interactions between the components of the flow is left to others. This discussion can best provide a comprehensive view of the conditions that apply as a starting point for such an investigation. This is in keeping with the thrust of this investigation as a broadly based empirical process model supported by basic engineering calculations.

6.2.2 Blowline Pressure Drop.

The pressure drop in the blowline has not been seen as significant in the operation of the MDF plant. With the blowline being much larger than necessary to carry the flow of steam and in the absence of any means of calculating this flow, the question of the resulting pressure drop was somewhat academic.

The blowvalve on the outlet of the refiner housing provides a means of creating a
pressure drop in the discharge line from the refiner. It is closed during startup so that the refiner pressures can be established with steam only flowing and is opened as the fibre flow increases. In some installations the resin injection point is incorporated in the blowvalve, on the basis that the turbulence following the blowvalve would contribute to effective fibre-resin mixing.

Under steady operating conditions the pressure drop across the blowvalve and in the blowline must equal the pressure in the refiner housing. As the pressure drop in the blowline increases the blowvalve will also be opened further to maintain the housing pressure at the desired level.

The converse of this situation is that the blowvalve opening at maximum fibre flow provides a useful indication as to how much the blowline diameter can be reduced. As most blowlines have larger diameters than necessary, the blowvalve is generally only partially open, with some significant consequences:

- The instantaneous pressure drop across the blowvalve is likely to cause some damage to the fibre, an example of the explosion pulping process used by Mason (1926).

- The blowvalve wears more as the pressure drop across it increases. Blowvalve replacement is a significant cost in plants where sand and similar contaminants are not removed from the feed material. This is often the case where cleaning or washing of the fibre source material is not easily achieved, as in the case of sawdust and shavings.

- The blowvalve has a very poor control characteristic and does not provide the level of control of the pressure change over the refiner plates. Control of the housing pressure is usually achieved by controlling a flow of steam into the refiner housing to maintain the pressure at this point.

- Recently blowlines have been designed to operate with as much as possible of the pressure drop between the refiner housing and the dryer occurring in the blowline so that the blowvalve is only required for startup. There are indications that refiner stability improves when this is achieved.
The pressure drop in the blowline can be calculated for steam flow alone, with no fibre flowing. The steam mass flow in the blowline is calculated in the refiner mass-energy balance, shown in Table A5 on page 42. The Darcy–Weisbach equation is used with this steam flow, but in a reverse integration. Since the known conditions are at the discharge end of the blowline, the integration is carried out stepwise from this point back as far along the blowline as is desired. The friction factor is taken as that for an essentially smooth pipe. Streeter, (1971) gives a value of 0.011 for this factor at Reynolds numbers in the range $1 - 2 \times 10^6$.

- The pressure drop for the calculated steam flow in the blowline is of no significance for the operation, as this condition is never encountered. What is significant is that the pressure drop in the blowline when fibre is flowing is so much higher than that for the same mass flow of steam alone.

- For the blowline example used, with the steam flow from Table A5 on page 42, the pressure drop for steam only is calculated in Table A12 for the existing blowline and for the smaller diameter selected to give improved resin blending from Table A10 on page 64. The blowline has two long radius swept bends and is treated as a straight length of pipe for this calculation.

### Table A12 - Blowline Pressure Drop - Steam only

<table>
<thead>
<tr>
<th>Steam Flow</th>
<th>kg s$^{-1}$</th>
<th>1.726</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blowline length</td>
<td>M</td>
<td>20.6</td>
</tr>
<tr>
<td>Friction factor</td>
<td></td>
<td>0.011</td>
</tr>
<tr>
<td>Blowline Diameter</td>
<td>M</td>
<td>0.10225</td>
</tr>
<tr>
<td>Pressure at end</td>
<td>bar</td>
<td>0</td>
</tr>
<tr>
<td>Pressure drop in blowline</td>
<td>Bar</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Calculation of the pressure drop attributable to the flow of steam alone confirms that the pressure drop in the blowline increases significantly when fibre and resin are present in the flow. For the case in Table A4, on page 40, the pressure at the refiner exit when fibre and resin are present was estimated at 5 bar so that the pressure drop in the blowline when fibre and resin are present is some 9 times that for the steam alone, calculated above as 0.54 bar for the original 102 mm diameter blowline.

The contribution of particles to the pressure drop in fluid flow in pipes is well established at the velocities used in transport systems, but the effect at the high
Reynolds number flows encountered in the blowline is less well documented. The increased pressure drop results from the interactions between the particles which can be seen as an apparent increase in viscosity of the fluid in an Eulerian treatment of the flow (Crowe et al, 1998) and may be attributed to the energy absorbed by the collisions in the blowline, particularly those between the particles and the wall of the blowline.

The conditions in the blowline are further complicated by the interaction between the liquid resin droplets and the fibres. In the blending model developed earlier in this thesis the breaking of a liquid resin bond between two fibres is important in reducing the size of the resin droplets on each fibre and hence significant in the blending outcome.

The analysis of this situation has not been attempted and few blowlines have the instrumentation needed to provide reliable indication of pressure drop in the blowline. But there are some indications from plants where some of this instrumentation is installed that the pressure drop in the blowline increases when the resin flow is started, suggesting that the presence of resin droplets in the flow provides an additional pressure drop increment. This would be expected from the collision-separation model. In addition to the energy changes associated with the collisions between the fibres and the resin drops, there is an additional energy component associated with the stretching of the liquid bridge between the two particles to the point of breakage.

6.3 Blowline Blending Model Outcomes

One of the major reasons for adopting blowline blending was to eliminate the resin spots that occurred when the resin was added after the dryer. This reduced, but did not eliminate the problem, as shown by Cooper (1992) in the investigation into the cause of resin spots and by Smith (1998) in a survey of resin blending in North American MDF plants, which showed resin spots as being 4th in the list of the most common problems with blowline blending.

This model described in this thesis establishes a continuum between conditions leading to small resin particles on the fibres, which give good resin efficiencies at one
end and an aggregation process, facilitated by large resin droplets, that leads to poor resin efficiency and eventually to resin spots at the other end.

The investigation shows that the outcome is determined not only by blowline velocity and the size of the resin droplets at entry, but also by the size of the fibres involved. Fibre fragments will be much more likely to lead to the aggregation outcome as the shear force gradients necessary to cause separation must be greater to generate the separation outcome where one of the fibres is much smaller. Both outcomes can occur simultaneously within a given blowline, particularly if there is a significant level of fines and if there is a wide range of resin droplet sizes.

The experience discussed in Section 3.2.2 on page 17, where resin spots resulted when the resin flow through the injection nozzles in plant T was reduced and disappeared when it was increased has been discussed earlier, as has the effect of increasing blowline steam flow (Plant X, Section 3.2.3 on page 19). The evidence that fibre fragments are also significant is more circumstantial, but is likely to be the reason that MDF panels made from fibres containing significant levels of fibre fragments, specifically those made from sawdust and other smaller particles generally require higher resin levels to achieve standard strength properties.

6.3.1 Optimised Blowline Design

The blowline optimisation programme requires that an accurate picture of the refiner be obtained, with steam flows consistent with the feed material and the refining energy used. Once this has been obtained the data is extrapolated to the maximum fibre flow/maximum refining energy condition for the plant that gives the maximum blowline steam flow.

- The blowline diameter in the blending section is then selected from available pipe sizes to give a steam velocity of $80 - 100 \text{ m s}^{-1}$ at 4.5 bar pressure.

- The velocity at the discharge to the dryer is checked for the choke flow condition at ambient pressure. If the flow exceeds the speed of sound in steam limit, the pressure rise at the end of the blowline that will maintain the velocity below this limit can be calculated. A choke pressure of up to 0.2 bar
can be helpful to ensure rapid dispersion of the fibre within the dryer airflow. If the choke flow condition creates a higher pressure drop than this, it may be necessary to provide a short (10-12 x diameter) length of larger diameter pipe at the end of the blowline to reduce the choke pressure to control this expansion.

- The resin nozzle location is then selected. Generally the blowline is designed with the resin injection close to the blowvalve. Experience with this model applied to a number of blowlines has shown that, providing blowline velocities are correct, the blowline length required for successful blending can be reduced. A 7 m length between the resin entry point and the end of the blowline is operating with good resin efficiencies. This is the only a guide; there is as yet no means of calculating what the blending length should be. If possible the blending length should be straight. Bends should be swept to avoid buildup; impact bends that use a cushion of fibre and resin to reduce wear are a source of resin spots as this material breaks away.

- The remainder of the blowline back to the refiner is purely transport, so the diameter is less important. In most cases this can be left as the original blowline.

- Resin nozzles are selected for the required resin flow.

- A pressure tapping on the blowline close to the nozzle provides an indication of the pressure at this point. The refiner steam flow is then adjusted to ensure that this pressure is as high as possible to give the highest velocities in the resin blending section.

Figure A22 on page 73 shows the recommended blowline diameter for optimum resin blending performance as a percentage of the original blowline diameter, for the plants where the study has been carried out. This shows that most blowlines were larger they should be for good resin blending. With no design criteria and no real evidence that the blowline conditions were significant in the blending outcome, it is perhaps understandable that the blowline diameter was selected to ensure that this did not limit refiner capacity.
In some blowlines the diameter was reduced for a short length in the section where the resin nozzles were situated (Plant S). This would be expected to give some improvement, but the subsequent reduction in velocity in the larger diameter section would negate most of this gain.

In the case at the left of the graph, (Plant B), the blowline diameter had previously been reduced in the final section of the blowline to the point where a choke pressure of 0.81 bar was reached at the end of the blowline. The consequence of this is considered on Section 6.3.6 on page 78.

The recommended blowline size was within 90% of the original in only 3 of the 25 plants investigated (Plants K, A and U). These 3 plants showed reasonable resin consumption figures.

6.3.2 Resin Solids Content

Dilution of resin is the one area where plant experience, as indicated by its widespread adoption, suggests that improved blending performance has been achieved. The resin solids content data for the Plants investigated are shown in Figure A3 on page 16. Plants have adopted the strategy of adding water to the resin to reduce the solids level, despite the additional water increasing the dryer load, presumably because this was found to give other benefits that outweighed this cost.
Reducing the resin solids level by adding more water leads to less resin in each droplet, while the lowered viscosity may also contribute to a smaller resin droplets for a given nozzle configuration. The reduction in resin solids level thus results in droplets containing smaller quantities of resin solids. These increase the possibility of the separation outcome in the blowline, contributing to an increase in the number of potential bonding sites on each fibre.

6.3.3 Changes in Plant Operating Parameters

There are two instances where the blending model explains the reason for the observed response to changes in operating conditions in plants.

- There is a general observation that an increase in resin addition rate is needed to maintain properties (specifically IB levels) as panel thickness increases. There is no reason why this should occur directly as a result of the change in thickness. However the press volume production rate falls as thickness increases, because the heat has to travel a greater distance from the hot platen to the centre of the panel. The fibre production rate necessary to meet the press requirement falls, requiring less steam to maintain preheater conditions and a reduced energy level in the refiner. These changes reduce the blowline steam flow. There is also a decrease in resin flow for the same resin addition rate, increasing resin droplet size if the nozzle configuration remains unchanged. In terms of the blending model, both these changes contribute to a reduction in resin efficiency. Increasing resin addition rates addresses the resin droplet issue to some extent, but increasing the housing steam flow to maintain blowline steam flow has not been used in any of the plants investigated.

- There is a similar response to a reduction in resin flow. If the plant is running with IB levels well above target, it could be assumed that the resin addition rate could be reduced while still meeting the specification. In fact a small reduction in resin (say from 10.5% to 10.0% on fibre) can lead to a much greater drop in IB levels. In data from one plant (X), a 5% reduction in resin addition rate led to a 23% reduction in IB level, with this observation being common to most plants. The reduction in resin flow through the nozzle leads to increased resin droplet size, with a consequent reduction in resin efficiency.
6.3.4 Resin Spots

The model discussed in this thesis suggests a continuum between the best possible resin efficiency at one end and the formation of resin spots at the other end. The establishment of this in early work contributed significantly to the development of the model. Significant reductions in resin spotting have been achieved both by increasing blowline velocities by decreasing blowline diameter and by reducing resin droplet size by improved resin nozzle performance.

In one instance, (plant H) severe resin spotting in the panel was reduced by moving the resin injection nozzle from a point where the blowline diameter was 154 mm, to a point downstream where the diameter was 102 mm. While the distance between the two points was approximately 1 m, the effect was a significant reduction in resin spots. The observation provides an insight into the aggregation process identified earlier as significant in the resin blending model.

- The aggregation process became dominant within a very short distance from where the resin was injected, providing an insight into the distance necessary for the effects of the fibre – resin droplet collisions to become established.

- The observation confirms the effect of blowline velocity in the resin mixing process with velocities in the 100 NB diameter section being 2.34 times those in the 150 NB diameter section.

- It also shows that while the resin spots had formed in the low velocity section, these did not breakup in the subsequent higher velocity section.

6.3.5 Blowline Buildup

The collision - separation model can be applied to impacts between the resin droplets, either individually or attached to a fibre and the blowline wall. When this occurs the resin will form a liquid bond with the inner wall of the blowline.
• If the fluid forces acting on the material attached to the wall are greater than the force holding it to the wall it will be removed. Any resin remaining on the wall will be removed by subsequent fibre impacts.

• If the fluid forces are not sufficiently strong to remove the material from the wall it will remain in contact with the inner surface of the blowline, moving very slowly, if at all. The increased time at the elevated temperature in the blowline will cause the resin to set, increasing the strength of the material attached to the wall.

The fluid forces acting on such an assembly attached to the blowline wall will be much greater than those operating on a similar assembly carried within the blowline flow. The buildup on the blowline wall will only occur at blowline velocities well below that necessary to achieve the desired separation outcome in the blowline flow. The converse of this situation is that a blowline with a significant buildup, often requiring periodic removal by scraping or water blasting, is an indication that the blowline velocities are well below those necessary to achieve good blending.

The buildup on the blowline wall can be a significant source of formaldehyde in the dryer exhaust. This was demonstrated in an observation from plant C where the existing 102 mm internal diameter blowline was replaced with 78 mm diameter pipe. The calculated steam velocity at 4.5 bar was 46 m s\(^{-1}\) for the existing blowline. For the same refiner conditions, the reduced flow area increased blowline velocities by 72%. The change to the smaller diameter blowline resulted in a 25% reduction in formaldehyde in the dryer exhaust. This observation was verified by changing back to the original blowline, which resulted in a return to the original level of formaldehyde.

The breakdown of the resin attached to the blowline wall into its components of urea and formaldehyde under the conditions in the blowline provides a mechanism for the release of this component. The formaldehyde appears in the dryer exhaust, where it is in many locations a controlled component. Ultimate disposition of the urea has not been determined, but there are several possibilities which would enable this to become separated from the fibre, so that it would not be measured in the Kjeldahl nitrogen measurement used to determine resin level on fibre.
This observation supports the model of the blending process. The reduction in blowline size in this case is among the largest recommended, so that the initial velocities were some of the lowest observed, consistent with the application of the separation model to the buildup on the blowline wall. The optimised blowline may thus enable the formaldehyde level in the dryer exhaust to be reduced to the point where it may not be necessary to treat the dryer exhaust stream to remove this.

As the blowline buildup increases, the effective flow area in the blowline decreases, increasing the velocity to the point where the buildup no longer occurred. This was demonstrated in a blowline at plant F, where it was recommended that the existing 78-mm diameter blowline be replaced with a 52.5 mm diameter pipe to achieve good resin blending. In this case the calculated velocities at 4.5 bar were below 40 m s\(^{-1}\) and the buildup in the original blowline required that this be cleaned once every 8 hours. While some buildup often occurs at bends, this example is significant in that the buildup was occurring in a straight section of blowline, after a few hours of operation.

It should be noted that most blowlines have several bends and that sometimes impact bends are used to protect the metal of the bend from wear. These rely on a buildup of material in a dead end to reduce the wear on the blowline in the area of the bend. Increasing blowline velocities may not eliminate buildup at these bends and resin spots may continue even when other aspects of the blowline have been improved.

The presence of natural resins in the wood can also contribute to the fibre attaching itself to the walls of the blowline and this will provide a bond which will not necessarily behave in the same way as one formed by the amino-based adhesives used in MDF manufacture.

While the breakdown of the resin results in formaldehyde in the dryer exhaust, it also represents a loss of binding capacity, as well as generating spots in the panel from material breaking away from the wall. These spots are identifiable by a fracture edge that differentiates them from a spot formed by aggregation in the blowline flow. The buildup on the wall occurs at blowline velocities (calculated at 4.5 bar) typically below 50 m s\(^{-1}\), both examples discussed having velocities with the existing blowline below
this level. However the build up at impact bends suggests that these should be avoided in a fully optimised blowline design.

