COMPUTER CONTROL AND MONITORING OF
PSYCHROMETRIC CONDITIONS

A THESIS
SUBMITTED IN FULFILMENT
OF THE REQUIREMENTS FOR THE DEGREE
OF
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By

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SUMMARY

This report describes a project undertaken to monitor and control the different air states in an air conditioning plant.

From previous equipment purchases and development work, the Department of Mechanical Engineering in Canterbury University has a Hilton® A770 air conditioning rig for demonstrating the basic psychrometric processes, and an environmental control chamber for providing any particular 'outside' air state.

In this project a model ‘building’ has been installed inside the environmental chamber to simulate an inside air-state of a building and, has been interconnected to the Hilton rig to supply and condition the air (to the model building) as required. The supplied air state to the model building is controlled by means of the different air conditioning components installed in the Hilton rig such as a preheater, steam generator, refrigerated cooling coil, and a reheater.

In turn, the Hilton rig has been modified to use a controlled air state, drawn from the environmental chamber, to simulate winter, summer or any other supply state to the model which is acting as a space load for the Hilton rig.

Data acquisition electronics such as sensors, multiplexers and signal conditioners have been installed in the system to manipulate the large amounts of data on real time.

Provision of real time display of the values being measured is updated after each sample through a software program written for Windows95®, with a 3-D graphical user interface and other many enhancements.
An important feature of this software is that the different air conditioning processes can be displayed on a linked on-screen psychrometric chart developed in the Department of Mechanical Engineering, which can be printed out.

Overall, the facility represents, on a much-reduced scale, a building and its air conditioning system operating within an artificially created and controlled outdoor environment. And, using a personal computer, psychrometric conditions are monitored and controlled; the energy transfers are verified; and the different processes are displayed on a psychrometric chart.
ACKNOWLEDGMENTS

First, I would like to thank my supervisor Dr. Alan S. Tucker who benevolently guided me throughout this project, sustained me with his valued support and advice, and inspired me with a rational approach towards problem solving.

Special thanks must go to Mr Ron Tinker, the senior technician of the Thermodynamic Laboratory, for his technical assistance and support.

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<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
</tr>
<tr>
<td>T</td>
<td>Absolute temperature</td>
<td>K</td>
</tr>
<tr>
<td>t</td>
<td>Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>t_w</td>
<td>Wet bulb temperature</td>
<td>°C</td>
</tr>
<tr>
<td>t^*</td>
<td>Thermodynamic wet bulb temperature</td>
<td>°C</td>
</tr>
<tr>
<td>φ</td>
<td>Relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>W</td>
<td>Humidity ratio</td>
<td>kg_w/kg_a</td>
</tr>
<tr>
<td>h</td>
<td>Specific enthalpy</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>c_p</td>
<td>Specific heat at constant pressure</td>
<td>kJ/kgK</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>m³</td>
</tr>
<tr>
<td>ν</td>
<td>Specific volume</td>
<td>m³/kg</td>
</tr>
<tr>
<td>.</td>
<td>Volume flow rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>kg</td>
</tr>
<tr>
<td>.m</td>
<td>Mass flow rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>.q</td>
<td>Heat flow rate</td>
<td>kW</td>
</tr>
<tr>
<td>I</td>
<td>Electric current</td>
<td>A</td>
</tr>
<tr>
<td>E</td>
<td>Electro-motive force</td>
<td>V</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>kPa</td>
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<tr>
<td>R</td>
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### Subscripts
- **abs** refers to absolute value of pressure
- **a** refers to air substance
- **w** refers to water substance
- **r** refers to refrigerant substance
- **s** refers to saturation temperature or pressure
- **f** refers to a property of the saturated liquid state
- **g** refers to a property of the saturated vapour state
- **fg** refers to the liquid-vapour phase at constant pressure
Chapter 1

INTRODUCTION

1.1 Monitoring?

There is a myth that buildings designed to be energy-efficient are somehow less comfortable for their occupants than ordinary buildings. Recent research conducted on air conditioning systems in commercial buildings (Rogers, 1997) defeats that illusion and describes how buildings with a high occupancy comfort and satisfaction level can achieve good energy efficient ratings. Rogers states “A significant factor as to why buildings with a high occupancy comfort and satisfaction level achieve good energy efficient ratings is because demand and supply are effectively matched. This is achieved through careful performance monitoring, attentions to user complaints and relatively rapid feedback loops and well defined diagnostics”. Accordingly monitoring is the cornerstone of an energy-efficient and comfortable system.

The subject of this study is to set up a computer monitoring system in a model air conditioning plant where psychrometric
conditions are monitored and controlled, and the energy transfers are evaluated.

1.2 The experimental air conditioning rig

The equipment used in an air conditioning plant may include a number of components such as fans, filters, mixers, heat exchangers, humidifiers, dehumidifiers, instruments and controls, and other associated equipment such as boilers and refrigeration units.