This has been demonstrated in Plant Y where a reduction in blowline diameter resulted in improved resin efficiency, but resin spots did not reduce until an impact bend after the resin injection point was replaced.

6.3.6 Buildup in the Dryer

The buildup of material on the dryer wall is often a problem. The material attached to the wall can break away and form spots in the panel. These are distinguishable from those formed in the blowline by the curvature of the dryer wall appearing on one surface, but can still lead to downgrading of the panel. The material also constitutes a fire hazard and periodic cleaning of the dryer is often necessary.

The dryer for MDF fibre is a flash tube, with a temperature-controlled air stream that carries the fibre from the blowline, through the flash tube where the drying takes place, to the cyclone where the dry fibre is separated from the conveying air stream. The blowline discharges the flow from the refiner into a straight section of the dryer tube, with care being taken to ensure that both the blowline flow and the dryer air stream are fully developed and that the blowline is carefully aligned with the centre line of the dryer.

The calculation of the discharge velocity from the blowline provides an insight as to how this can influence the buildup on the dryer walls.

- With most blowlines being of larger diameter than is necessary, velocities are generally lower than they should be to achieve a good blending result, with aggregation being a more significant outcome. The larger particles resulting from the aggregation process will require longer drying times. The lower velocities at the exit of the blowline will also result in a more stable jet entering the dryer, so that the dispersion of the fibre in the dryer air stream will be slower, also increasing the drying time. It is also possible that collisions between the fibres
The consequence of this condition is that the drying may not be completed by the time the fibre reaches the first bend in the dryer, leading to a buildup at this point. In addition, the larger material may settle out of the dryer air stream and build up on the bottom of the dryer tube.

If, however, the calculated velocity at the end of the blowline exceeds the speed of sound in steam, the choke flow situation applies. The pressure in the blowline at the dryer entry will remain at a point where the density of the fluid, steam in this case, is such that the local velocity will not exceed the sonic limit. The flow leaves the blowline with an internal pressure that will cause it to expand as it leaves the constraint of the blowline. If this expansion is too great, some fibre may contact the wall of the dryer tube immediately downstream of the fibre entry point. This situation was encountered at plant B where the calculated entry velocity at atmospheric pressure was 875 m s\(^{-1}\), with severe buildup in the dryer tube just downstream from the fibre entry point. The pressure at the end of the blowline would rise to 0.81 bar to maintain the blowline velocity below the sonic level and this pressure caused the jet to expand sufficiently against the dryer air stream to contact the walls of the dryer. In this case it was necessary to clean the dryer tube after 48 hours operation.

Between these two extreme points there is a velocity range which will ensure that the incoming fibre is distributed quickly through the dryer airflow. Some expansion of the blowline jet is beneficial in achieving this, separating the fibres and minimising the possibility that further collisions will occur in the dryer. From this perspective the velocity at the point where the blowline discharges into the dryer should be just above the choke point when calculated at atmospheric pressure.

For a typical blowline, a velocity of 80 to 100 m s\(^{-1}\) at the 4.5 bar pressure point will result in a velocity for the same blowline diameter of approximately 500 m s\(^{-1}\) at ambient pressure. These velocities have been found to give good resin blending. Should higher velocities be indicated, or required, then the choke condition can be controlled by providing a short section of increased diameter pipe at the discharge of
the blowline to reduce the velocity at this point. This approach has been used where the dryer entry velocity for the recommended blowline size is too high. It will become more significant if higher blowline velocities in the blending section are found to be beneficial.

The dispersion of fibre is an important facet of dryer design. Typically the blowline enters the dryer axially in a straight section which may be 40 – 100 m long. If the blowline entry velocity can be controlled precisely at a point where expansion of the jet ensures a rapid dispersion of the fibre in the dryer airflow then this section of the dryer could be shorter. This will reduce the capital cost and provide for more flexible plant layout.

These illustrations demonstrate how the blending model provides logical and consistent explanations for situations which, until this model, have not been satisfactorily explained.

6.4 Refiner Mass - energy Balance

The mass - energy balance over the refiner has proved to be a useful tool in its own right, proving useful as a training tool for refiner operators, as well as identifying situations where the operation could have negative impacts on fibre quality (Chapman, 2001).

Dilution water flows are often set without a real understanding of the impact of these on the condition of the feed material to the refiner. In one case (Plant X) the large fibre component known as shives, formed by bundles of unseparated fibres could not be controlled by increasing refining energy. Applying the mass - energy balance to this case showed that the flow of cold dilution water added to the material was more than sufficient to condense all the steam coming forward with the refiner feed material. This caused a drop in temperature in the material entering the refiner to the point where the benefit of the preheater was being negated, resulting in a fibre with high levels of both fines and shives. Heating the dilution water before adding this to the refiner is one way of overcoming this situation, but the mass - energy balance
can also be used to calculate the dilution water flow necessary to give a selected water: fibre ratio at the refiner.

One of the reasons for adding dilution water is to reduce the thermal breakdown of the feed material in the refiner plates. This material builds up in the grooves of the plates, reducing the flow capacity and eventually reaching the point where it is necessary to replace the plates to retain capacity. This situation occurs much more rapidly when the material within the refining plates reaches the point where there is insufficient water in the material to absorb the refining energy by converting it to steam. This leads to increases in temperature of the material to the point where the thermal breakdown rate increases.

This point can be calculated with the mass-energy balance. The example quoted (Figure A13, page 41) shows the liquid water at the plate exit as $1.17 - 0.4165$ or $0.7435$ kg H$_2$O kg$^{-1}$ ODF. This is for a high moisture content chip feed with a low refining energy. For a low moisture content feed with a high refining energy the addition of dilution water is necessary to avoid the situation where the liquid water in the fibre is all evaporated in the refiner plates.
6.5 Summary

The examples quoted demonstrate how the blending model explains and suggests solutions for problems that are often a continuing part of the operation of an MDF plant. In addition to the objectives of improved resin addition rates and reduction of resin spot downgrade, the solution for a particular blowline can be directed towards solving particular problems in the areas discussed in this chapter.

The validation of the refiner mass-energy balance has been discussed earlier. The explanations of other plant problems in terms of blowline conditions and the success of the solutions which come from this, provide additional validation of the method.

There has never been a serious challenge to the model either in the plant investigations that have been done, or as a result of the presentations of the technique.

One further outcome of the work has been a resin injection nozzle for blowline blending. This is discussed in the next Chapter.
Most MDF plants have experimented with different nozzles and resin injection conditions for blowline resin addition and arrived at a best solution for them. However nozzle design is not discussed in any of the published reports on blowline blending and none of the equipment suppliers appears to have offered an approach that offers significant advantages.

While there may be some uncertainty in the droplet size calculations in Chapter 7, there is a clear indication from the analysis that the size range of resin droplets produced in an atomising nozzle is consistent with the prediction of the blending model and with plant experience in achieving good resin efficiency.

Two possibilities for producing droplets from the resin stream were examined in Chapter 5 on page 44. One considered the atomising effect of the interaction between the resin jet and the steam flow in the blowline, while the other considered the droplets produced by nozzles in both pressure and gas-atomised configurations.

These predictions need to be used with care. In using the total blowline steam flow in the calculation, it is implicitly assumed that all this flow plays some part in the atomisation of the resin. Similarly, in the nozzle calculations it is assumed that the atomisation process is able to be completed without significant interference from external conditions such as the steam flow in the blowline.

### 7.1 Atomisation in the Blowline Environment

Cooper (1992) calculated the penetration distance into the blowline steam flow for a circular, pressure-atomised nozzle perpendicular to the blowline flow, using equations which show this to be controlled by the relative momentum of the two flows. For the case where the blowline steam velocity is 100 m s\(^{-1}\) and the liquid
velocity is $13 \text{ m s}^{-1}$ the calculated penetration is approximately $50\%$ of the $102 \text{ mm}$ diameter of the blowline at that point.

If the blowline velocity is low, as has been found in most of the blowlines investigated and the resin nozzle produces a cohesive jet, then it is possible for the jet to reach the far side of the blowline and impact on the wall. This situation was observed in early trials, where the flow through one nozzle was progressively increased. Initially the resin efficiency improved as the resin droplets became smaller, as a result of the improved atomisation from the higher pressure drop across the nozzle. However beyond this point the resin efficiency fell quite dramatically. This effect is best explained by the resin jet penetrating the steam flow and hitting the opposite wall of the blowline. This trial (Plant X) was done before the detailed blowline calculations were in use, so these cannot be determined with any degree of accuracy. However the blowline conditions in this plant were established in a later investigation, with an indicated blowline steam velocity (calculated at 4.5 bar pressure) at time this trial was done in the range $50-60 \text{ m s}^{-1}$

This experience shows that where blowline velocities are low, a high pressure drop across a pressure-atomised nozzle can produce a resin efficiency result worse than that achieved at a lower pressure drop. It perhaps explains why nozzle pressures tend to be kept lower than necessary to produce small resin droplets. These can only be increased once blowline steam velocities have been increased.

The experience also suggests that there is some atomisation, probably at the periphery of the jet, but the centre of the jet remains intact for some distance. Atomisation eventually occurs, unless the jet strikes the far wall of the blowline, in which case the resin is probably distributed by contact with fibres hitting the resin film formed on the wall.

It also suggests that to be effective, atomisation should be completed as close to the nozzle as possible, before the resin jet is captured by the blowline steam flow.
7.2 Current Blowline Resin Injection Nozzles

Several approaches have been observed in operating MDF plants aimed at allowing the atomisation process to be completed with as little interference as possible from the blowline steam flow.

- In some cases the nozzle has been placed in a recess off the blowline so as to give the spray of resin droplets space to develop. However the turbulence in the blowline steam flow enters this space, leading to fibre buildup which then affects the spray development and will almost certainly be a source of resin spots.

- Placing the nozzles at the inside of a long radius bend was thought to be beneficial, taking advantage of the lower velocities in this area.

- Nozzles have been installed at a variety of angles in relation to the blowline steam flow, injecting resin both upstream against the resin flow and downstream with the flow.

- Injecting the resin upstream into the blowline steam flow maximises the interaction between the resin jet and the blowline steam flow.

- In some cases the resin nozzle has been installed at the centreline of the blowline, but these have encountered high wear rates.

None of these appear to have offered improved performance, although in many cases the blowline velocities were also likely to be below the optimum.

Many different nozzle types have been observed in the plants investigated.

- Pressure atomised nozzles are commonly used, with a pressure drop across the nozzle of between 2 and 7 bar.

- Multiple nozzles are often used, up to 9 in one plant (A), but more commonly two or three. In this case individual nozzles need to be able to be brought into service
or stopped as required to match nozzle capacity to the resin flow needed.

- The problem of maintaining pressure drop across the nozzle is recognised in most plants. Two approaches have been tried to achieve this.
  - Variable geometry nozzles are used, but this adjustment is normally manual and not usually sufficiently frequent to achieve the best resin efficiency.
  - In two plants (D and Z) a variable dilution system is used. The required resin flow is determined and delivered to the nozzle, while the flow of dilution water is determined by the pressure drop across the nozzle. This approach is relatively easily automated and works well, providing the limits to dilution are recognised. The dilution water also increases the dryer load and this approach would limit capacity in a plant where dryer capacity was the bottleneck.

The "no - nozzle " approach is found in some plants, with the resin entering the blowline through a pipe. This relies on the interaction between the resin flow entering the blowline and the blowline steam flow as the sole means of atomising the resin. As shown in the droplet size analysis (Figure A21, page 59), this approach leads to large resin droplets, with consequent resin spots in the panel and low resin efficiency. This method is commonly used where blowline velocities are low so that pressure atomised nozzles could have a negative effect. The resin usage in these plants tends to be high as a result of the combined effect of the low blowline velocities and the large resin droplets.

Smith (1998) quotes average resin usage rates (% resin solids on ODF) of 7% for post dryer blending and 11% for blowline blending in the survey of North American MDF plants. For plants with optimised blowlines using chip as opposed to a sawdust/shavings/chip blend as a feed material, resin levels of 7 – 8% on ODF are achievable (plant U and others).

The service conditions are important in the selection of nozzle type. Smith (1998) identified plugged resin lines and nozzles as the second most important in his list of problems identified in his survey. The nozzle cannot be removed for cleaning while the blowline is in operation, while the temperature in the blowline will cause any of the thermoset resin remaining stationary in the nozzle to cure in a relatively short
time. Nozzles are often water cooled to minimise this possibility and a movable central plug is sometimes used to prevent fibre coming into the nozzle when it is not in use.

With no one approach demonstrating a clear advantage, there is a market opportunity for a nozzle specifically designed for the blowline situation, particularly where this can be offered as a part of a blowline optimisation product.

### 7.3 Resin Injection Nozzle – Design Criteria

The following objectives for the design were set as a result of the experience gained in a number of plants. These can be summarised as:

- Good atomisation performance,
- Maintaining this over a range of resin flows.
- Reliable operation in the blowline environment.
- Wear parts should be easily replaceable.
- The design should allow for a change in the nozzle size so that the flow range can be changed if the need arises.

### 7.4 Nozzle Type

While pressure atomisation is the simplest approach, the complication of the variable geometry necessary to maintain atomising performance as flows vary, counts against this design. The variable dilution approach is attractive in that it is easily implemented and controlled and gives good results, but the resultant increase in dryer load is not acceptable where dryer capacity limits the capacity of the plant.

The analysis above suggests that for nozzle atomisation to be effective it must occur very close to the nozzle, before the jet is captured by the blowline steam flow. A review of commercial spray nozzles shows that even for fan or cone shaped nozzles, the breakup into droplets does not occur immediately. Lefebvre (1981) discusses the atomisation process for high viscosity liquids in a gas–atomised nozzle in terms of the development of liquid ligaments drawn from the lip of the nozzles by the
atomising gas flow, whereas the pressure atomised nozzle produces a high velocity jet where the atomisation occurs largely as a result of the drag forces acting on the jet from the atmosphere into which the jet is injected.

This suggests that a two fluid nozzle, where a gas stream provides atomisation energy at the nozzle could be a useful approach, particularly if the gas atomising effect could offset the increase in droplet size when the liquid flow through the nozzle is reduced.

Characteristics for such a nozzle have been calculated both as a pressure atomised and as a steam atomised nozzle using equations A5.4 and A5.5, (Section 5.4, page 56) for varying resin flows, as shown in Figure A23. The nozzle is designed for a resin flow of 25 l min\(^{-1}\), with a 5 mm diameter liquid path. The gas flow is calculated on the basis that the flow at the smallest area in the gas path flow path reaches the choke condition. For the nozzle under consideration this flow at an assumed pressure of 7 bar at the choke point is 0.05 kg s\(^{-1}\). For a liquid density of 1250 kg m\(^{-3}\) the liquid mass flow is 0.52 kg s\(^{-1}\). The gas: liquid mass ratio in this case is 0.1.

![Droplet Size for Two Nozzle Types](image)

*Figure A23 - Droplet size for pressure and steam atomised nozzles.*

The gas: liquid mass ratio term is significant in equations for the gas atomised nozzle and in this case is relatively low. Deysson and Karian (1979) show a correlation of droplet size against this ratio which shows a substantially linear relationship for the gas: liquid mass ratio over the range 0.05 – 10. At a gas: liquid mass ratio of 0.1 the effect of the gas atomising will be less significant. However for a case where the
atomizing gas flow stays the same and the liquid rate falls, the gas atomisation effect will increase.

As seen in the nozzle equations A5.4 and A5.5, the general forms for the two nozzle types are quite different, suggesting that the atomising processes are also quite different. No equations have been found for a combined pressure and gas-atomised nozzle. Generally the gas atomised nozzle uses a relative gas-liquid velocity term calculated as the difference between the two velocities, with the droplet size decreasing as the relative velocity increases. For this case, increasing liquid velocity will increase the droplet size, although the effect will be small as the liquid velocity is typically 5%–10% of the gas velocity.

Calculating the droplet size for the proposed nozzle for both pressure and gas atomised cases for varying liquid flows using equations A5.4 and A5.5 gives the graph shown in Figure A23 on page 88. In view of the comments above on the radically different approaches in the two equations, the overall agreement between the two predictions is regarded as fortuitous rather than reliable, but it does demonstrate that the concept of a combined pressure and gas atomised nozzle providing a more uniform droplet size as liquid flow varies is feasible.