To teach students air-conditioning engineering practice and analysis, the Department of Mechanical Engineering, University of Canterbury has owned a Hilton A770 Recirculating Air Conditioning rig for several years. With the exception of filtration, which has essentially no effect on the moist air, this laboratory experimental rig has been designed to model and to evaluate the energy transfers occurring in all the psychrometric processes likely to be met in an air conditioning plant.

The Hilton rig shown in Fig.1.1 is mounted on a frame, which houses a refrigeration unit and a boiler. All controls and instrumentation are at eye level and logically arranged so that the operator quickly becomes accustomed to their use. The duct has a clear perspex front, and all the components through which the air flows may be seen.

In its originally purchased configuration, the air-state currently prevailing in the laboratory is drawn into the unit where it can be subjected to various conditioning processes. The Hilton rig employs wet and dry bulb thermometers for determining moist air states, but uses thermocouple sensors instead of ‘mercury’ thermometers.
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The airflow entering the Hilton rig passes through the following elements:

1. **Airflow measuring intake orifice with inclined tube manometer.**
2. **A mixing zone,** where adiabatic mixing of two airstreams occurs. The re-circulated airflow and the fresh airflow drawn from the laboratory are mixed together into this mixing zone. The mixing process is particularly interesting since it demonstrates the effects on temperature and humidity when two airstreams combine.

---

1 Source: The Hilton rig user’s manual
3. A preheater consists of two extended fin electric heating elements, 0.5 and 1.0 kW nominally at 230V.

4. A humidifier supplied with steam from a boiler electrically heated and working at atmospheric pressure. This boiler is fitted with a water level gauge and float level controller. It has one heating element x 1.0 kW, and two x 2.0kW, nominally at 230V. Humidifying is achieved by injecting steam directly into the airflow. The steam is injected against deflector plates to ensure an even distribution of moisture across the duct.

5. A cooler/dehumidifier with an outlet for precipitated water. This cooler is an evaporative direct expansion, extended fin coil with a cooling capacity of approximately 1.7 kW. The refrigeration unit is hermetic using refrigerant R12 with an air-cooled condenser. Dehumidifying is achieved by passing the airflow through the cooling coil. When dehumidifying is carried out, cooling takes place at the same time.

6. A reheater (as for the preheater described above).

7. An axial flow fan with infinitely variable speed control. The maximum air throughput is 0.13$m^3$/s and the power factor of the fan motor can be taken as $\cong 1.0$

8. An airflow measuring duct orifice with inclined tube manometer.

9. A damper, which controls the quantity of air discharged to the atmosphere. Any air not discharged is re-circulated and mixes with the fresh air.

### 1.3 Deficiencies of Hilton rig and planned development

Although the Hilton rig in its original configuration (as purchased) was capable of demonstrating the basic air conditioning processes, it had three major deficiencies. This
section highlights those deficiencies and the developments that were planned to overcome them.

First, the intake air-state to the Hilton rig was uncontrollable because the air was directly drawn from the surrounding laboratory. To overcome this problem it was planned to build up a control chamber (environmental chamber) where the state of the incoming air could be changed as required before entering the Hilton rig as shown in Fig.1.2.

![Fig.1.2: Outdoor air-state control before supplying the Hilton](image)

Second, except from the ventilation and the heat dissipated to/from surroundings, there was no practical air conditioning load on the Hilton rig. Hence, it was planned to incorporate a model building capable of providing heating or cooling load to the Hilton rig as shown in Fig.1.3.

![Fig.1.3: The model building inside the environmental chamber and connected to the Hilton rig](image)
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Third, all information from the Hilton rig was calculated manually using measuring instruments such as a temperature display, manometers, a voltmeter, and an ammeter. Because careful performance monitoring assumes using automatic data processing to get instant results, it was planned to upgrade the Hilton rig measurement system to a PC controlled monitoring system.

1.4 Developments accomplished prior to this project

Development of the Hilton rig initially started with the data acquisition system. Previous successive final year students had set up different data acquisition elements in the Hilton rig. These students had built up the foundation of this project over several years (Eaton, 1992), (Radford, 1994) and (Duff, 1996).

Eaton had set up the data acquisition card and a pressure transducer to monitor the airflow and the temperatures on a PC. Radford and Duff had set up the pressure transducers and the flowmeter in the refrigeration to automate the refrigeration information measuring system.

In 1994, David Lewes designed and built the environmental control chamber to provide a controlled air-state to the Hilton rig intake (Lewes, 1994). The environmental control chamber is a room in which the air-state can be closely controlled and monitored within given limits. The internal environment in the chamber has been adequately insulated from the surrounding environment where the chamber is built-up inside the Thermodynamic Laboratory, University of Canterbury.
As shown in Fig. 1.4, equipment similar to that used in the Hilton rig was installed by Lewes under the floor to supply and control the airflow in the environmental control chamber.

The additional equipment consisted of a preheater, a steam generator, a cooling/dehumidifying coil, a reheater, and a circulating fan. The portion of the circulated air is dependent on the fresh air intake to the Hilton rig.

Lewes had developed as well the software needed to control the equipment operation and to monitor the different air states in the environmental chamber. This software was developed in the C language for MS-DOS® platform.

By this development, a changeable air-state became available to supply the Hilton rig intake regardless of the air-state in the surrounding laboratory.
1.5 The current development and objectives

The next stage of development, which is included in this project, is setting up a Model Building within the environmental control chamber, and supplying this model from the Hilton rig. In this way, the Hilton rig would be able to be configured to act as an air conditioning system for the model building, which “externally” would be exposed to a controlled environment representing a desired outdoor air-state.

This “same” outdoor air-state would be the fresh air-state utilised by the Hilton system for ventilation purposes. Overall, then, the facility would be able to represent, on a much-reduced scale, a building and its air conditioning system operating within an artificially created and controlled outdoor environment.
Substantial modifications and extensions to the hardware, electronics and software would be required to run and control the integrated system.

Thus, the second and principal objective of this project was to set up a computer-controlled monitoring system able to perform the following specific tasks:

1. Monitoring the psychrometric conditions inside the Hilton rig, the model building, and the environmental chamber to an accuracy of ±0.2°C on both dry and wet bulb temperatures\(^1\).
2. Controlling the environmental chamber equipment to achieve and maintain a predefined psychrometric condition to an accuracy of ±0.5°C on both dry and wet bulb temperatures\(^2\).
3. Performing energy balance analyses in the preheater, cooling coil and the reheater stations in the Hilton rig.
4. Showing the different air conditioning processes on an on-screen psychrometric chart.
5. Providing file saving and printing services for all the acquired data.

### 1.6 Future development

It has been planned in a future stage to implement a cyclic condition profile for modelling the daily or annual temperature variations to study the behaviour of different thermal storage materials.

---

\(^1\)\(^2\) At typical comfort conditions of 20°C DBT and 50% relative humidity, these temperatures (dry and wet bulb) accuracy would fix the uncertainty in the relative humidity to approximately 50±2.5% and 50±6.5% respectively.
Moreover, the completed facility can be used to study the effect of maintaining an internal positive pressure inside buildings on the infiltration.

1.7 Thesis structure

This thesis spans seven chapters. In this chapter, the scope and the objectives of this project have been set up. In the next chapter, the concepts of the psychrometric properties are introduced. The third chapter describes how the model has been set up. The data acquisition electronics are explored in Chapter 4 and the software written to control these data acquisition components are explained in Chapter 5. The results of the experimentation runs are presented in Chapter 6, and finally, the conclusions and recommendations are discussed in Chapter 7.
Chapter 2

PSYCHROMETRIC CONDITIONS

2.1 Introduction

The air in which we live is a layer surrounding the surface of the earth called the atmosphere. The lower atmosphere is a mixture of dry air and water vapour often known as moist air. Psychrometrics deals with the determination of the thermodynamic properties of moist air and the utilisation of these properties in the analysis of conditions and processes involving moist air (ASHRAE, 1997).

This chapter explains the nature of the moist air and how the air-state can be described by means of the psychrometric properties.

2.2 Moist air composition

Moist air is a binary mixture of dry air and water vapour. Although the dry air portion is a mixture of several gases, it is treated as being a single component. This is permissible because
the composition of dry air is essentially invariant throughout the earth’s atmosphere and, for air conditioning purposes, there is no concern about the possibility of one or more of the constituent dry gases starting to condense out or to liquefy (Tucker, 1994). Thus, moist air can be considered to be a single phase, two-component mixture of water vapour and dry air. It should be noted that the fog condition is a two-phase, two-component mixture, because the water component is present in both vapour and liquid phases.

2.3 Psychrometric properties

The following properties are used in describing the moist air states. It should be noted that all specific (i.e. per unit mass) properties are based on the mass of dry air only since the water vapour mass may vary during processing.

a) Dry-bulb temperature $t$

This is the temperature of the mixture of dry air and water vapour indicated by a thermometer. The thermometer bulb must be clean, dry, and properly shielded to prevent radiant heat exchange between the thermometer and any objects or surfaces which are at a temperature different from that of the moist air itself. It is often abbreviated to DBT.

b) Thermodynamic wet-bulb temperature $t^*$

That is the temperature at which water, by evaporating into air, can bring air to saturation adiabatically at the same temperature. Alternatively, it is referred to as the adiabatic
saturation temperature. In the steady state of a saturation device as illustrated in Fig.2.1:

\[ h_1 + (W_{s,2} - W_1) h_{f,2} = h_{s,2} \]  \hspace{1cm} (2.1)

where \((W_{s,2} - W_1)\) kilograms of water, having initial specific enthalpy \(h_{f,2}\) corresponding to saturation at the water temperature \(t_2\), evaporate into the air to produce the saturated air state also at temperature \(t_2\).