The main advantage in the gas atomised nozzle is that it achieves the atomisation closer to the nozzle, providing better control of the process before it becomes dominated by the blowline steam flow. The atomising gas can be either compressed air or steam. Plant compressed air is typically available at 7 bar pressure, too low where the blowline pressure at the resin injection point is about 5 bar. Steam is available in an MDF plant at typically 12 bar pressure and is usually produced by burning process waste streams, giving a lower cost as well as a more suitable pressure. The steam entering at the nozzle becomes part of the blowline flow.

The steam flow is left on the nozzle whenever steam is flowing in the blowline so that these passages remain clear of fibre. The use of steam, however, means that the nozzle will become hot and requires a different approach to preventing the resin in the nozzle from setting.

The approach adopted is to flush the resin from the nozzle as part of the shutdown procedure for the nozzle. Water is commonly used to flush the resin, but other
approaches are needed with resins that are unstable in contact with water. In this case a two stage flush is used, first with steam or a resin that does not react with water, to clear the resin, followed by a water flush to cool the shutoff valve which has resin on the other side.

The nozzle incorporates a straight-through resin path, with an internal rod controlled by an air cylinder which can be used either to "rod" the resin path to clear it, or left in the down position to keep fibre out of the resin path when resin is not flowing.

7.5 Nozzle Capacity

Refriner sizes are increasing as press capacity increases. There are smaller refiners in older plants, but a practical minimum of 10 te.h⁻¹ fibre is assumed. Current refiner capacities are up to 40 te.h⁻¹.

The range of products produced in an MDF plant has broadened. Standard MDF has a resin usage ranging from 7% – 12% (resin solids to oven dry fibre) while newer products made at lower densities, or to meet higher performance levels may have resin usage rates twice this level. The resin injection system must be able to handle this range of flows, while maintaining atomisation performance over the full range of resin flows.

For the example used to illustrate this study, with a fibre capacity of 12 te h⁻¹ the resin flow for standard density MDF at 65% solids content is 24.8 l min⁻¹. This is added through a 5 mm diameter nozzle. A 6 mm diameter nozzle would have a flow area 44% greater, with a flow capacity at the same liquid velocity of 36 l min⁻¹. The pressure drop across the nozzle depends on the viscosity of the resin, but is typically about 5 bar at the quoted flow.

The design, shown in Figure A24, on page 91 allows alternative liquid and gas flow arrangements to be implemented easily. There appears to be no "best arrangement" for the liquid – gas interface and Lefebvre's (1981) review paper describes a wide range of possible configurations recommending only that the best result is achieved where the liquid stream is transformed into a thin film before contacting the gas flow.
For blowline resin injection the need for reliable operation dominates the design at least until reliability has been demonstrated. It is possible to incorporate new designs for the gas and liquid paths once this has been achieved.

The nozzle has proved to be very successful. It is usually installed as part of a blowline upgrade, so it is difficult to assign the benefits between the improved atomisation performance and the increased blowline velocity. It has been used in specific applications to solve nozzle blocking problems and also where dryer capacity is limited. The ability of the nozzle to handle high solids resin allows the dryer load to be reduced, freeing up capacity for fibre drying.

![Blowline Resin Injection Nozzle diagram](image-url)

**Figure A24- Blowline Resin Injection Nozzle.**
Part A: Chapter 8
Conclusion – Blowline Blending

This section of the thesis describes the development and application of a plant-based model of the blowline blending process in MDF production to mix the resin, used as an adhesive, with the prepared fibre. This approach was developed as a response to the need to reduce resin consumption and to address other issues which required the plant to shut for cleaning. It is the first comprehensive blowline blending model to be published.

The blowline blending process was adopted early in the development of the MDF manufacturing process as a solution to the resin spots that occurred in the panel when the resin was mixed with fibre after it had been dried. This new approach reduced the resin spot problem, but as shown (Smith, 1998) did not eliminate it. Despite an increase in the resin requirement variously estimated at 15% – 40% compared to the dry blending case, (Smith, 1998) the blowline blending process has become the norm for MDF manufacture.

The reason for the increased resin requirement was examined in several early publications, with the conclusion that the solution to the problem would be found in modified resin formulations. There appears to have been little significant progress in this area. Investigations within plants showed that dilution of the resin appeared to be beneficial. The evidence for this is circumstantial, but it has become accepted practice, despite an increase in dryer load and consequent energy cost.

There were indications that the blowline conditions could be significant in the blending outcome, but it was not until 1998 that the model which is the subject of this thesis was presented. This model is based on plant experience and trials. It links blowline conditions and resin atomisation in a comprehensive model which has proved to be robust and reliable.

The model has been applied in 25 MDF plants throughout the world and data from these investigations conclusively supports the model. In only one case was the
blowline smaller than the predicted optimum. In all other cases the blowline diameter could be reduced to achieve the higher velocities that have been found necessary for a good blending result. Low blowline velocities limited the effectiveness of the injection nozzles that could be used, leading to resin droplets larger than those necessary for good blending performance.

It is concluded that the combined negative effect of these two factors is the reason for the increased resin requirement associated with blowline blending. Plants with high blowline velocities and injection nozzles capable of producing small resin droplets are able to meet MDF panel strength requirements, with resin contents similar to those quoted for post-dryer resin addition systems.

The model also explains a number of other consequences of the MDF process, specifically build up on the dryer wall and also the presence of formaldehyde in the dryer exhaust, some of which had not previously been associated with blowline conditions. Successful resolution of these problems using the model provides additional validation.

In this thesis the model is presented and key points analysed and assessed. There are three levels at which the approach can be considered.

1. As a plant-based model it has successfully demonstrated how the blowline blending process works and how this can be controlled to improve the overall outcome, both in terms of reduced resin requirement and in other areas of blowline performance.

2. The model is supported by detailed calculations based on refiner conditions that allow the blowline steam flow to be determined in each case. Resin droplet size is examined, particularly in relationship to the size of the fibres and also from the perspective of the atomisation approaches used. These calculations have validated the conclusions of the plant-based model and have provided new insights into the MDF process, particularly as to how it can be controlled.

3. At a third level, the modelling of the interactions between the fibres and the resin droplets in the blowline conditions using techniques such as computational fluid
Part A: Blowline Blending Model  page 94

dynamics will provide new understanding in this area, particularly in estimating the length of blowline required to achieve the best resin blending outcome.

The objective in this thesis is to describe work done in the first two of these areas in order to provide a sound basis for others to develop the third level.

The work has focused on two main points seen to be significant in the blending outcome, with a link between them which is also significant.

- The steam velocity in the blowline should be as high as possible from the point where the resin is introduced, to the discharge of the flow from the refiner into the dryer. At present steam velocities up to $105 \text{ m s}^{-1}$ have been reached; increasing this velocity further is limited by the available pressure drop between the refiner and the dryer and also by the choke flow limit at the discharge to the dryer.

- The resin droplets should be as small as possible. Comparison with the size of a fibre shows that mean droplet diameters in the range 10 – 20 microns are needed to provide multiple resin droplets for each fibre, or more particularly for fibre fragments. These droplet sizes are close to the limits for pressure atomised nozzles, particularly those able to operate reliably in the blowline conditions.

- The blowline velocity places an upper limit on the pressure drop across the resin injection nozzle. If the pressure drop is too high the jet will travel across the blowline and hit the far wall of the blowline.

In each case the desirable conditions are close to a physical limit, as indicated by the calculated values. However it would also appear that there would be further benefits if ways around these limits could be found. There are some possibilities which are being pursued in the continuing application of the method. Plant experience will continue to be the major input into developing the application, requiring a practical approach which minimises the possibility of adverse results.
8.1 Blowline Velocity.

The choke flow condition, where the calculated velocity at a given pressure exceeds velocity of sound, places a limit on the actual attainable velocity reached in the enclosed pipe of the blowline. If the velocity in the blowline at the point where the flow is discharged into the dryer is close to this limit, then the blowline will give a reasonable blending result. To date this criterion has been used as the design point for the optimised blowline.

Increasing the diameter of the blowline for the last section before the discharge into the dryer reduces the pressure at this point allowing higher velocities to be reached upstream of this point. This approach has only been used sparingly to date, but it does allow higher velocities to be used in the section of the blowline where the resin and the fibres interact.

Measurement of the pressure at the discharge end of the blowline can indicate the onset of the choke flow condition and provides a useful technique for controlling the steam flow in the blowline at the point where the steam velocities in the blending section of the blowline are maximised and the expansion of the jet as it enters the dryer is such as to ensure rapid dispersion of the fibre in the dryer air stream.

Further work is needed to determine the minimum length of pipe that would be necessary to allow the flow to re-establish after the increase in diameter. It may also be that two or more increases in diameter would be beneficial in maximising the velocities in the resin blending section while retaining control of the pressure in the jet as it leaves the blowline.

Higher velocities will increase the pressure drop in this section of the blowline. For the velocities used to date there is sufficient pressure available between the refiner housing and the dryer, at least in the shorter blowlines. This has been achieved by transferring pressure drop from the blowvalve to the resin blending section. In addition to the improved resin blending conditions, load swings on the refiner have been reduced when the pressure drop across the blowvalve is minimised.

Further increases in velocities will increase pressure drop in this section of the blowline. The available pressure is the difference between that in the refiner
housing and in the dryer. Once the blowvalve is fully open, increasing velocities in the resin blending section will only be accommodated by reducing the pressure drop in the section of the blowline before the resin injection point. Beyond that point the length of the resin blending section becomes the significant factor. Reducing the length of this section becomes the only option to allow higher velocities to be achieved.

8.2 Blending Length

Resin has been injected at many points over the length of the blowline, with no apparent advantage for any particular point. Other factors such as blowline diameter also affect the blending outcome and this could have had a more significant effect on the outcome than the nozzle position. Resin injection capability has been built into blowvalves to take advantage of the turbulence associated with the pressure drop at this point.

This investigation shows that the turbulence at the resin injection point does not necessarily provide gains that are maintained throughout the length of the blowline. Other data shows that the fibre - resin interactions can produce resin spots within a relatively short length of blowline. This suggests that the necessary mixing of the fibre and resin can be achieved within a relatively short length of blowline. The shortest blending length encountered was 7 m. This was giving a very good blending result in a blowline with close to optimum diameter (plant K).

From a practical viewpoint the resin injection point needs to be accessible, so that the portion of the blowline inside the dryer, typically 3 m – 5 m, establishes a minimum length for this section. The blending length recommended is typically 7 m – 15 m. This is much shorter than the overall blowline length which ranges from 14 m to a maximum of 55 m and which is the effective blending length when the resin injection point is close to the blowvalve on the refiner. It is expected that the blending length will become more critical if blowline velocities are increased.
8.3 Resin Droplet Size

Experience in plants confirms that resin droplet size is significant in the blending outcome. The droplet size analysis shows that the largest of the droplets are the most likely to lead to the fibre-resin aggregates that in turn lead to resin spots in the panel.

The conclusion from this is that while the overall atomisation characteristic is important, the large droplets are most likely to cause resin spots. The atomisation requirement is therefore for a uniform droplet size, rather than for the smallest possible size. The steam atomised nozzle has proved to be very successful, but with a design favouring reliability over the best possible atomisation configuration. Further development of this design is possible now that reliability has been achieved.

While atomisation would improve with a greater number of smaller nozzles, cost and complexity would count against this approach. Development should be aimed at improving the performance of the nozzle. For the steam atomised nozzle the direction would be to move towards the thin liquid film suggested by Lefebvre (1981) as the way to improve the uniformity of the resin droplet size, with a configuration that also allows an increased mass flow of the atomising gas. However if the steam velocity at the resin injection point can be increased, then the pressure drop in the nozzle could also be increased.

8.4 Future Development

Development of the technique as a commercial product will continue along the lines indicated. This thesis has provided an opportunity to review and test the work done to date with a rigour that is not possible within the limits of a commercial application. It has also provided new insights into the process and these insights will shape the future direction of the work.

Finally the work provides a sound basis for the application of advanced fluid flow analysis techniques to the resin-fibre interactions in the blowline conditions. While these advanced techniques will become increasingly important in developing the process, there is much yet to be done based on the understanding brought to the subject in this thesis.
Part B.

The Effect of Temperature, Moisture Content and Fibre Characteristics on the Stress-Strain Response of Dry-formed Fibre Mats.
Part B: Chapter 1
Introduction

Medium Density Fibreboard, or MDF, is a composite panel made by pressing a mat of fibre derived from wood or other cellulose based material, mixed with a thermosetting resin. The fine structure of MDF, compared with other composite panels such as particleboard, enables it to be sawn, machined into shapes and finished with the techniques and technologies used for solid wood. The uniformity of these properties has been important in allowing MDF to be used in automated machining and finishing lines producing components for furniture and cabinetry uses, an area responsible for much of the growth of the MDF market.

The process of mixing the resin with the fibre is discussed in Part A of this thesis. The fibre, with the resin now attached, is dried, to the moisture content required in the press, typically between 9 % and 13 %. The fibre is then formed into a mat with uniform mass per unit area, so that after the panel has been pressed to the desired thickness, it has the required average density. In the press, the mat is compressed and heated so that the adhesive sets, forming a panel with the desired properties.

The strength of the panel is largely determined by the quantity of resin added to the fibre and the effectiveness of mixing this with the fibre, as discussed in Part A of this thesis. However the strength properties are also density dependent, so that the distribution of density through the thickness of the panel also exerts a significant influence on the balance of properties through the panel. In the case of MDF, the density of the surface of the panel affects the absorption rate of paints and lacquers. If the surface density is low, the absorption of the paint into the panel is more rapid, reducing the surface coverage. If the surface density varies over the panel the variable response to the paint affects the finish, requiring additional effort to achieve a uniform result. The machining response of the edge of the panel is also density-dependent, with a higher density in this area giving a cleaner cut.

The distribution of density within the thickness of the panel is termed the vertical density
profile or VDP. The VDP results from the establishment of density differences in the mat as the hot pressing proceeds. These arise from the interaction between the heat, and mass transfer induced by heat moving from the platen into the material and from the compression from the closing of the press.

The VDP is measured by exposing a sample (typically 50 mm square) to a narrow collimated radiation beam so that the beam travels through the sample parallel to the face of the panel from which the sample has been taken. The radiation beam is generated by a radio isotope source, or in more recent machines by an X-ray source. The absorption of radiation is proportional to the density of the material in the path. By moving the sample progressively through the beam path from one face of the panel to the other, the density at each point through the thickness of the panel can be determined. The VDP is usually presented in graphical form. Typical profiles for MDF and for particleboard are shown in Figure B1.

![MDF and Particleboard Density Profiles](image)

*Figure B1. Vertical Density Profiles – 18 mm thick MDF and Particleboard Panels*

The particleboard profile is much more rounded than the one for MDF. In each case the high-density faces are separated by a low-density area within the panel. In the profiles shown, the MDF profile has higher face and core densities than for the particleboard profile, despite the average densities being similar for the two cases. The uniform density between the faces is important in achieving this. It is also important because the machining response of the central area of the panel will also vary if the density in this area changes.

The importance of VDP in determining the properties of the MDF panel was recognised
early in the development of the product. Suchsland and Woodson (1974), in a laboratory press study, showed that increasing the maximum pressure in the closing stage of the press increased the bending strength of the panel. The VDP of the panel was measured by weighing and measuring the panel after removal of material from the outer face of the sample. This enables the density of the section removed to be determined, providing a coarse view of the VDP.

The development of radiographic means of visualizing the density profile was noted by Nearn and Bassett, (1968). This technique effectively took an X-ray photograph through a thin section of the panel. From this the scanning profileometers were developed, with a number of commercial instruments now available. Initially radio isotope sources were used as the radiation source; more recent instruments use X-rays, reducing scan times. Alternative mechanical methods have been investigated (Winistorfer et al. 1995), but the radiation absorption method has become the standard. Most recently an instrument that measures the VDP of the moving panel as it leaves the press, using an X-ray backscatter technique has become available (Dueholm,1996). The instrument is expensive, but its considerable sales success indicates the importance placed on the VDP as an indicator of panel quality.

Haylock (1977) reported on early experiences at the Canterbury Timber Products Ltd MDF plant, and described a new method of controlling the closing of the press by “position” rather than pressure. By closing the press to a uniform time - position profile, a more consistent density profile was obtained. Further experiences at Canterbury Timber Products Ltd were reported by Chapman (1979) who described the development of an MDF panel for use as a structural flooring panel, where a high bending strength was important. This was achieved by significantly changing the press closing strategy from that developed by Haylock. In this case the initial closing of the press was stopped at 105% of the final panel thickness out of the press, as against 115% when a machining grade MDF was produced. Density profiles were obtained by machining successive layers from the sample. This paper also raised the possibility of a mathematical model of the pressing process.