For constant total pressure \(p\), the quantities \(W_{s,2}, h_{f,2}, h_{s,2}\) are all functions of \(t_2\) only so this temperature \(t_2\) must be function of the inlet air state, ie.

\[ t_2 = t_2 (h_1, W_1, p) \]  \hspace{1cm} (2.2)

this temperature is therefore a thermodynamic property of state 1 and is called thermodynamic wet-bulb temperature \(t^*\) of the air at state 1. Its general defining equation is therefore:

\[ h + (W^*_s - W) h^*_f = h^*_s \]  \hspace{1cm} (2.3)
Because the above equation (2.3) contains no direct reference to the quantity $t^*$, the following can be used as an alternative defining equation to the thermodynamic wet-bulb temperature (Threlkeld, 1970):

$$W (h_g - h_r^*) = W^* s h^*_{fg} - c_p(t - t^*)$$

(2.4)

**b) Wet-bulb temperature $t_w$**

This is the temperature which is measured by covering the bulb of an ordinary dry bulb thermometer with a wet wick. When air flows across the wick, water evaporates and absorbs latent heat, which makes the temperature of the wick drop. The rate of evaporation depends upon the amount of water required to saturate the air surrounding the wick. At a saturation condition no further evaporation will occur and the wet bulb temperature will then be the same as the dry bulb temperature.

In the wet bulb process a small quantity of water is exposed to a flowing stream of unsaturated air, and for practical purposes there is no change in the state of the air. In contrast with the process of adiabatic saturation, there is a large amount of water exposed to the air and the air-state does change.

For all the usual psychrometric calculations, the use of the terms *wet-bulb temperature* and *thermodynamic wet-bulb temperature* as synonyms is convenient and correct to a reasonably good accuracy (but they are completely different for other mixtures of vapours and gases). The deviation between the wet-bulb temperature and thermodynamic wet-bulb temperature can be minimised by a sufficiently high air velocity which reduces the
effects of radiation and conduction on the ordinary unshielded wet-bulb.

The wet-bulb temperature given on the psychrometric chart is that indicated by a wet-bulb thermometer placed in an air stream at 3.5 m/s or more as recommended in the Hilton User’s Manual. Unfortunately, this is not the case in the Hilton rig. Therefore appropriate corrections shown in Appendix D have been considered while calculating the results in Chapter 6.

c) Dew point temperature $t_d$

This is the temperature at which the moisture content of the given moist air-state would be sufficient to exactly saturate the air at the same total pressure. During such a cooling process there would be no change in the mass of water vapour present per unit mass of dry air which means that the numerical value of the humidity ratio $W$ would be unchanged.

d) Relative humidity $\phi$

Relative humidity gives an indication as to whether the air can take more moisture or not and is usually expressed as a percentage. Under the excellent assumption that both dry air and water vapour behave as ideal gases relative humidity is defined by:

$$\phi = \frac{p_w}{p_{w,s}}$$

where $p_w$ represents the partial pressure of the water vapour in the mixture (the pressure that it would exert if it alone occupied
Chapter 2: Psychrometrics

the whole volume of the moist air being considered), while \( p_{w,s} \) is the saturation pressure of water vapour corresponding to the moist air temperature assuming that the two components are of moist air are in thermal equilibrium, ie. at the same temperature.

e) **Humidity ratio (or moisture content) \( W \)**

Humidity ratio relates the mass of water vapour to the mass of air.

\[
W = \frac{m_w}{m_a} \tag{2.6}
\]

where \( m_w \) is the mass of water vapour, and \( m_a \) is the mass of dry air. The humidity ratio on its own gives no indication of how close to saturation condition an air-state is. It is an absolute quantity, which in a typical moist air-state is less than 3\% of the mass of dry air in a given volume. Although this proportion is numerically small, it has very significant influence on moist properties such as enthalpy, and also a very significant influence on human comfort.

f) **Specific Enthalpy \( h \)**

The total internal energy of a mixture of gases is equal to the sum of the internal energies of the individual constituents when each occupies a volume equal to that of the mixture (at the temperature of the mixture). This combined law on pressure and internal energy is known as Gibbs-Dalton Law.
Thus the enthalpy of the moist air can be calculated by adding together the individual enthalpies of the two components, water vapour; and dry air.

\[ h = h_a + W h_w \]  \hspace{1cm} (2.7)

where \( h_a \) is the specific enthalpy of the dry air component in kJ/kg\( a \) and \( h_w \) is the specific enthalpy of the water vapour component in kJ/kg\( w \).

For dry air at around atmospheric pressure and normal temperatures, enthalpy is a function of temperature only.

\[ h_a = c_p t \text{ [kJ/kg} a\text{]} \]  \hspace{1cm} (2.8)

where \( c_p \) is dry air specific heat which equals 1.005 kJ/kg\( a \)K at room temperature.

To a very good approximation the water vapour component enthalpy can be represented by a linear equation:

\[ h_w = 2501 + 1.84t \text{ [kJ/kg} w\text{]} \]  \hspace{1cm} (2.9)

where the reference datum for the enthalpy of water is 0°C. Combining Eq.2.4 and Eq.2.5, the moist air enthalpy becomes:

\[ h = 1.005 t + W (2501 + 1.84 t) \]  \hspace{1cm} (2.10)

Equation 2.10 can be simplified into the following form:

\[ h = c_p' t + 2501 W \]  \hspace{1cm} (2.11)
where \( c'_p \) may be regarded as the specific heat of moist air, but still expressed on the basis of unit mass of dry air in the mixture as shown in the following equation.

\[
C'_p = 1.005 + 1.84 \, W \quad [kJ/kg_a K] \quad (2.12)
\]

Appendix A describes in detail how the enthalpy, the relative humidity, and the humidity ratio can be calculated from given dry and wet bulb temperatures.

g) Specific volume \( v \)

The specific volume is defined to be the volume occupied by moist air per unit mass of dry air, i.e. m\(^3\)/kg\(_a\). By applying Dalton’s Law and assuming ideal behaviour, the dry air partial pressure \( p_a \) equals:

\[
p_a = p - p_w \quad (2.13)
\]

where \( p \) is the total pressure (generally the atmospheric pressure) and \( p_w \) is the partial pressure of the water vapour. Thus the unit mass of dry air in the mixture will occupy a volume \( v \) as follows:

\[
v = \frac{R_a T}{p - p_w} \quad (2.14)
\]

In fact this is the same volume which the mixture itself occupies. This is based on the mass of dry air, which is invariant to changes in moisture content as the air moves through the various air conditioning components. The mass flow rate on the
other hand may vary from component to component as moisture is added or removed.

2.4 Fixing the state of moist air

The number of independent properties, which must be specified to fix the air-state, can be obtained from Gibbs phase rule:

\[ f = n - p + 2 \]

where

- \( n \) ...................... the number of components
- \( p \) ...................... the number phases

So, three independent properties are necessary and sufficient to completely identify the state.

Knowing the total pressure, generally the atmospheric pressure, which prevails and in most instances does not alter during the process, it is necessary to have values of two other independent properties in order to specify a moist air-state.

Because of the need for two independent properties (in addition to the pressure), there are certain pairings of parameters which will not fix a moist air-state. Either because they are dependent such as:

- Humidity Ratio \( W \)
- Dew Point \( t_d \)

or difficult to resolve such as:

- Spec. Enthalpy \( h \)
- Wet Bulb Temp \( t_w \)
Of the possible combinations, there are two combinations, most generally used for specifying a moist air state at a given total pressure. They are:

\[
\begin{align*}
\text{Dry Bulb Temp} & \quad \& \quad \text{Relative Humidity} \\
t & \quad \& \quad \phi
\end{align*}
\]

And

\[
\begin{align*}
\text{Dry Bulb Temp} & \quad \& \quad \text{Wet Bulb Temp} \\
t & \quad \& \quad t_w
\end{align*}
\]

The combination used in this project to determine the air-state is the dry and wet bulb temperatures utilising thermocouple sensors.

### 2.5 Psychrometric properties calculations

The amount of water vapour in moist air varies from zero to a maximum which depends on temperature and pressure. The latter condition refers to saturation, a state of neutral equilibrium between moist air and the condensed water phase. Principally the \textit{water vapour saturation pressure} is required to calculate the saturation humidity ratio as a first step in determining the moist air properties. After determining the value of the water vapour saturation pressure (Irvine & Liley, 1972), other properties accordingly can be calculated.

Appendix A includes the calculation procedure used in this project to obtain the relative humidity, humidity ratio, and specific enthalpy.
2.6 Basic processes in air conditioning

There are eight basic thermodynamic processes by which the state of moist air can be altered as shown in Fig. 2.2. The first two processes, the sensible heating and cooling, involve only a change in the dry bulb temperature, whereas the processes of humidifying and dehumidifying involve only a change in the moisture content. Thus when the state of the air moves from O to A or to E, there is no change in the moisture content of the air. If the state changes from O to C or G the dry bulb temperature remains constant.

Fig. 2.2: The basic psychrometric processes

1. Sensible heating - OA
2. Sensible Cooling - OE
3. Humidifying - OC
4. Dehumidifying – OG
5. Heating and humidifying - OB
6. Heating and dehumidifying - OH
7. Cooling and humidifying - OD
8. Cooling and dehumidifying - OF

Most practical moisture-transfer processes involve both changes in temperature as well as in humidity as shown in the last four fundamental processes listed above.
**Closure:**

In this chapter, the concept of the moist air and its psychrometric properties are introduced. The next chapter will demonstrate how the model building has been designed, constructed, and established inside its environmental chamber.
Chapter 3

THE MODEL BUILDING

3.1 Introduction

The model building has been built to provide the Hilton rig with an air conditioning load. It has been located within the environmental control chamber, which controls the outside air state around it. In this chapter, the general design and construction of the model building are described, and the basic requirements for the model building in its environmental chamber are established.