Kunesh (1961) studied the compression of wood samples over the temperature and
moisture range encountered during the pressing of wood-based composite panels and identified the plastic components of the stress - strain relationship as being significant in the pressing of composite panels. Palka (1973) reviewed previous work on the effect of temperature and moisture changes on the strength properties of wood. By comparing data from species of different densities he also showed a relationship between density and stiffness. Van Houts et al. (2003) measured the strain relaxation of MDF fibres, and of panels made with and without resin, over a range of temperature and humidity conditions similar to those encountered in the hot press.

Maiti et al. (1984) discussed the deformation characteristics of cellular solids, including wood. The non-linear stress - strain behaviour of wood is described in terms of the failure mode of the cell walls, with three distinct failure modes considered. The first of these was the elastic buckling of the cell walls, which occurred for solids with a relative density of 0.3 (equivalent to a voids ratio of 0.7). The second involved a plastic failure within the cell wall arising from plastic hinges formed within the walls of the cells. The final form was a brittle failure where the walls of the cells were sufficiently rigid to fail in shear. In this analysis the Modulus of Elasticity of the material is used as the basis for the stress - strain calculations. The Modulus of Elasticity is adjusted to reflect the temperature and moisture conditions, but density changes and stress relaxation effects are developed into a non-linear strain function to represent the influence of time.

Wolcott, Kamke and Dillard (1990) discussed the visco-elastic behaviour of wood flakes, particularly the stress relief mechanisms in terms of the glass transition behaviour. The paper acknowledged the uncertainty in the glass transition temperature, and concluded that this was highly moisture dependent. It was concluded that the lignin and hemicellulose portions of the wood responded differently to changes in temperature, that each of these was dependent on the moisture content and that the effect of these changes would be seen less in the wood properties than in those of the individual polymer components.

The glass transition temperature of lignin and cellulose was discussed by Black and Salmen (1982) and by Salmen (1984). The glass transition temperature of the carbohydrate components was shown to fall as moisture content increases up to 15%.
The glass transition temperature of the lignin initially falls as moisture increases from zero to 3%, but plateaus at 100 °C as moisture content increases beyond this point.

Wolcott, Kamke and Dillard (1990) discussed the visco-elastic behaviour of wood as a cellular foam. This approach considered elastic failure of individual cell walls within the foam matrix as a significant failure mode. In subsequent studies (Lang and Wolcott, 1996 a, b) the analysis was extended to the stress - strain behaviour of simulated mats prepared from wood flakes. Lenth and Kamke (1996) developed this approach again for wood flakes, and made some points which would be useful in extending this approach from flakes to individual fibres.

Several mathematical models of the pressing of composite products seek to predict the VDP from a situation with known mat and press conditions.

Suo and Bowyer (1994), in their particleboard model, calculated the stress - strain relationship based on the Modulus of Elasticity (MoE) of the material, using a relationship between elastic properties and both moisture content, and temperature based on work by Palka (1973). In using the Modulus of Elasticity the method assumed that this property uniquely characterises the stress - strain relationship, despite the fact that the density of the product is higher than the density of the wood from which it is made.

Harless et al. (1987) describe a model of the particleboard pressing process. The stress - strain relationship for the material was measured experimentally at four temperatures, but there is no indication as to how the effect of moisture change is included. Winstorfer et al. (1996) described a statistical approach to modelling the density profile, based on analysis of a designed experiment with different starting conditions, and successfully used this to predict identified features of the density profile.

Dai and Steiner (1993) presented an analysis of a flakeboard mat, using a method developed by Kallmes (1961) to determine the configuration of a network of flakes in layers, in terms of the free flake length and the number of flake crossings present in a given area. The flakeboard analysis was done in order to determine the density
variation in the horizontal plane of the panel. It calculates the area of the mat over which the local compression of the mat must be accommodated by compression of the particles.

Bolton and Humphrey (1988, 1989a), Bolton, Humphrey & Kavvouras (1989 a,b,c) Humphrey and Bolton, (1989 a,b) have published a comprehensive series of papers that review the pressing process for dry-formed wood-based composites and have developed a model of the pressing process. The model was based on particleboard, which Humphrey described as including sawdust, splinters, flakes or wafers. The model was a three dimensional one that included horizontal heat and mass transfer within the mat in the press. Humphrey and Ren (1989) also discussed the development of the strength of the resin bond, and described an instrument which allows this to be measured.

Thoemen and Humphrey (2003) extended the previous work by Humphrey to a model specifically developed for continuous presses. The response of the fibre to the strain generated by the press is described in terms of a five element Berger model.

Zombori et al. (2001) discussed the development of a model of the processes that occur in the pressing of wood-based composite panels focusing on the definition of the mat characteristics and in a subsequent paper discussed the internal mat conditions (Zombori et al. 2003).

Suo and Bowyer (1994) noted the importance of moisture in the transfer of heat through the mat. The influence of moisture on the pressure and temperature within a flakeboard mat was described by Kamke and Casey (1988), who concluded that the voids within the mat were filled with saturated steam at the end of the press operation, and showed that the steam pressure increases as the moisture content of the material into the press increased. This required that the air contained within the mat at the start of the pressing operation had dispersed, through the edges of the 510-mm by 560-mm mat. Bolton, Humphrey and Kavvouras (1989 a) modelled the moisture movement within a particleboard mat during the time the mat is in the press, showing a maximum moisture content in the centre of the mat of 15.5% for a mat with an initial moisture content of 11%.
While there is a considerable literature discussing the factors that are significant in the generation of the VDP, very little of this is specific to MDF, despite this being the product where the overall influence of VDP on panel performance is most significant and where there is greater ability to influence the shape of the VDP through control of the press and other process conditions.

Most MDF plants have evolved strategies that allow the VDP to be controlled, with varying degrees of success. This knowledge is specific to each plant, often with individual operators proving to be more successful than others in creating the desired profile, or maintaining this as other variables change. The density profile of the panel as it leaves the press is monitored in some plants. This is a significant advance in controlling the VDP of the panel as it is produced. However it is not a substitute for effective control of mat conditions at the entry to the press, particularly the fibre moisture content.

Characterisation of the relationships between fibre conditions and press closing strategy will provide a logical tool for understanding where efforts to improve control of variables will provide the greatest gains. It will also be useful in training operators to understand the variables and their interactions that together determine the VDP. This aspect is seen in plants as more important than a model of the process, particularly where this may not be an accurate representation.

The differing shapes between the VDPs of MDF and particleboard as shown in Figure B1 (page 100) suggest that there are some differences in the processes that lead to these profiles and that generalizing models prepared for one specific panel type to a broader range may not be justified. This appears to be more significant in the strain response of the mat of fibres to the compression generated in the hot press. This aspect of fibre mats is not covered in the literature to an extent necessary to give confidence in applying any of the available models to the MDF situation. An investigation of this aspect of the formation of the MDF VDP would be a useful advance.
1.1 Generating the Density Profile

The work to date on modelling the generation of the density profile in the press is important in understanding the processes that occur. The basic relationships that make up the model are well established. Heat is transferred from the platen into the mat, and then through the thickness of the mat. Increasing the temperature in the mat leads to moisture being evaporated. This moves to cooler areas of the mat where it condenses, raising the both the temperature and the moisture content in these areas. The changes in temperature and moisture influence the stress-strain relationship of the fibres in the mat. This leads to different rates of strain within the mat, causing density differences within the mat. At some point the resin begins to cure, developing bonds which change the stress-strain relationship. These processes proceed from the outer faces of the mat in the press, with the press cycle completed when the resin cure fronts, moving in from each face of the mat, meet in the centre. There are thus three different zones present in the mat as the press cycle proceeds, each present on either side of the centreline of the mat in the press. These zones are not rigidly defined, with a transition between them and can be described as:

1. The zone between the platen and the resin cure zone where resin cure has largely been completed. The temperature continues to rise and the moisture falls. Resin bonds continue to develop strength which provides additional points for load transfer between fibres.

2. The zone where resin is curing. The resin cure rate is temperature dependent. Humphrey and Bolton (1979) describe a family of curves showing that UF resins develop a strength equivalent to 50% of the ultimate bond strength over a time of 250 s at 70°C, reducing to 70 s at 100°C and 40 s at 110°C. A similar criterion is used in commercial MDF production where the press cycle is deemed to be complete some time (typically 30 s) after the temperature at the centre of the mat reaches a defined temperature (105°C), with the temperature continuing to rise after this point is reached.

3. Inside the resin cure zone the fibre is present in the condition that it entered the
press. The temperature will start to increase as moisture moves into this zone and condenses.

Stress relaxation will occur at each point, but its significance is not established. The time available for this effect is limited to the total press time, typically 5 minutes for an 18 mm thick panel. Throughout the mat any change affecting the local compressive modulus will be reflected in a change in density. Closing the press changes the average density of the mat, but this change is distributed through the thickness of the mat by the changing stress – strain response within the mat.

As the press starts to close the whole mat is at the initial condition. By the time the fast close stage of the press has been completed, the density differentials that will appear as the density peaks have largely been created. The resin then cures and the resin cure zone moves progressively through the mat to the centre, with the press cycle being complete when the resin cure zones reach the centre of the mat.

It might be expected that the formation of resin bonds between fibres will change the compressive strength of the network by providing alternative load transmission paths between fibres. The extent to which this occurs depends on the number of these bonds and the location of these on the fibre, as discussed in Chapter 7 of Part A of this thesis. In that analysis the focus was on how the fibre network with fully cured resin bonds responded to the tensile stress in the IB test. The weakness in the fibre wall identified in this analysis as being significant in the tensile test is less significant in the compression encountered within the press, except perhaps in the case were the bond is at 90° to the strain direction. In this case the intra-wall weakness will be subject to a shear stress, and failure may occur. This suggests that the resin bonds are unlikely to change the compressive strength significantly where the local density is high, with considerable contact between fibres. It may be more significant at lower densities where some of the strain in the mat can be accommodated by bending of the fibres.

The success of any model lies in its ability to predict accurately the outcome of a physical process. If the objective is to model the development of the density profile in a composite panel, then the VDP predicted by the model should be the same as that measured on a panel made and pressed under the same conditions. Such validation is
not established in any of the models discussed.

There are five main components in a model of the development of the VDP of a wood-based composite panel. These are:

1. Heat transfer from the press platens into the mat in the press and also through the material in the press until this is discharged.

2. Mass transfer within the mat, particularly the movement of moisture which is significant in the transfer of heat.

3. A stress - strain response model for the material in the press that is able to characterise this over the whole range of conditions, particularly temperature and moisture, encountered during the press cycle, as well as the range of densities that must be achieved in the VDP.

4. A resin cure model to predict the changes that occur in the mat as the resin bonds develop strength.

5. A calculation framework that allows the above elements to be integrated in a manner that enables the significant interactions between the components to influence the outcome.

While significant progress has been made in the work done to date, it is considered that none of the models presented has reached the point where there is a satisfactory representation of the pressing process as it is known to occur in plants producing these products. Ideally each of the four primary components would be validated over the range of conditions encountered.

In discussing this aspect it is helpful to review the density profiles for MDF and for Particleboard as shown in Figure B1 on page 100, and to discuss these in the light of plant experience.

- Both profiles are symmetrical about a panel centreline, and show high density
faces with the density falling to the centre of the panel.

- Both profiles are on sanded panels. The VDP measured on the panel after the press but before sanding will show a rapid drop off in density from the peak to zero on the outside the profiles shown. The mass of material removed from the panel in the sanding operation depends on the thickness of the panel, ranging from 5% in the case of thick panels (> 18 mm) and up to 20% for thin (< 6mm) panels.

- The peak density for the particleboard VDP of less than 1000 kg m\(^{-3}\) occurs some distance from the surface of the panel, because the distance between the density peaks is less than the final thickness of the panel. The maximum density for the MDF VDP occurs at the surface of the panel. It is possible that the density continued to rise beyond the indicated peak, but this could only be established from the VDP done on the panel before sanding.

- Inside the density peaks the density drops to the core value. This drop is more rapid in the MDF case and levels out to the flat profile in the core area. The particleboard profile drops away more slowly, with a continuous curve linking the high density faces.

Comparing the two profiles it appears that the VPD for MDF can be manipulated to a greater extent than that for particleboard. The size and shape of the particles is one factor that differs between these two panels. The density profile models often purport to be general, but the detail difference between the two profiles suggest that this assertion may not hold and generalised approach may not be justified.
1.2 Preparation of the Fibre Mat

In commercial MDF production the prepared fibre, with the resin attached, is dried to the moisture content required for the hot press and delivered to the mat-forming line through a transport system that may also be designed to heat the fibre ahead of the press. The fibre is formed into a mat as wide as the press and with the fibre content in the mat controlled to a specified mass per unit area so that when compressed to the desired thickness, this will give the overall density required for the panel. The fibre will consist of a varying proportion of whole fibres and fibres damaged in the earlier processing stages. There may be some segregation through the thickness of the mat as the fibre fragments are able to move through the network of larger fibres, but systems are designed to minimise this. It is generally assumed that there is no segregation of the fibre within the thickness of the mat.

1.3 Precompressor

The fibre mat has a low density when formed, typically in the range of 20 – 35 kg m$^{-3}$ and is quite fragile. To increase the strength of the mat so that it can be handled without damage, it is passed through an inclined belt precompressor. The mat is formed on a moving belt that also carries the mat through the precompressor. The fibre mat is confined between the forming belt and an inclined belt, with the distance between the belts reducing as the mat moves through the precompressor, as shown in Figure B2. This compresses the mat, increasing its density. The objective is to increase the strength of the fibre mat and also to reduce the size of the opening necessary to get the fibre mat into the press.

The variation of density and of mat height (expressed as a multiple of the thickness of the panel) throughout the prepress is shown in Figure B2 on page 111. The density of the mat at forming is dependent on fibre type, with longer softwood fibres giving a lower density mat from the mat-former than either hardwood fibres, or those from sawmill residue feeds containing a higher level of fibre fragments. The thickness of the mat also decreases as fibre moisture content increases.
The thickness of the mat before and after the precompressor is difficult to measure accurately, but the overall mat height is reduced from 20 – 25 times to 8 – 10 times the final panel thickness. Most of the increase in density is attributed to a rearrangement of the fibres within the network, with the elastic recovery arising from those fibres which have deflected under the strain generated in the precompressor without being displaced. The fact that the density at the minimum thickness point in the precompressor is twice that of the fibres as arranged in wood indicates that compression of the lumen must also occur. It is likely that the delayed visco-elastic recovery is associated with some recovery of the lumen shape.

Published data on prepressing mats (Thorbjornsson, 1985) showed that the final height of the mat after the prepress was lower where the same total load was applied in a number of applications, than in a single application. The decrease in mat height is attributed to a rearrangement of the fibre network occurring when the load is released. Subsequent load applications caused further rearrangements within the fibre network, decreasing the height of the mat.
1.4 The Hot Press

In the press the fibre mat is compressed between two heated platens. While batch presses are used, the newer technology of straight-through continuous presses is becoming common. In these presses the mat is carried through a zone where heat and pressure are applied to the fibre mat as it is carried through the press between two steel bands.

In a batch press, the mats are loaded into the space between two heated platens. The platens are forced together, usually by a hydraulic ram system. To provide sufficient platen area, the press is usually configured with several platens stacked vertically, with a common hydraulic system applying the force to all platens simultaneously. The fibre mat is compressed by a decrease in the distance between the platens over time until the final thickness of the panel is reached. It is convenient to refer to closing of the press as a "strain" on the mat. This generic use of the term is not to be confused with the engineering use of the term as used in the stress-strain relationship used to define the mechanical response of the material to an imposed stress. The platens, which are heated to a temperature of 160 − 220°C, transfer heat to the mat. The pressing operation is complete when the temperature at the midpoint of the mat thickness has reached the value where the thermoset adhesive cures and is maintained for a specified time, typically about 30 s.

Control of press cycles has improved as its importance in determining the VDP of the panel has been recognised. Initially the press closure was controlled by the maximum pumping capacity of the hydraulic supply, and the pressure needed to overcome the compressive resistance of the material in the press. The next development was control of the closing velocity of the press platens so that the press closed to a specified time-platen distance profile. This became known as "position control", and was first described by Haylock (1977).

Effective control of the density profile requires that the initial closure of the press be as rapid as possible. This stage is complete when a specified platen distance position is
reached; this is typically 100 – 120 % of the final thickness of the panel in the press. The further the press closes in this stage, the higher the face density will be. The press then closes more slowly, reaching the final position where the platen distance is equal to the thickness of the panel just before the press opens.