3.2 Components of space load

In summer, solar and internal gains add to the space cooling requirement whereas in winter such gains reduce the space heating requirement. That means the most demanding scenario for load estimation is in summer rather than wintertime, therefore the component of space load will be described in terms of being space gains. These components are sensible and latent
heat gains. All sensible and latent gains to a space added together represent Total Heat Gains as shown in Fig.3.1.

![Diagram of cooling/heating load components](image)

**Fig.3.1: Cooling/heating load components**

**a) Sensible heat gain**

Sensible means without addition or removal of moisture and therefore it is represented as a horizontal line on the psychrometric chart as shown in Fig.3.1. The following are the main sources of the sensible heat gain of a building:

**External sources:**
The main external heat sources are the direct and indirect solar radiation gain, the heat transmitted through glazing and walls due to the inside-outside temperature difference, and the infiltration of outside air through cracks in the building fabric.

**Internal sources:**
The main internal heat sources are electric lighting, sensible heat emitted by the occupants, and electrical power dissipated from any appliances operating within the space.
b) Latent heat gain

Latent means addition or removal of moisture without changes in the dry bulb temperature as represented as a vertical line on the psychrometric chart in Fig. 3.1. The following pictures show the main sources of the latent heat inside a building:

![Diagram of latent heat gain inside a building](image1)
(a) Moisture generated inside a building

![Diagram of moisture entering a building](image2)
(b) Moisture enters a building

Fig. 3.2: Latent heat gain inside a building

---

1 Source: GIB® Dry Wall System (product brochure).
Moisture enters from outside

As shown in Fig.3.2(a) moisture can enter from outside into a building either by ventilation where the amount of moisture can be controlled or by infiltration through walls cracks, doors, windows etc., where the amount of moisture is uncontrollable.

Moisture generated inside space:

At 25°C and 50% relative humidity the interior air of a moderate house of 150m² area may hold around five litres of water floating around, looking for a cold surface to condense on. Water vapour is generated inside a building from people, cooking, showering and bathing, washing and drying, pets, and plants as shown in Fig.3.2(b).

3.3 The model design

To determine the temperature-driven rate of heat transfer into or out of the model building it has been necessary to plot values to use for both the interior and exterior temperatures.

3.3.1 Outdoor design condition

All external heat sources of a conductive or convective nature discussed above have been considered to influence the model building but the direct and indirect solar radiation effect has been excluded because the environmental chamber has not been designed to provide this type of heat source. However, the outdoor design temperatures of Christchurch City according to ‘NIWA’ National Institute of Water & Atmosphere Research Ltd. (IRHACE, 1999) are shown in Table 3.1.
Table 3.1 Outdoor design temperatures for Christchurch City
(from National Institute of Water & Atmosphere Ltd.)

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th></th>
<th>Winter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DBT&lt;sub&gt;max&lt;/sub&gt;</td>
<td>WBT&lt;sub&gt;max&lt;/sub&gt;</td>
<td>DBT&lt;sub&gt;min&lt;/sub&gt;</td>
<td>WBT&lt;sub&gt;min&lt;/sub&gt;</td>
</tr>
<tr>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>30</td>
<td>28</td>
<td>26</td>
<td>21</td>
<td>20</td>
</tr>
</tbody>
</table>

Data period: 1986 – 1995

DBT<sub>max</sub> = Maximum dry-bulb temperature which will not be exceeded more than 1%, 2.5%, or 5 of the time (as specified) during hours 0800 – 1800 NZ Local time, 1 November to 30 April.

WBT<sub>max</sub> = Similarly for wet-bulb temperature, during the same hours, 1 November to 30 April.

DBT<sub>min</sub> = Minimum dry-bulb temperature below which the temperature will fall not more than 1%, 2.5%, or 5 of the time (as specified) during hours 0800 – 1800 NZ Local time, 1 May - 31 October.

WBT<sub>min</sub> = Similarly during the whole 24 hours, 1 May to 31 October.

The outdoor design maximum dry and wet-bulb temperatures have been chosen at 2.5% to be 28°C and 20°C (47% relative humidity). The minimum dry and wet-bulb temperatures have been chosen as 5°C and 3°C (70% relative humidity) because this is the bottom level of the operating envelop which is the environmental chamber capable of providing (Lewes, 1994).

### 3.3.2 Indoor design condition

The indoor design temperature in a particular space is very dependent on the use of that space. Because the use of the
model building is assumed to include human occupancy, the indoor design condition has been based upon human thermal comfort. Figure 3.3 shows the comfort condition zone for summer presented from data collected for an air velocity of 0.1 m/s and climatic conditions around Sydney, (Devasahayam, 1977).

From the plant point of view, it is desirable to keep winter indoor design temperatures to the lowest acceptable level whereas in summer the highest acceptable temperature would require the smallest cooling plant with the lowest energy consumption. In addition to that, when there is a greater than 10K difference between the outdoor and indoor dry bulb temperatures, a person

---

1 Source: Devasahayam, 1977
entering or leaving the air-conditioned space will experience a thermal shock. The indoor design condition might typically call for achieving an indoor dry bulb temperature of 20°C in winter and 23°C with 50% relative humidity in summer.

### 3.3.3 Choice of supply conditions

When simulating summer conditions in the environmental chamber, the air supplied to the model building will have a sufficiently low temperature and moisture content to absorb the total heat gain of the space. As the air flows through inside the model, it is heated up and can be humidified using any water vapour source inside the model. If the system is closed loop, the air is then returned to the conditioning equipment, which is the Hilton rig, where it is cooled and dehumidified and supplied to the model building again.

In addition to the maintenance of temperature and humidity it is also important to maintain air quality. Fresh outdoor air can be mixed with the return air for maintaining indoor air quality. The exhaust door on the Hilton rig can be controlled –manually- to introduce the desired flow level of the fresh air, which can be determined from the pressure drop at the fresh air inlet.

In winter mode, the same general processes occur but in reverse.

In spring or fall mode, when the specific enthalpy of the outdoor air is lower than the enthalpy of the recirculating air, or when the outdoor air temperature is lower than the recirculating air temperature an economiser cycle can be used to conserve energy. An economiser cycle is an air conditioning cycle that
utilises the free cooling capacity of outdoor air rather than using refrigeration or evaporative cooling to offset the space cooling load.

### 3.3.4 Model sizing

The available space inside the Environment Control Chamber, where the model has been constructed, is very limited. That small surface area combined with the limited temperature differential would not be enough to show significant energy transfer processes. That conflict was resolved by increasing the surface by attaching a convoluted thin metal sheet –aluminium– to the bottom of the model as an additional heat exchanger.

Another limiting constraint has emerged (in addition to the confined space inside the environmental chamber) upon estimating the air conditioning load according to the summertime scenario. The refrigeration unit in the air conditioning plant (Hilton rig) is not powerful enough to provide a cooling effect more than 1.6 kW. Consequently, the design of the model building has been extremely affected by the limited power of the air conditioning plant. However, in this respect the 1.6kW cooling effect, along with the other necessary data including the 10K temperature differential from the inside and outside design conditions, material heat transfer coefficients for aluminium and wood, maximum permissible dimensions, have been loaded into a spreadsheet.

The scenario of the spreadsheet was set up to give the maximum heat transfer in the lower section (the attached heat exchanger) by maximising the number and the depth of the bottom convolutions. It was also set up to give the minimum amount of
heat transfer in the upper section (the conditioned space) by using building materials with lower thermal conductivity. The dimensions which resulted from the spreadsheet are shown in Fig.3.4.

This spreadsheet represented a heat transfer model based on taking the inside surface thermal resistance of the building material as 0.17m²K/W and 0.2m²K/W for the vertical and horizontal surfaces respectively (NZS 4214, 1977). The outside surface thermal resistance for the same material was taken as 0.11m²K/W for the vertical walls and 0.09m²K/W for the horizontal surfaces. The thermal conductivity is 0.13W/mK for plywood and 201W/mK for aluminium at 20°C (AIRAH Handbook, 1995).

3.4 Model construction

As the supplied air moves through the space its enthalpy and its humidity ratio change as it is subjected to loads in the space. The supply air distribution system is required to be designed in such a way that the space loads are taken by the supply air in a
mixing zone outside the occupied area of the space. A mixing zone is used so that the occupants themselves are not exposed to air at conditions other than the required state. Although the mixing zone is generally above head level in practice, it is the lower section of the model building which has been utilised for this purpose.

Figure 3.5 shows a picture of the environmental chamber hosting the model building, and attached to the Hilton rig.

![Figure 3.5: A picture for the model building setting inside the environmental chamber and attached to the Hilton rig at the right hand side.](image)

**a) The upper section construction**

The upper section has been built as a welded aluminium frame holding two fixed walls, roof, and two changeable walls. The
front changeable wall is made from transparent acrylic material in case the air movement needs to be visualised as shown in Fig.3.5.

A steel frame has been used to secure these changeable walls. The model is sealed in a way that makes changing walls at any time easy.

b) The lower section construction

The lower section is built from 10 squared aluminium channels extending for 2m length, 50mm width, and 350mm height. These channels have been shaped, overlapped and attached to a wooden board to guide the airflow into the model.

c) Interconnecting the model with the Hilton rig

Four duct adaptors have been installed between the model building and the Hilton rig. These ducts are made from aluminium sheet and fitted with internal splitters to provide better flow distribution.