The development of continuous presses has improved the level of control over the press cycle. In the continuous press the mat is carried through the heating and pressure zones between two steel bands with a roller bearing system to minimise the friction between these moving bands and the stationary platens. The platens supply heat which is transferred through the rollers and the steel band into the mat. The platens also apply the pressure that is needed to maintain the required platen distance at this point in the press. A series of frames along the press incorporates hydraulic cylinders which generate the pressure to create the strain on the mat. Position and pressure sensors at each frame allow the platen position or pressure to be controlled at each of these points. The factors used in setting the press cycle have been described elsewhere (Chapman, 2002).

The arrangement of the continuous press, where the different stages of the press cycle occur at different points along the press, allows both "position" and "pressure" control strategies to be implemented at different points in the press cycle. There are some significant differences in these two approaches from the perspective of the material in the press:

- The position control approach determines the closing rate of the platens at each point in the cycle so that the force required to maintain this rate is determined by the compressive resistance of the material in the press.

- The pressure control approach is the reverse of this situation. The force on the material is determined by the pressure determined for this point in the press cycle. The rate of platen closure resulting from this force is determined by rate of change of the resistance of the material to compression.

- In each case and at a given point in the press, the force acting on the fibre is the same at every point through the thickness of the material.
The overall moisture content in the fibre is important in determining the response of the fibre in the press, both in its availability to transport heat through the mat, and in its effect on the strength of the fibres. The mat enters the press with a uniform moisture content throughout its thickness. As a result of the heat transferred into the surface of the fibre, moisture is evaporated, becoming steam. This steam moves through the fibre network, creating pressure gradients that will depend on the steam flux, the pressure in the system and the flow characteristics of the fibre network. The steam will condense in cooler areas, increasing the local moisture content and increasing the temperature by releasing the latent heat. As a result of this process both moisture and temperature profiles develop through the mat. Conduction is also significant, with the heat being transferred through the fibre by both processes, with the balance between them determined particularly by the quantity and availability of the water in the fibre.

The location of the moisture within the fibre structure is significant. This is shown in plants where the air used to transport the fibre to the mat former is heated to increase the temperature of the fibre ahead of the press. Humidity control is essential to minimise the moisture change in the fibre. If the humidity in the transport air is set so that the fibre moisture content in the surface of the fibre increases slightly, the response of the fibre in the press is significantly more rapid than it is where the humidity in the fibre transport system is set to cause some loss of moisture from the fibre. This suggests that the location of the moisture within the fibre wall is significant in determining the response in the press.

Within the press, the decreasing distance between the platens leads to an increase of overall density of the mat. The material in the press resists this decrease in volume with a force that is determined by the compressive strength of the material in the press at the conditions in the mat at that point in the press. Temperature and moisture gradients are established as heat flows from the platens into the mat. These variables determine the compressive modulus at each point in the mat, (Kunesh, 1961). At each point in the press, the incremental reduction in platen distance is distributed through the thickness of the mat in such a way that the decrease in thickness of an element of mat is determined by the compressive modulus at that point, with the sum of the thickness reductions at each point equaling the overall change in platen distance.
It may be assumed that the mat enters the press with uniform density, composition through its thickness, fibre characteristics and moisture content. The hypothesis is that the differential densities that result in the density profile through the panel can only be established as a result of changes occurring in the mat during the pressing operation. The most likely changes are in temperature and moisture levels within the mat. If the compressive modulus of the fibres changes as a result of these moisture and temperature changes, the total strain induced in the mat by the press closing occurs more in some zones of the mat than in others. This could explain the variable density observed in the panel, measured as the VDP. In order to test this hypothesis, the response to compression of fibre mats under a range of temperature and moisture contents was undertaken.
2.1 Scope

The investigation covers an evaluation of the stress – strain response of MDF fibre mats over the range of conditions encountered in the hot pressing operation that forms the MDF panel.

The VDP is generated in the hot press, from a mat that may be assumed to be uniform as it enters the press. In the press the hot platens transfer heat into the adjacent fibre establishing temperature and moisture gradients in the mat (Humphrey and Bolton 1989). It is these temperature (ambient to 100°C) and moisture ranges (0% to 20% moisture content) that change the compressive resistance of the fibre, leading to the density differences represented by the VDP. The strength of wood over this range of conditions is well established, but the extension of this data to a mat of discrete fibres, even though these are derived from wood, cannot be assumed.

An experimental determination of the stress – strain response of the fibre over the range of temperatures and moisture contents encountered during the pressing operation is described. A small press that operates in a compression testing machine allows the stress – strain relationship, including stress relaxation, of a fibre mat to be determined over the range of moistures and temperatures encountered in the commercial hot press application and the range of densities that are achieved in generating the VDP. The fibre mat in the press is conditioned uniformly through its thickness by an oscillating column of temperature and humidity controlled air moving through the fibre mat.

The data are evaluated with the effects of temperature and moisture, density, and stress relaxation treated separately and compared with published stress – strain relationships for wood and for fibres.
2.2 Objective

The stress – strain response of the fibre mat in the hot press is a major component of mathematical models that seek to predict the density profile through the MDF panel, a parameter that has a significant effect on the balance of properties within the panel. While some of the available models developed for particles claim to be sufficiently general to cover fibres, there are detailed differences between the profiles for particleboard and MDF that suggest that this assumption may not be valid. An understanding of the compressive response of the MDF fibre mat in conditions encountered in the hot press is important in the validation of such models for MDF.

The objective in Part B of this thesis is to determine experimentally the stress – strain relationships of MDF fibre mats over the range of density, temperature and moisture contents encountered in the hot pressing operation that forms the MDF panel and to review this against published material and models.

The results will characterise the compressive response of a fibre mat in a way that can be incorporated in a comprehensive mathematical model of the changes that lead to the VDP in the MDF pressing operation.
The objective was to measure the stress - strain response of MDF fibre mats under the temperature and moisture condition encountered in the hot press. A small circular press was designed for the following conditions:

- To operate within a 100 kN Instron testing machine enabling both stress and strain to be measured.
- To heat and condition the mat by moving an oscillating column of humidified air through the mat. The air could be heated and humidified by adding steam.

With the maximum load in the Instron of 100 kN, a maximum stress of 12.73 MPa would be possible with a 102 mm diameter mat. In the literature there are examples of stresses ranging up to 50 MPa (Wolcott et al. 1990). Actual stress levels in MDF pressing are 4 – 5 MPa, based on total panel area.

3.1 Fibre.

Two types of Pinus Radiata fibre were supplied by Forest Research from their MDF research programme. The fibres have been characterised by Murton (1997), with basic data from this report summarised in Table B1. In addition some fibre from the local CHH plant was used for some development runs. This fibre was from a production MDF line, and would have had resin mixed in with it.

Table B1. Fibre Details

<table>
<thead>
<tr>
<th>Fibre Source</th>
<th>Thinnings (Thin)</th>
<th>Slabwood (Slab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Number</td>
<td>97551</td>
<td>96791</td>
</tr>
<tr>
<td>Wood Density</td>
<td>356 kg m⁻³</td>
<td>496</td>
</tr>
<tr>
<td>Fibre Length</td>
<td>2.2 mm</td>
<td>3.2</td>
</tr>
<tr>
<td>Fibre Width</td>
<td>.0274 mm</td>
<td>.0316</td>
</tr>
<tr>
<td>Fibre Wall thickness</td>
<td>.0034 mm</td>
<td>.0045</td>
</tr>
<tr>
<td>Refining Energy</td>
<td>350 kWh te⁻¹</td>
<td>176</td>
</tr>
</tbody>
</table>
3.2 **Experimental Conditions.**

3.2.1 **Moisture Content**

Pressing times for MDF are longer than for particleboard of the same thickness, but the reason for this is not clear. The moisture content of the fibre as it enters the press is generally in the range of 9 – 13%, although a much narrower range is preferred. Heat transfer by conduction could be expected to be slower through a fibre network than through the particles that make up particleboard. However the greater surface area of the fibre should make the moisture both more readily available to become steam and more rapidly absorbed. If this is the case the moisture peaks will be sharper for a fibre network than for one made of wood particles. On the basis of this data the upper limit for the moisture content in the mat is assumed to be 20%, which is below the fibre saturation point at ambient temperatures. Bolton, Humphrey and Kavouras (1989a) quote a maximum moisture content reached in the mat when simulating a particleboard press cycle of 15.5%. This establishes the range of moisture contents to be covered.

The actual moisture content for each test is determined by drying the mat (24 hours at 105°C) after the stress - strain measurements have been made.

3.2.2 **Temperature Range**

The fibre is handled and the mat usually formed at ambient temperatures, although heating of both the fibre and the mat is sometimes used to reduce the heating load in the press with the objective of increasing press capacity. The lower temperature limit is thus an ambient condition. The upper limit for temperature is determined by that needed to achieve a satisfactory cure level in the urea-formaldehyde adhesive most commonly used for MDF. This requires a temperature of 100° - 105°C at the centre of the panel to achieve a level of cure that allows the panel to be removed from the press. The stress - strain relationship up to these temperatures is significant in generating the VDP and
should be covered in the investigation.

The changes in the strength of the mat produced by the formation of resin bonds between the fibres, with the continuing drop in moisture content as the temperature continues to increase after the resin cure condition has been reached combine to create different conditions after this point has been reached in the press cycle. These two factors combine so that the modulus of elasticity is increasing as the moisture content decreases, with an additional increment from the resin bonds that is difficult to quantify. Stress relaxation will occur during this phase. On the basis of the increases in strength that occur after the resin cure point the upper temperature limit for the stress – strain measurements is taken as 100°C.

3.3 Experimental Press Design

The press, shown diagrammatically in Figure B3 and, with the outer cover removed, in photographs in Figures B4 a – b on page 122 was built and installed in the 100 kN Instron Model 1195 testing machine (Instron Corp., Canton Ma 02021-1089) in the Wood Technology Laboratory in the School of Forestry, University of Canterbury. The testing machine provided controlled closing rates over the range 0.2 – 30 mm s⁻¹, measurement of the reaction force from the fibre mat with a 100 kN load cell (±0.1% full load) and strain by distance measurement of the loading frame (±0.005 mm).

The press was constructed with perforated platens, so that air could be passed through the mat. Heating chambers above the top platen and below the bottom platen allowed the temperature of the air and hence the mat, to be controlled, while steam could be added to the chamber below the mat to control humidity in the air stream and hence moisture levels in the mat.

The press was not sealed, with the mat area remaining at atmospheric pressure. A reciprocating air pump based on a mechanically driven air cylinder with a 150 mm diameter piston, provided air movement through the mat, both pressure and suction so that leakage at the edge of the mat would be minimised. A pumping rate of 300 strokes per minute was used.
Stainless steel pot cleaners were placed around the heating elements to improve heat transfer to the air, and also to act as regenerators, keeping both heat and moisture within the press chambers.

Temperature controllers for both top and bottom zone heaters were provided, using RTD sensors positioned close to the platens. Mat temperatures were measured by a type K thermocouple inserted in the centre of the mat, and connected to a handheld temperature indicator (Fluke model 52 S/N 709 9006). A humidity sensor (Vaisala HMP 230MP), reading out on a digital voltmeter display, was installed above the platen in an enclosure with a non return valve, so that it measured the humidity of air that had just passed through the mat.
Figure B3. Press - diagrammatic

Figure B4 – Press Photographs
3.4 Mat Forming.

A mat former constructed to produce the circular mats for the press is shown diagrammatically in Figure B5. A mass of fibre calculated to give a compressed mat of the required density at a final thickness of 1.2 – 1.8 mm was placed in the fibre bin. Rotating spiked rolls forming the base of the fibre bin teased the fibre from the bottom of the fibre column into the suction of the transfer fan. The fibre was discharged into the forming chamber from a nozzle which was moved by hand to place the fibre uniformly over the forming area. A vacuum fan provided suction through the mat to remove the transport air. Following forming the mats were compacted manually and removed from the forming chamber.

![Figure B5. Mat Former](image)

The formed mats were handled between mesh screens to minimise damage and were held for external conditioning or pressing. Mats pressed at ambient conditions were conditioned in the test room or in constant humidity containers using the salts shown in Table B2 to provide high and low humidity conditions. Mats pressed at elevated temperatures were conditioned for both temperature and moisture content within the press.
Table B2. Fibre Conditioning

<table>
<thead>
<tr>
<th>Humidity Control</th>
<th>R. H. - % at 20°C</th>
<th>EMC. - %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCl. H₂O</td>
<td>15</td>
<td>1.7</td>
</tr>
<tr>
<td>Conditioned Room</td>
<td>65</td>
<td>11.7</td>
</tr>
<tr>
<td>Na₂SO₃.7H₂O</td>
<td>95</td>
<td>18.9</td>
</tr>
</tbody>
</table>

3.5 Mat Size

The press was designed for mats of 102 mm diameter. Early trials with mats of this diameter showed that radial expansion of the mat created significant drag on the sides of the press, influencing stress measurements. The diameter of the mat was reduced to 89 mm to overcome this drag. There was some radial expansion of the mat as the press closed, reducing the density at the circumference of the mat. This effect is ignored in the calculation of the density of the mat, which is based on the original diameter of the mat.

The thickness of the mat is determined by the quantity of the fibre. The accuracy of platen distance measurement at the final closed position is critical in determining the final density of the mat. Increasing this value provides more accurate measurement of density. However increasing the quantity of fibre to achieve this lead to instability in the mat, with greater edge effects and shear fractures within the mat when it was compressed. The selected fibre mass of approximately 10 g gave a mat height at forming of 45 mm with an initial density of 36 kg m⁻³. The initial closing of the press to 25 mm platen distance gave a mat density of 65 kg m⁻³ when the air pump was turned on.
3.6 Press Operation

3.6.1 Establishment of Platen Distance

The press assembly was 400 mm in length, and included thermal insulation material of unknown compressive strength. The distance between the platens was not measured directly, but was calculated from the cross head position on the testing machine. This was corrected for the compliance of the press which was measured at each run and at each change in temperature.

The compliance of the press was measured by zeroing the gauge length of the testing machine at a load of 20 kN, with the two screens that would carry the mat in place between the platens. The load was then reduced to 10 kN, and the crosshead movement recorded. This measurement was repeated at 20, 30, and in some cases 38 kN. These data were used to determine the relationship between the crosshead position and the platen distance as the load changed. In this measurement the load was taken at the periphery of the press. The deflection at the centre on the platens was also measured independently by concentrating the load at the centre of the platen. The deflection (at a load proportional to the area of the loading block between the platens) was found to be some 25% greater than the compliance of the press as a whole.

Data for a series of calibration runs done before and after runs 96 – 107 (all at a nominal 50°C temperature) are shown in Table B3, and are graphed in Figure B6, with additional data at 38 kN load for some runs.

On this basis the press compliance at loads up to 38 kN can be represented by a linear equation. The shift between the initial zero gauge length at 20 kN, and the subsequent measurement at 20 kN is attributed to movement of the mesh screens that were in place during the compliance measurement. This movement would be less significant in the case where the fibre mat is between the screens.

Based on a 3 x SD, the platen distance at 30 kN load is within ± 0.1 mm of the indicated crosshead position modified by the compliance relationship. This is the most significant error source in the density calculation, becoming more significant as the platens become
closer and the density increases. At a typical platen distance of 1.6 mm at the maximum load point, the density will be within ± 6.25% of the value calculated from the crossbar position modified by the compliance at that load.

Table B3 – Press Compliance - mm

<table>
<thead>
<tr>
<th>Run</th>
<th>Load kN</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>38</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>0.2644</td>
<td>0.0344</td>
<td>-0.2435</td>
<td>-0.4239</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>0.3213</td>
<td>-0.009</td>
<td>-0.254</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.3341</td>
<td>-0.0075</td>
<td>-0.2573</td>
<td>-0.4436</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>0.2621</td>
<td>-0.0314</td>
<td>-0.293</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107</td>
<td>0.2635</td>
<td>-0.0485</td>
<td>-0.3153</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.2672</td>
<td>-0.0227</td>
<td>-0.2850</td>
<td>-0.4478</td>
<td></td>
</tr>
<tr>
<td>Std dev</td>
<td>0.0391</td>
<td>0.0344</td>
<td>0.0357</td>
<td>0.0379</td>
<td></td>
</tr>
</tbody>
</table>

Figure B6 Press Compliance – mm at selected loads
3.6.2 Press Closing Rate

Once reliable mat making and press operation had been established, a series of runs was done to determine the effect of changing the press closing rate. Rates of 18, 36, 72 and 144 mm min\(^{-1}\) were used with mats made from the same fibre and treatment. Stress levels at densities of 800 and 1000 kg m\(^{-3}\) were extracted. These data are plotted in Figure B7.

![Figure B7 - Stress at various Press Closing Rates](image)

The data for the stress at selected density points was obtained using the procedure described in Section 4.2 on page 131. The data shows that the stress is reproducible for the two runs at 36 mm min\(^{-1}\) and that the stress levels out above this speed. The stress drops at the lowest speed of 18 mm min\(^{-1}\) rate to 94% of that at the higher strain rates. While the calculated stress would be more stable at the higher rates, these were ruled out on the basis of maintaining safe operation of the testing machine at the 1 – 2 mm final platen distance, and a strain rate of 18 mm min\(^{-1}\) (0.3 mm s\(^{-1}\)) was used. The drop in stress at the lower strain rate is attributed to stress relaxation in the fibre mat affecting the stress - strain relationship at the lower strain rates.
3.6.3 Mat Conditions

External conditioning was carried out in a conditioned test room controlled to 65% RH, 20° C. Two saturated salt solution conditioning chambers in the test room provided conditioning at moisture contents above and below the test room conditions as shown in Table B2. For elevated temperatures the mat was conditioned to the required temperature and moisture content in the press using the air pump to move air from the chambers on either side of the platen through the mat. Steam was introduced to increase the humidity in the press for higher mat moisture levels. In each case the compressed fibre mat was weighed after removal from the press and dried in an oven for 24 hr at 105° C to determine the mat moisture content that was used in the analysis. Some mats conditioned in the press were sectioned into three vertical layers to determine moisture variation within the thickness of the mat. This showed that the vertical variation through the mat was less than 2% moisture.

The range of mat conditions achieved is shown in Figure B8

![Graph showing temperature-moisture map for area covered.](image)

*Figure B8 – Temperature – Moisture Map for area covered.*

There was a reasonable spread of moisture contents at lower temperatures, but there was insufficient steam available to reach higher moisture contents as the temperature was increased. It would have been necessary to condition the mat with saturated steam to reach 20% moisture content at 100° C (Humphrey and Bolton, 1989) The press did not have this capability.
3.6.4 Press Operation

The press was set at the required temperature, with the air pump turned on to ensure temperature uniformity as the required set point was reached. The press compliance test was then done with the mesh screens in position. The press was opened and the outer cover removed so the mat could be placed in position, with a thermocouple in the centre of the mat. The press was then closed to a platen distance of 25 mm which confined the fibre and allowed the air pump to be used without disturbing the fibre.

For higher moisture content mats steam was introduced into the press chamber. The moisture change in the mat could be followed by the temperature change associated with moisture being absorbed by or lost from the mat. When conditioning was complete, usually in 8 or 9 minutes, the air pump was stopped and the press was closed at the preset strain rate to the predetermined end point. The peak load occurred at the maximum density point. The press was held in this position to record the stress relaxation response of the mat.

The press was opened and the mat removed, inspected and weighed before being transferred to the oven for determination of the moisture content. The result was discarded if the mat from the press showed inconsistencies such as fracture, or uneven fibre distribution across the platen area.

The load – time – crosshead position data from the Instron computer was transferred to an Excel spreadsheet for analysis.
4.1 Density Change as a Strain Analogue

In this analysis, density change is used as an analogue of strain. There is a direct relationship between the strain (calculated as $\Delta L / L_1$, as defined below) and the density change that results from that strain.

If a fibre mat of mass $M$ and cross sectional area $A$

has an initial height: $L_1$

the density $\rho_1$ of the mat is: $M/(A \cdot L_1)$

If the mat is compressed a distance $\Delta L$ the strain is: $\Delta L / L_1$

the new height of the mat is: $L_1 - \Delta L$

the density $\rho$ is: $M/(A(L_1 - \Delta L))$

Transforming these relationships gives the relationship between strain and density as:

between strain and density as: $\Delta L / L_1 = 1 - \rho / \rho_1$ (B4.1)

or if $\rho - \rho_1$ is defined as $\Delta \rho$

$\Delta L / L_1 = \Delta \rho / \rho$

There are several reasons for adopting this approach.

- The assessment of the initial point for the measurement of strain is difficult with the low density mat, as the initial stress levels are very low, whereas the density can be calculated from the volume available for the fibre at any point.

- Stress – strain relationships for wood – based composites in Lang and Wolcott (1996) show a very flat response for the linear part of the curve up to a strain of 0.6. Between 0.6 and 0.9 strain the stress rises very rapidly in the area of greatest interest in the formation of the VDP.

- The outcome of the press closing is a change in density, both over all as determined by the total change in volume generated by the movement of the platen and locally at each point within the mat.
4.2 Data Analysis and Processing

The schedule of all runs is included as Appendix B1. As noted earlier some results were discarded on the basis of observed failures in the mat after pressing. The runs are coded in the analysis using the following system;

\[ \text{nnn} \quad \text{Run number} \]
\[ F \quad \text{Fibre source} \quad T - \text{thinnings} \]
\[ S - \text{slab} \]
\[ \text{CHH} - \text{production MDF fibre} \]
\[ \text{MM.M} \quad \text{Moisture content (%) after pressing} \]
\[ \text{TTT} \quad \text{Temperature of the mat in the press}. \]

So a run is described as \( \text{nnn}(FMM.M/TT) \)

The temperature of individual runs varied somewhat. Data for this variable is grouped in one of 4 temperature ranges, viz 20, 50, 75 and 100\(^o\) C. Several runs done at 35\(^o\) C were grouped with 50\(^o\) C data.

The run data were taken from the Instron computer system as a text file as a time, crosshead distance and force set. Other data (temperature in the mat, mat weight and moisture) were recorded manually for each run, as were the press compliance data for each group of runs.

From the data a force - time plot was prepared.

\[ \text{Figure B9a} - \text{Run 14, Force - Time plot} \]
\[ \text{B9b - Peak load detail from B9a} \]

The example shown from run 14 (T/13.1/23) in Figure B9a,b was left in the press to observe the stress relaxation response over an extended time.
Run 14 shown in Figure B10 was a trial run with a final density of 393 kg m$^{-3}$. The force – time plot is similar in form to those runs where the final density was much higher, as shown in the force - time plot for run 43 (T/11.8/20) in Figure B10a. The data for this run is transformed into the force – density plot shown in Figure 10b by calculating the density from the theoretical area of the mat and the crosshead position corrected for the press compliance deflection at the measured load.

In this case the density at the end of the compression was 1005 kg m$^{-3}$. When the press stopped, the force began to fall as stress relaxation reduced the back pressure on the press. As the force fell, the compliance of the press caused the platen distance to decrease, with the resulting increase in density shown after the maximum force point in the force – density plot shown in Figure B10b. In this case the maximum stress, calculated on the initial area of the mat, was 6.54 MPa, with a moisture content in the mat, after pressing, of 11.8%. The stress on the mat is calculated on the 89 mm diameter of the formed mat.

The reproducibility of the results is shown in Figure B11, where the stress – density plot for three runs, selected because they were relatively close in moisture content, are grouped. The selected runs are:

- Run 43 (T/11.8/20)
- Run 64 (S/11.6/20)
- Run 129 (T/12.9/20)
The selected runs comprise two thinnings samples (43 and 129) that show a high level of agreement, while the slab sample (64) differs significantly, reaching the same force at a density some 20% lower. Calculating trend lines for the portion of the curve up to the maximum force point gives the results in Table B4.

Table B4 – Stress - density Regression equations (up to the peak) for runs in Figure B11.

<table>
<thead>
<tr>
<th>Run</th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>43 (T/11.8/20)</td>
<td>$\sigma = \frac{7E-06}{\rho}^2 - 0.0005\rho - 0.0012$</td>
<td>0.9999</td>
</tr>
<tr>
<td>64 (S/11.6/20)</td>
<td>$\sigma = 1E-05\rho^2 - 0.002\rho - 0.0741$</td>
<td>0.9996</td>
</tr>
<tr>
<td>129 (T/12.9/20)</td>
<td>$\sigma = \frac{7E-06}{\rho}^2 - 0.001\rho + 0.0445$</td>
<td>0.9998</td>
</tr>
</tbody>
</table>

$\sigma$ is the stress in MPa, and $\rho$ is the density in kg m$^{-3}$.

The correlation coefficients indicate an excellent fit with the quadratic equation. This has allowed further analysis to be based on the force- density points taken from each run at the following densities: 200, 400, 600, 700, 800 and 1000 (or maximum density) kg m$^{-3}$. The 700 kg m$^{-3}$ point was selected as being a point reached in the greatest number of runs with acceptable data.
4.3 Fibre Type

Data showing the stress at a density of 700 kg m$^{-3}$ for both slab and thinnings fibre is shown in Figures B12 – B15 at the four temperatures investigated from 20 – 100° C. The graphs show that the reproducibility of the data falls as temperature increases, as does the maximum achievable moisture in the experimental press.

The data support the conclusion that at the 20° C temperature level, the slab fibres, from wood with a higher basic density (496 kg m$^{3}$, Table B1, page 118) generate a higher resistance to compression than the lower density thinnings fibres, (356 kg m$^{3}$) with some indication that these converge as moisture content falls. At 50° C the regression lines are very much the same, while the variability at the two higher temperature ranges is too great to differentiate between the two fibre types.

Grouping data at all temperatures as shown in Figure B16 shows different linear trend lines for slab and thinnings. Correlation coefficients are not high enough to give great confidence in the prediction, but despite the wide spread of the data, the linear trend lines are almost parallel. This suggests that there is some difference in the stress - density relationship between the two fibre types. The two lines converge slightly as the moisture level falls.

The analysis suggests that the effect of fibre type is rather less significant than the change in moisture content. With the assumption that fibres of different characteristics are distributed uniformly within the mat, the effect of different types of fibres on the VDP can be ignored. This conclusion applies only to fibres derived from chip. It cannot be assumed to apply to the much shorter fibres derived from sawdust or similar residues.
Figure B12 - Stress at 700 kg m\(^3\) Density 20\(^\circ\) C

Figure B13 - Stress at 700 kg m\(^3\) Density 50\(^\circ\) C

Figure B14 - Stress at 700 kg m\(^3\) Density at 75\(^\circ\) C

Figure B15 - Stress at 700 kg m\(^3\) Density at 100\(^\circ\) C
Figure B16 – Stress at 700 kg m\(^{-3}\) Density – all temperatures

Figure B17 – Stress at 700 kg m\(^{-3}\) Density – Slab, all temperatures

Figure B18 – Stress at 700 kg m\(^{-3}\) Density – Thinnings, all temperatures
4.4 Temperature and Moisture Effects

The temperature plots (Figures B17 – 18, page -136) suggest that the compressive resistance falls as temperature increases, but the variability of the results at elevated temperatures in particular, mask this. The trend line equations for thinnings as plotted in Figure B19 appear to be the most consistent.

The graphs (Figures B19 and 20) suggest that the compression resistance of the mat at the same moisture content falls as the temperature increases. The indicated convergence of the lines at higher moisture contents is supported by data (Figure B13), but the indicated increase for the 75°C line above 10% moisture content is thought to be an aberration. There are not sufficient data for the 100°C temperature group to be included in the analysis. It is concluded that the stress needed to compress the mat at moisture contents below 10% falls as temperature increases.

These data use only one point from the stress – density plot, the stress at a density of 700 kg m⁻³. To explore this further, data selected at fixed densities of 200, 400, 600 and 700 kg m⁻³ were extracted from each run and plotted on the stress – moisture plot as shown in Figures B21 – B26. Separate plots have been made for Slab and Thinnings at 20°C and 50°C, with data for 75°C and 100°C grouped. Overall the graphs have a similar form, with the linear trend lines for the Slab -20°C plot (Figure B22), and the Slab - 75°C & 100°C the exceptions.
Part B: Stress – Strain response of Fibre Mats

Key – Density kg m$^{-3}$  
700 □ 600 ▲ 400 ◇ 200 x

Figures B21 - Stress – moisture plot Thin, 20$^0$C  
Figures B22 - Stress – moisture plot Slab, 20$^0$C

Figures B23 - Stress – moisture plot Thin, 50$^0$C  
Figures B24 - Stress – moisture plot Slab, 50$^0$C

Figures B25 - Stress – moisture plot Thin, 75 -100$^0$C  
Figures B26 - Stress – moisture plot Slab, 75 -100$^0$C
4.5 The Effect of Mat Density

The regression lines for the stress - density trend line (Table B4 on page 133) were quadratic equations with correlation coefficients very close to one. This suggests that the stress required to compress a mat is proportional to the square of the density. In order to demonstrate that the result in Table B4 is not an isolated example, the correlation coefficients were calculated for over 50% of the runs for which the data has been used in the analysis. The data cover the whole range of conditions and are sorted in increasing $R^2$ values in Table B5.

**Table B5 – Correlation Coefficients for Stress – Density trend lines**

<table>
<thead>
<tr>
<th>Run</th>
<th>$R^2$</th>
<th>Run</th>
<th>$R^2$</th>
<th>Run</th>
<th>$R^2$</th>
<th>Run</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>134(T10.6/50)</td>
<td>0.9986</td>
<td>96(S2.7/67)</td>
<td>0.9998</td>
<td>106(T1.4/50)</td>
<td>0.9999</td>
<td>121(T8.7/75)</td>
<td>0.9999</td>
</tr>
<tr>
<td>128(S19.1/20)</td>
<td>0.9988</td>
<td>97(S1.9/50)</td>
<td>0.9998</td>
<td>103(T1.9/50)</td>
<td>0.9999</td>
<td>122(T9.1/75)</td>
<td>0.9999</td>
</tr>
<tr>
<td>60(T9.4/20)</td>
<td>0.9990</td>
<td>111(S14.6/50)</td>
<td>0.9998</td>
<td>99(T1.7/50)</td>
<td>0.9999</td>
<td>123(T2.5/100)</td>
<td>0.9999</td>
</tr>
<tr>
<td>125(T9.2/20)</td>
<td>0.9990</td>
<td>118(S5.4/75)</td>
<td>0.9998</td>
<td>98(T1.7/50)</td>
<td>0.9999</td>
<td>61(T9.9/20)</td>
<td>1</td>
</tr>
<tr>
<td>133(T10.7/50)</td>
<td>0.9992</td>
<td>62(T9.9/20)</td>
<td>0.9999</td>
<td>100(S1.9/53)</td>
<td>0.9999</td>
<td>109(T16.2/50)</td>
<td>1</td>
</tr>
<tr>
<td>64(S11.6/20)</td>
<td>0.9995</td>
<td>127(9.3/20)</td>
<td>0.9999</td>
<td>101(S1.5/54)</td>
<td>0.9999</td>
<td>63(S12.1/20)</td>
<td>1</td>
</tr>
<tr>
<td>65(S11.7/20)</td>
<td>0.9997</td>
<td>132(T10.6/20)</td>
<td>0.9999</td>
<td>104(1.1/52)</td>
<td>0.9999</td>
<td>112(S10.2/50)</td>
<td>1</td>
</tr>
<tr>
<td>105(S2.0/53)</td>
<td>0.9997</td>
<td>131(T10.1/50)</td>
<td>0.9999</td>
<td>116(S1.08/75)</td>
<td>0.9999</td>
<td>113(T1.0/72)</td>
<td>1</td>
</tr>
<tr>
<td>129(10.6/20)</td>
<td>0.9998</td>
<td>119(T9.3/50)</td>
<td>0.9999</td>
<td>117(S1.8/75)</td>
<td>0.9999</td>
<td>120(T11.8/75)</td>
<td>1</td>
</tr>
<tr>
<td>136(T11.0/20)</td>
<td>0.9998</td>
<td>110(T1.9/50)</td>
<td>0.9999</td>
<td>114(T1.2/75)</td>
<td>0.9999</td>
<td>124(T0.7/100)</td>
<td>1</td>
</tr>
<tr>
<td>102(T2.1/50)</td>
<td>0.9998</td>
<td>107(T2.0/50)</td>
<td>0.9999</td>
<td>115(T0.9/75)</td>
<td>0.9999</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.6 Characterising Stress Relaxation

Stress relaxation is a significant aspect of the stress-density relationship. This was measured for each run, at the maximum density point reached at the end of the compression. Stress relaxation data were extracted for 10 runs, covering the full range of moisture and temperature conditions are shown in Figure B27. Various approaches to separating the data have been examined, but there is no reliable indication of a consistent moisture or temperature bias in the spread of the data.

Characterising the stress relief as a percentage of the maximum stress gives the best grouping of the data. Data from run 14, with a maximum load of 7 kN, some 20% of the other runs, are also included to see if this approach holds for a lower loads. The trace for this run lies in the middle of the group, suggesting that this approach is valid over the whole stress range.

![Figure B27 - Stress Relaxation after Crosshead Movement Stops.](image)

The stress drops rapidly to 90% of the peak load in a time ranging from 2.4 to 11.8 seconds. The effect of press closing rate on the maximum stress with mats prepared as uniformly as possible is shown in Figure B7 on page 127. This shows that the peak stress was similar for closing speeds of 36 mm min\(^{-1}\) and above, but fell off at speeds below this point. This suggests that stress relaxation will be significant at least during the slow closing stages of the press cycle after the face density peaks have been generated.

The stress relaxation observed in these experiments is not recorded at zero strain. The platen distance is calculated from the crosshead position modified by a load dependent
factor representing the compliance of the press as discussed in Section 3.6.1 on page 125. The press compliance measurement was an elastic response with the force changing as the crosshead position moved. This shows that the stress - time response shown in Figure B9 a and b on page 131 is caused by the changing response of the fibre rather than the press. As the stress resistance of the fibre falls the press platen moves in accordance with its own elastic properties. This provides a continuing decrease in the distance between the platens, increasing the density of the fibre in the mat. This condition is perhaps closer to what happens in the actual MDF press where the range of conditions within the mat will ensure that stress relaxation will rarely occur under true “zero strain” conditions.

The press closes rapidly to a point where the mat thickness is between 1.0 and 1.2 times the panel thickness. The average density of the mat will be the final panel density divided by the thickness factor. For a 720 kg m\(^{-3}\) final panel density, the average mat density at the end of the fast close stage is 600 kg m\(^{-3}\). This can be taken as the lower density limit at which stress relaxation needs to be considered. Figure B27 shows that Run 14, with a final density of 373 kg m\(^{-3}\), fits the pattern of a percentage stress reduction with time allowing this approach to be used over the density range where stress relaxation is considered.

The time available in the press depends on the thickness, but is typically 5 minutes for an 18 mm panel. Stress relaxation in the press is limited to this time, so that the stress relaxation significant in the generation of the VDP is that occurring within the first 5 minutes of the reduction in strain rate.

Stress relaxation may continue after the panel has left the press. This will be determined by residual stresses in the panel as it leaves the press and moisture and temperature profiles through the panel established during the pressing operation respond to the changed conditions outside the press. This situation is not considered here. Experience with the measurement of VDP immediately leaving the press indicates that this profile is very close to that measured in a laboratory instrument after the panel has conditioned, suggesting that changes to the VDP after the panel leaves the press are not large.
The non-linear stress-strain relationship that occurs when wood is pressed to make a composite panel is acknowledged in most of the models surveyed and is treated in different ways. The comprehensive pressing models (Suo and Bowyer, 1994, Harless et al 1987) have tended to focus on this aspect in less detail. Others (Wolcott et al. 1990; Lenth and Kamke, 1996) have approached the characterisation of the stress-strain response from a more basic position as a prerequisite to understanding the response of the material in the hot press. These models have focused increasingly on an analysis of the wood as a cellular material, using models developed for cellular foams.

5.1 The Effect of Density on the Stress-Strain Response

Palka (1973) has provided data on the changes in wood properties with temperature and moisture over the range of interest in pressing panels and with changing wood density. This work showed that the elastic properties of wood can be estimated from known data on the basis of a density ratio raised to a power so that:

$$E_2 = E_0 (\rho_2 / \rho_0)^n$$  \hspace{1cm} (B5.1)

where $E$ is the elastic modulus at a density $\rho$. The subscript $0$ is a known data set, while subscript $2$ is a wood with a known density and elastic modulus. Palka gives values of 1 or 1.25 for $n$. The value of 1 gives a conservative estimate, with the elastic modulus proportional to the density.

The alternative approach of considering the wood as a cellular foam is presented by Lang and Wolcott (1996) and by Lenth and Kamke (1996). The form of the equation developed to relate the modulus of elasticity to the change in density as given by Lenth and Kamke is similar in form to that of Palka (1973):
where $E$ is the elastic modulus at density $\rho$, and the subscript $s$ refers to the material from which the foam is made. The exponent $n$ has a value $1.5 - 3$ according to Lenth and Kamke (1996), implying not only a much greater rise in stress as density increases than would be indicated by Palka's prediction, but also a very wide range of uncertainty.

Maiti et al. (1984) discussed the failure mode in cellular foams and showed that for an equation of the same form as B5.1, the value for the exponent $n$ is 2 for the case where the strain is accommodated by bending of the cell walls. The exponent remains at 2 for the elastic buckling case, falling to 1.5 for the plastic hinge case. This analysis suggests that the index should be 2 for the situation where the plastic failure is not a significant failure mode. There is no indication as to what the exponent should be for wood.

This approach is used by both Lang and Wolcott (1996) and Lenth and Kamke (1996) in discussing the viscoelastic stress-strain response of wood flakes. As these flakes retain a significant part of the wood structure, they can be treated as a cellular solid. The question remains as to whether this approach can be extended to the compressive response of discrete fibres in a mat.

The cellular structure provides links between the cells that allow the dispersion of stress throughout the network. There is thus an inherent structural component in the cellular arrangement, which maintains the lateral relationship between the cells. This support does not appear to be recognised in Maiti's (1984) analysis, which treats the failure mode as simple bending, buckling, or formation of plastic hinges in the cell walls, without imposing any lateral restraint on an element as it fails.
5.2 Application of the Foam Model to a Fibre Mat

The fibre mat comprises fibres with a length to diameter ratio between 80 and 100 for the whole fibres. There will also be some fibre fragments where a fibre has been damaged or cut during the fibre preparation stages. The fibres in wood are in the form of a largely regular polygon, often close to circular, in section. This aspect of the fibre may change in the fibre preparation and drying process to a flattened form as shown in Figure A15 on page 46.

The fibres are formed into a low density mat. As this mat is compressed, the length axis of the fibres will become increasingly horizontal, so that the stress acts transversely through the fibre. From the diagram of the precompressor in Figure B2 on page 111 the mat is compressed from a density of 30 kg m\(^{-3}\) to 800 kg m\(^{-3}\), by a reduction in mat thickness to \(\frac{1}{27}\) of its original value. In the worst case a 3 mm long fibre standing vertically in the mat as it is formed, could remain vertical within the mat, but it is more likely to bend into a position close to horizontal. The predominantly horizontal arrangement of fibres is apparent in the photograph of an inner plane parallel to the surface of the panel shown in Figure A14 on page 45.

The fibre mat in a section parallel to the direction of the applied strain thus appears as a series of flattened tubular elements. Apart from the connections between the cells, this can be considered equivalent in form to the cellular foam.

For a unit volume section through the mat perpendicular to the direction of the applied stress, with a density \(\rho\), made up of a material with a density \(\rho_s\), the volume fraction of material in this unit volume is \(\frac{\rho}{\rho_s}\) and the voids ratio is \(1 - \frac{\rho}{\rho_s}\). By selecting \(\rho_s\) as the density of the cell wall material the analysis also accommodates the lumen space within the fibre. This volume fraction is used by Maiti et al. (1984) to describe the foams on which that analysis is based. From the density perspective the fibre mat can be considered equivalent to the foam.

However the connections between the foam cells provide load transmission paths that may not be present within the fibre mat. To examine this aspect, a plane between two fibre layers is considered. The plane will intersect some fibres, but this does not affect
the analysis. In this case the area of fibre in contact with the plane is the material volume fraction $\rho/\rho_s$. This is also the probability that a fibre is in contact with the plane at any particular point. The probability that fibres occupy the same space on both sides of the plane and are thus in contact, is the product of the fibre volume fraction on either side of the plane. If the plane lies between two areas of equal density, $\rho$, the fibre contact area is $(\rho/\rho_s)^2$.

This is also the area available to transfer the stress across the plane. If it is assumed that the force required to compress an individual fibre is proportional to the area over which the stress is applied, as is suggested by applying the density relationship to this area, the foam model still applies.

There are two areas where the fibre network model and the cellular foam model differ. The gross movement of a fibre, either laterally by sliding, or by deflecting in bending to the point where it slips past the support, generates additional stress responses which are not considered in the foam model. The sliding of a fibre will increase the strain without an increased stress. On the other hand it is possible for an individual fibre to deflect in bending beyond the unit volume used to define the contact probability, transferring stress to another fibre outside the unit volume and providing a contact area greater than that defined by the probability consideration.

These two effects act in opposition to each other. Neither effect has been quantified, but the support by contact beyond the layer used to establish the contact probability is intuitively considered to be greater. With the fibres largely horizontal the lateral sliding and loss of support are more likely to occur where the contact is close to the end of one of the fibres; the probability of this outcome decreases as the slenderness ratio of the fibres increases.

On this basis it is concluded that the probability assessment of the contact area between fibres is possibly conservative, at least for whole fibres. The situation for fibre fragments with a much reduced slenderness ratio is likely to be different, with slippage much more likely and support from fibres beyond the layer used to determine contact area much less likely. This situation is much closer to the flake analysis presented by both Lang and Wolcott, (1996) and Lenth and Kamke (1996).
Having determined that the stress-strain model for a cellular foam can be used for a mat of discrete fibres, the stress-strain relationship within the fibre mat is calculated from the equation for the modulus of elasticity from Lenth and Kamke in equation B5.3

\[ E = kE_s \left( \frac{\rho}{\rho_s} \right)^n \]  

(B5.3)

where \( E \) is the elastic modulus at density \( \rho \)

- \( E_s \) is the elastic modulus at density \( \rho_s \), the cell wall material
- \( k \) is a constant
- \( n \) is an exponent within a range 1.5 – 3.

The relationship between strain and density change is given be equation B4.1 as:

\[ \frac{\Delta L}{L_1} = 1 - \frac{\rho}{\rho_1} \]  

(B5.4)

where \( \Delta L / L_1 \) is the strain generated by compressing a mat from an initial thickness of \( L_1 \) and density \( \rho_1 \) by a distance \( \Delta L \), to a density \( \rho \). Re-arranging this gives:

\[ \rho = \rho_1 L_1 / (L_1 - \Delta L) \]  

(B5.5)

The stress (\( \sigma \)) and strain at a particular point are related by the elastic modulus for the conditions of the material under stress at that point, so that:

\[ \sigma = E \Delta L / L_1 \]  

(B5.6)

Substituting the relationships in B5.3 for \( E \), and B5.5 for the density yields the stress-strain relationship. For the compression of a uniform mat the modulus is a relative one, and the constant is of no significance.

\[ \sigma = kE_s \left( \frac{\rho_1 L_1 / (L_1 - L)}{\rho_s} \right)^n \Delta L / L_1 \]  

(B5.7)

This equation applies for a change in density only, with temperature and moisture held constant. The modulus \( E_s \) is constant in this case.
Plotting this gives the stress - strain curves in Figures B28 a and B28 b. In each case the constant $k$ is selected so that the curves pass through the stress - strain point at the maximum density value of 949 kg m$^{-3}$ for run 129(T12.9/20). The stress - strain curve is calculated for three values of the exponent $n$ at 1.5, 2 and 2.5. The curves lie fairly close together. An expanded plot of the lower right area of the graph more clearly shows the difference between the $n$ values. Of the values used, the best fit is with $n = 2$; it improves slightly with $n = 2.2$. This suggests that, for the fibres used in this investigation, the transfer of load by fibres bending is more significant than the fibre slippage in the possible deviations from the cellular foam model.

The stress - density relationship is determined from equation B5.6 by substituting the strain - density relationship from B4.1 on page 130 to give:

$$\sigma_2 = E_s \left( \frac{\rho_2}{\rho_s} \right)^n (1 - \rho_s / \rho_2) \quad (B5.8)$$

where the density changes from $\rho_1$ to $\rho_2$

This equation becomes a quadratic for $n = 2$. The stress - density equations are consistently of this form (Table B5 on page 139), suggesting that 2 is the appropriate index for this case.

Three conclusions have been reached from the study of the effect of density on the stress - strain response.
The cellular foam compression model developed by Maiti et al. (1984) and applied to the compression of wood by Lang and Wolcott, (1996), and Lenth and Kamke (1996) can be applied to MDF fibre mats.

- The elastic modulus is proportional to the square of the ratio of the bulk density of the fibre mat to the density of the material in the fibre walls. This is significantly greater than the exponent proposed by Palka (1973) of 1 or 1.25 to relate the elastic modulus to density.

- On this basis there would only be a difference between the stress-strain response of different fibre sources if the density of the cell wall material differed. This model predicts that the stress-strain relationship for both fibre types used in this investigation would be the same.

### 5.3 Moisture and Temperature Effects on the Stress–Strain Response

As far as the MDF mat in the press is concerned, the squared density ratio acts against creating the density differences that can be achieved in the VDP. With this squared ratio, more of the strain will occur where the density is lower, tending to equalize the density. The compression of the mat without heat in the precompressor is followed by substantial, but not complete, recovery of the initial thickness of the mat, with no noticeable creation of zones of differing density through the thickness of the mat. The fact that the VDP can be created with very significant density differences within the hot-press, indicates that other factors are exerting a greater effect over the density changes than the density ratio does.

Palka (1973) presented data for wood indicating a linear relationship, with the elastic modulus falling with both increasing temperature and moisture content. However the correction factors given yield relatively low changes in the elastic modulus. For a 5% increase in moisture content (between limits of 5% and 30%) the modulus is multiplied by 0.99: a 40°C temperature change (between limits of 20°C - 60°C) gives a factor of 0.977. Palka makes the point that for changes in both moisture and temperature the factors are multiplied.
Kunesh (1961) gives modulus of elasticity values for various moisture contents between 4% and 28% at temperatures of 80°F (26°C) and 200°F (93°C) using yellow poplar (liriodendron tulipfera). Extracting values for the conditions closest to those calculated for the mat conditions above gives the following:

Table B6 – Modulus of Elasticity - Variation with Temperature and Moisture Content – from Kunesh, (1960)

<table>
<thead>
<tr>
<th>Mat</th>
<th>Temperature °C</th>
<th>Moisture %</th>
<th>Radial MoE MPa</th>
<th>Tangential MoE MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Conditions</td>
<td>26</td>
<td>10</td>
<td>63.4</td>
<td>24.1</td>
</tr>
<tr>
<td>Density peak</td>
<td>93</td>
<td>16</td>
<td>11.7</td>
<td>8.27</td>
</tr>
<tr>
<td>MoE Ratio</td>
<td>5.42</td>
<td>2.91</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These data are for solid wood. The question as to whether these relationships can be used as is, or in modified form for the fibre mat also arises in this case. The experimental data measured on the fibre mats and presented in Chapter B4, does not provide the data necessary to calculate the elastic modulus over the moisture and temperature ranges encountered during the formation of the vertical density profile.

The characterisation of the elastic modulus as proportional to the square of the density ratio provides an opportunity to evaluate the relative changes in modulus caused by changes in moisture and temperature with those necessary to cause the density range that is achieved in MDF production.

A typical requirement is to create a panel with a face density of 1000 kg m⁻³ and an average panel density of 720 kg m⁻³. The initial compression of the mat to a thickness of 1.2 times the thickness of the panel results in an average mat density of 600 kg m⁻³. This is assumed to occur in a very short time 5 – 8 seconds for a 12 mm thick panel in a continuous press.

To reach the face density level of 1000 kg m⁻³, the density ratio between the fibre that will form the high density faces of the panel and the bulk of the fibre between these areas within the mat is 1000/600, or 1.67. With no change in temperature or moisture content, the elastic modulus in the high density section will be 1.67² or 2.79 times that in the lower density section of the mat.
For the required face density to be generated, the elastic modulus in this area must fall to approximately 1/3 of that of the fibre in the remainder of the mat. Clearly the wood model in Palka (1973) does not apply in this case.

The moisture change that might occur within such a mat is shown in Figure B29. It is assumed that the temperature rise is due solely to condensation of water vapour generated from fibre closer to the hot platen. The heat required to provide the specified temperature increase is calculated as an increase in the moisture content of the recipient layer. The percent moisture comparison is between the layer being heated and the balance of the fibre inside this layer. With a 90° C temperature rise, the fibre temperature increases from an initial 20° C to 110° C, the value at which resin cure will become significant. In this case, for an initial fibre moisture content of 10%, the moisture will rise by 6.1% to 16.1%. This provides an estimate of the maximum changes in both temperature and moisture which are likely to occur within the mat.

![Figure B29 - Calculated fibre moisture increase for a given temperature rise.](image)

These points can be plotted on the moisture - stress summary graph in Figure B19, shown here as Figure B30 on page 151. The two points are:

- The initial conditions apply for the inner part of the mat with 10% moisture at 20° C.
- The second point represents the area where the high density face is being formed. Here the temperature has risen to 110 °C, caused by an increase in moisture of 6%, to 16%. The stress level is taken as 1/3 of that necessary to compress the mat under the initial conditions.
The lack of data at high moisture contents and high temperatures does not allow validation of this point. It is, however, consistent with the trend of the data with the elastic modulus falling with increasing temperature and moisture content as shown in Figure B30.

The approach used by Palka (1973) to correlate data for different species suggests that it is reasonable to assume that the elastic modulus ratios can be transferred to other species. The difference between radial and tangential moduli in Kunesh’s data (Table B6 on page 146) is significant, but this measurement was done on solid wood and may be associated with the wood structure as opposed to the structure of the fibre. If it is a feature of the fibre, it is not known whether the fibres in the mat are aligned so that the stress acts in the radial or tangential direction for the fibre as it was in the parent wood.

Despite these uncertainties, the change in modulus as a result of the temperature and moisture changes estimated to occur in the mat is sufficient to cause the density difference between the peak, at the face of the panel, and the average density of the panel.
5.4 Stress Relaxation

The effect of stress relaxation is to provide an increase in the density of the mat where the time is long enough for this effect to become significant. While stress relaxation is normally expressed as a reduction of stress, in the case of the fibre mat with its zones of material modified by the changes induced by the heat moving from the hot press, it is helpful to see this in terms of a change in density in the zone under consideration.

Stress relaxation is characterised by a time dependent reduction in the stress needed to maintain a zero strain condition. As shown in Section 4.6 (page 140) the compliance effect of the experimental press caused a measurable increase in density to occur on the mat as the stress reduced. Although this might prevent the observed relaxation results being seen as due solely to stress relaxation effects, the measurements are in fact closer to what occurs in the mat in the hot press.

Kunesh (1961) presents the empirical equations used by Kitazawa (1947) (B5.9) and Youngs (1957) (B5.10) to describe the time dependent stress reduction function for wood as:

\[ \sigma = \sigma_0 (1 - m \log t) \]  
\[ \sigma = \sigma_0 (t + 1)^b \]

Where  
- \( \sigma_0 \) is the stress at time \( t = 0 \)  
- \( \sigma \) is the stress at time \( t \) in minutes  
- \( m \) is a relaxation coefficient  
- \( b \) is similar to \( m \), both vary with test conditions in a similar manner.

These equations are plotted on the stress relaxation graph (Figure B27, page 140), reproduced as Figure B31 with only the upper and lower experimental plots. In this case both \( m \) and \( b \) are selected and the values calculated so that the equation plots lie roughly in the middle of the experimental plots, in this case with \( t \) in seconds.
Figure B31 – Stress Relaxation plot – outer plots from B27, with Kitazawa and Youngs predictions selected for best fit at 100 s

The predictions are generally of the same shape as the actual plots, but are less accurate at times below 15 s.

Kunesh (1961) gives values of $b$ in equation B5.10 (page 152) for wood (Liriodendron tulipifera L.) over the range of temperatures and moistures covered in the study, with $b = -0.1042$ at $26^\circ$C and 11.3% moisture, and $-0.2246$ at $93^\circ$C and 13.1% moisture, in this case with time measured in minutes. The stress - time plots selected to represent a midrange of the experimental MDF stress relaxation plots are shown together with Youngs' predictions for wood at $26^\circ$C and $93^\circ$C in Figure B32.

Figure B32 – Stress Relaxation - Predicted stress – time plots for wood and MDF fibre.
This shows that while stress relaxation occurs much more rapidly for MDF fibre than for wood, there are indications that the ultimate reduction in stress is much greater for the high temperature case for wood, at least for the species from which the data used in this prediction was obtained.

The data recorded during the stress relaxation phase at the completion of the compression phase allows the change in density that accompanies the stress reduction to be plotted, as shown in Figure B33.

![Figure B33 – Stress – Density plots for Stress Relaxation Phase](image)

In this case the stress relaxation phase starts at the high stress end of the line where the density is at the lowest point. As the stress relaxation phase proceeds the stress falls in accordance with the time dependent function developed earlier and the line rises as the density increases. As discussed earlier, these data were collected when the crosshead was stationary, with the change in density arising from an essentially elastic expansion within the press assembly as the compressive resistance of the fibre mat fell.

The resulting family of curves in Figure B33 can be represented by linear trend lines with an $R^2$ above 0.99 in every case and a similar slope. The variation of this slope with moisture and temperature is examined in Figures B34a and b on page 155.
The plots in Figure B34 show that moisture has a greater effect on the slope than does temperature. The 100°C runs were clearly at the limit of the press capability with the data from these runs most likely to be questionable. It is not possible to exclude these data from the analysis completely, but repeating the regression line in B34a without these points raises the $R^2$ value to 0.8688, reinforcing the conclusion that the 100°C data may not be accurate.

Stress relaxation data determined for a group of individual MDF fibres have been reported by van Houts et al. (2003) and show an increasing level of stress relaxation as both temperature and moisture increase, with the temperature effect being greater than that of moisture.

The stress relaxation observed in the pressing experiments described in this thesis are not carried out under the zero strain conditions used by van Houts et al. (2003). The moisture and temperature response may not be the same in both cases. However the stress relaxation observed in the small press is closer to conditions in a commercial press where the zero strain condition is most unlikely to be encountered in a layer of the mat as the changes proceed.

In the commercial press the stress is determined by all the layers in the mat responding to the overall strain induced by closing the press. This stress acts on every layer in the mat and determines the thickness change in each layer, with the thickness change able
to be expressed as a density change. The moisture dependent slope of the stress density lines in Figure B33 suggests that the change in density in a layer due to stress relaxation can be calculated from the change in stress and the moisture content, as long as the stress reduction occurs over a longer time than predicted by the time-dependent stress reduction relationship.
5.5 Generation of the Density Profile

Quantifying the effects of the density, temperature and moisture changes on the stress – strain relationship of the fibre mat allows the changes which lead to the density profile to be described. The press closing occurs in two stages. The first stage is the rapid compression of the fibre mat to a thickness 10 – 20% greater than the thickness of the panel as it leaves the press. This leads to the formation of the high density face of the panel. Following this the press closes much more slowly to the final thickness.

The fibre mat responds within the press with the development of three zones within the mat as the temperature and moisture profiles develop. These are discussed in Chapter 1 (page 99)

1. The post resin cure zone lies between the hot platen and the resin cure zone and is characterised by temperatures above 110°C, and falling moisture content. The compressibility modulus for the fibre increases as the moisture content falls and the resin bonds contribute increasing strength to the network as a whole, increasing its resistance to compression. Stress relaxation is occurring within this zone.

2. The resin cure zone is where the temperature has risen to 80 – 110°C. The temperature increase is caused both by conduction through the fibre mat, and by the increase in moisture content as the water vapour generated in the outer zone condenses. The part that this water plays in the reconstitution of the resin into a liquid form that can lead to the formation of the resin bridges shown in Figure A16 on page 47, has not been elucidated.

3. Inside the resin cure zone the fibre mat is present in its original condition at the centreline of the mat, with the temperature and moisture content starting to rise in the area adjacent to the resin cure zone.

At the start of the press cycle, the mat is at the original condition. The fast close stage is typically between 4 and 12 seconds long. The end-point of the fast close stage has been shown to determine the peak density reached in the profile (Chapman 1979),
indicating that the conditions needed to create this density change have been reached, so that the three zones have been established by this point in the press cycle. As the slow close part of the cycle proceeds, the resin cure zone moves progressively to the centreline of the panel, reducing the size of this zone and increasing the size of the post resin cure zone.

The density change at each point is determined by the Modulus of Elasticity at the prevailing temperature and moisture at each point in the mat while meeting the squared density relationship. The changes necessary to establish the significant density change between the high density of the faces, and the core area of the panel have been examined in Section 5.3 (page 148).

Once this point has been established, the slow close part of the cycle proceeds, with the objective of firstly achieving a smooth transition between the peak density and the inner section of the VDP and secondly in maintaining a uniform density profile in this area. The same processes determine the stress response, but the effects are much more subtle. The density ratios encountered are much smaller in this section and therefore less significant in the compressive response, with the temperature and moisture effects becoming more dominant.

Stress relaxation is a part of the compressive response and under the conditions within the hot press, will reflect in density changes. The density changes increase with increasing moisture content and are thus greatest in high moisture content areas of the mat.

The pressing operation can thus be summarised as follows:

- Heat is transferred from the platen (or steel band in the continuous press) to the adjacent fibre.
- The increase in temperature causes the compression modulus of the fibres to drop, leading to increased strain in this area. The differential strain results in the establishment of density differences within the mat.
- The increased temperature also evaporates water from the fibre. The water vapour moves through the mat and condenses in cooler sections of the mat,
increasing both the temperature and the moisture content in this layer. Evaluation of this condition for the area of the mat that will become the high density face in the VDP shows that increases in both temperature and moisture are necessary to cause a drop in the local modulus that will allow the density ratio between the surface peak and the part of the mat not yet affected by increasing temperature and moisture.

- The formation of the face density peak. The stress – strain relationship within the mat changes after the resin cure point as the resin bonds develop strength.

- The permeability of the mat will determine how easily the water vapour can move through the mat. A high permeability will allow the moisture to spread further through the mat, lowering the moisture peak.

- Stress relaxation is significant, particularly at the end of the initial fast close of the press. This is the likely cause of some of the deviations from the desired profile that occur in the transition from the face to the core density region. These tend to require adjustments to the cycle earlier than would be required to directly influence that point in the VDP.

These points are all consistent with the observed behaviour of the mat in the press. The significance of the squared density ratio in the stress – strain response means that the moisture and temperature changes are more important in the generation of the density profile. This area was not fully covered in the experimental range of this investigation. It requires high relative humidity at the high temperature condition that could not be reached with the available equipment.

The importance of moisture in the pressing process has long been recognised. The model proposed in this thesis provides the reason for this. The stress relaxation response is also significant. It results in a change in the compressive modulus sufficiently large to cause density changes some seconds after the press closing rate has reduced. Recognizing this allows changes to be made in the press time – strain profile at a point ahead of that normally associated with generation of that particular point of the VDP.
The general experience in commercial MDF presses is that it is more difficult to achieve a specified density profile in circumstances where:

- Fibre moisture is low. As fibre moisture content increases, the possibility of a delamination after the press is greater. Delamination results where the internal steam pressure within the panel is greater than the bond strength developed at that point. The common response to this is to lower the target moisture content for the fibre into the press to the point where the level of delaminated panels is tolerable. With fibre moisture swings of 2% common, the fibre moisture content at the low point of the range will be reflected in a lower face density.

- Heating of the fibre ahead of the press is a common way of increasing press capacity. Typically fibre temperatures up to 50°C are used. Above this point it becomes increasingly difficult to achieve face density targets as the increased fibre temperature in the inner zone decreases the Modulus of Elasticity of this fibre, reducing the difference between this and the zone where the fibre is being compressed to the required face density.

- The location of the moisture within the fibre wall can be significant. Operating the fibre heating system at a humidity that results in the fibre losing a small (<1%) quantity of moisture makes it more difficult to reach the desired face density level. This appears to be caused by the moisture being less available to be converted into water vapour and shows that the location of the moisture within the fibre wall can influence the response of the fibre in the press.

The stress – strain response model developed for the fibre mats similar to those used to manufacture MDF has emphasised the combined importance of temperature and moisture levels in the development of the VDP. This emphasis is reinforced by the plant experience discussed above.
5.6 Future Work

The objective of this part of the thesis was to validate one of the major components required for a complete model of the processes that result in the development of the VDP in MDF, by an experimental determination of the stress - strain response of the fibre mat. While it is concluded that the cellular foam model can be used to represent the fibre response, one consequence of this is that the change of elastic modulus with increasing temperature and moisture content becomes more important. This area was outside the capability of the press as it was configured and data from the literature has been used for this point in the analysis. Because of the importance of this point it is desirable that this be obtained for the fibre used in this investigation.

There are three other areas where validation would increase confidence in the predictions of a press model; both are concerned with accurate determination of the changing moisture levels in the mat as the press cycle proceeds.

These are:

- Extend measurements of the stress - strain response of the fibre mat to the area 100°C and 16% moisture content.
- Measure the flow characteristics of the fibre mat at a range of densities and temperatures. This information is important in determining the shape of the moisture profile through the mat and hence in determining the peak moisture level.
- A measurement of actual moisture levels in the fibre mat during the pressing operation at a point in the press would be useful in confirming the moisture profile calculation.
Measurement of the stress – strain response of fibre mats has given new insights into the processes that lead to the generation of the VDP in MDF panels. The significance of moisture content in the fibre has been recognised in the operation of the press in plants producing MDF panels. This investigation contributes to an understanding of this response.

The mat enters the press with a uniform composition and moisture content. The press compresses the mat according to a predetermined time - distance profile while at the same time heating the material in the press. Closing the press generates a compressive strain on the fibre network. The reaction of the fibre to this strain is a stress which is reflected in the pressure that needs to be exerted by the press to cause the desired strain on the fibre mat.

Within the mat the stress on each layer is the same. The strain occurs in inverse relationship to the compressive modulus in each layer, which is determined by the temperature and moisture in the layer. It is the difference in the compressive modulus in different layers of the mat that leads to the density differences through the thickness of the mat.

The influence of density on the stress – strain relationship is central, particularly as a significant change in density within the thickness of the MDF panel is the major outcome of the model. Existing density profile models have used a range of approaches in establishing this relationship, ranging from the linear model proposed by Palka (1973) and used by Suo and Bowyer (1994), with experimental determinations used by Kunesh (1961) and Harless et al. (1987). Wolcott et al. (1990) extended a cellular foam model discussed by Maiti et al. (1984) to wood. In subsequent publications Lang and Wolcott
(1996 a and b) used the method of Dai and Steiner (1993) to define a flakeboard mat, describing the compressive response of this mat using the cellular foam model.

Most of the above work is presented in terms of the stress – strain response of wood. The data available in the literature on compressibility of fibre mats are largely concerned with the rheological behaviour of wood pulp as it is pressed to form the bales that are used for shipping this material. The models of the composite panel pressing process purport to be general (Bolton and Humphrey, 1988). However the plant experience demonstrating that the availability of the moisture to become steam is significant in producing the more sharply defined MDF VDP (when compared with particleboard) suggests that the approach of extending the scope of these models to include MDF cannot be justified without further examination.

It has been shown in this thesis that the cellular foam model can be extended to a mat made up of discrete random fibres and that the elastic modulus in this case is proportional to the square of the density. The corollary of this is that the effect of moisture and temperature on the elastic modulus of the fibre in the mat is more significant in the generation of the density profile than it would be if the relationship between elastic modulus and density was closer to the proportional one described by Palka (1973). This conclusion is supported by the plant experience where the significance of fibre moisture content on the density profile of the panel has been recognised.

The small press used to determine the stress response of prepared fibre mats proved to be successful, with repeatable results at lower temperatures. However the conditioning of the mats within the press at higher temperatures did not provide completely uniform conditions within the mat, increasing the uncertainty of data at the higher temperature ranges. As the press was configured, it was not possible to reach the high temperature – high moisture condition that the subsequent analysis has shown to be particularly significant in the density profile outcome.

Two fibre types, made from *P Radiata* wood of high (slab) and low (thinnings) bulk density, were studied. While the results indicate some difference in the stress – strain response for the two fibre types, this is within the error range of prediction. The finding
that the elastic modulus is solely dependent on the ratio between the actual density and the cell wall density supports the conclusion that these two fibres should show the same stress – strain response.

Examination of the data as a stress – density as opposed to a stress – strain plot has proved to be helpful. The stress – strain relationship for the fibre mat is not linear and using density change as an analogue of strain solves the problem of defining a starting point for the strain where the stress at low strains is very low. The stress – density plots show a consistent form, with correlation coefficients for a quadratic trend line very close to 1. This provides validation for the relationship between the elastic modulus and density that the cellular foam model implies.

The stress relaxation response of the fibre was measured by continuing to record the stress – strain data after the strain had stopped. The stress reduction response is best expressed as a percentage of the total stress. The observed response is similar to that described by van Houts et al. (2003), but it is concluded that moisture level has a greater effect than temperature on the density change due to stress relaxation, whereas van Houts et al. suggests that the temperature effect is more significant.

The investigation has provided a new approach to understanding the processes that result in the generation of the VDP in the pressing of an MDF panel. The model explains the significance of moisture content that has been noted in operating plants, suggesting that it would be worthwhile to extend the data obtained in this investigation into the area where moisture contents are highest and the temperature is also close to the maximum.
References


70. Williams, W. (Ed) (2002), MDF Yearbook, Data Transcripts Ltd. p 70.


### Appendix B1 - Schedule of Experimental Pressings.

<table>
<thead>
<tr>
<th>Run</th>
<th>Fibre</th>
<th>Mat Weight</th>
<th>Temperature °C</th>
<th>Humidity %</th>
<th>Speed mm m⁻¹</th>
<th>Moisture %</th>
<th>Comment</th>
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