3.5 Basic air conditioning cycles for the Model:

The basic operation cycles for conditioning the model building are illustrated in the following sections:
The summer mode

The summer mode basic air conditioning cycle with cooling/dehumidification and its corresponding schematic diagram of the air system are shown in Fig.3.6. This cycle consists of the following processes:

1. Mixing process r-m-o of recirculated air and outdoor air.
2. Cooling/dehumidifying process m-sc at the cooling coil.
3. Sensible heating sc-sf from supply fan power heat gain.
4. Sensible heating sf-s from duct heat gain.
5. Space conditioning process s-r.

Fig.3.6: Basic air conditioning cycle in summer, cold air supply
The winter mode

The winter mode basic air conditioning cycle with steam injection humidification and its corresponding schematic diagram of the air system are shown in Fig.3.7. This cycle consists of the following processes:

1. Mixing process r-m-o of recirculated air and outdoor air.
3. Sensible heating sh-sf from supply fan power heat gain and the reheater.
4. Sensible cooling sf-s from duct heat loss.
5. Space conditioning process s-r.

Fig.3.7: Basic air conditioning cycle in winter, warm air supply
Closure

In this chapter, the model building has been established in its environmental chamber. The next chapter will explain how the data acquisition system has been built up and utilised to monitor the air state and the different air conditioning processes.
Chapter 4
DATA ACQUISITION SYSTEM

4.1 Introduction

Any computerised data acquisition system, regardless of its type and what kind of variables it acquires from the real world, has some basic components. The specific measuring components may differ from system to system, however the general basic categories of building blocks are common to all of them. The basic building blocks for any computerised data acquisition systems are shown in Fig.4.1:

Fig.4.1: The basic building blocks for any computerised data acquisition System
The purpose of this chapter is to describe the configuration of the data acquisition system used in this project, and to explore the various components and their functions and capabilities.

### 4.2 Sensors

A sensor is defined as a device which responds to a physical stimulus. The sensor is the component of the system which changes the physical variable that needs to be monitored like temperature, pressure, flow rate, water level, into electrical form to enable the next block of the data acquisition system to recognise the variable. The sensors used in this project will be reviewed in the next section according to their functions. They are assorted into temperature sensors, air pressure sensors, electric power (voltage and current) sensors, refrigeration cycle sensors, and water level sensors for the steam generator.

#### 4.2.1 Temperature sensors

![Temperature Sensor Diagram](image)

The thermocouples that had been used in previous development of the Hilton rig and the environmental chamber were K-type (chromel-alumel). Therefore the thermocouples used in the model building had been chosen to be of the same type. Besides, the available hand-held digital thermometers in the Mechanical Engineering Department are K-type as well. These digital
thermometers have been used to calibrate and check the thermocouples’ performance.

All those thermocouples have been designed in a way similar to that used in the original Hilton rig and shown in Fig.4.2. A short stainless steel sleeve has been fitted on the tip of each thermocouple. They are held in their positions using acrylic tubes, which allow thermocouples wires to pass through. The acrylic material has very low thermal conductivity, so it will not transfer significant heat to or from surroundings. This method increases the thermal inertia of the thermocouple, which has the advantage of reducing sudden fluctuations that may be caused by non-uniform flow temperatures. However, a disadvantage of increasing the thermal inertia of the thermocouple is the slower response. In some situations a very fast response is desired but in this slowly changing situation, smoothed response was preferable.

In addition to that, on some places in the Hilton rig where the duct’s length is not enough to develop a uniform flow, two thermocouples have been connected in parallel. The resultant signal from this parallel connection gives the average temperature of the thermocouples as shown in Fig.4.3 (Benedict, 1969).

\[ T = \frac{(T_1 + T_2)}{2} \]

Fig.4.3: An average reading of two thermocouples
Wet bulb temperature monitoring

There are no humidity sensors used in this project. However, wet and dry bulb thermocouples have been used together to try and produce a sufficiently accurate estimate of the humidity ratio through the software. However, because air velocities over the wet bulb thermometers are not high enough in the Hilton rig, a correction to the wet bulb reading must be made (see section 2.3 and Appendix D). It should be mentioned that wet bulb thermocouple water reservoirs should be checked and filled with distilled water and the wick should be totally saturated.

To connect the thermocouples to the next building block, compensating wires have been used to reduce the cost. These wires have been connected using special polarised plugs to ensure proper contact.

4.2.2 Airflow sensors

So far, three pressure transducers\(^1\) have been used to sense air pressure values needed for psychrometric calculations. One has been used to sense the absolute atmospheric pressure, and another two to sense the differential pressure drop in both the Hilton rig and the environmental chamber. The absolute atmospheric pressure (total pressure) is one of three independent properties that are necessary to completely identify

---

\(^1\) Although the term transducer and sensor are often used interchangeably, a slight difference exists between them. Usually the term transducer is used for devices that are in raw form, whereas the term sensor is used for a transducer in finished form, which is more suitable for connecting to the data acquisition system. There is a growing tendency in the industry to use the term sensor and abolish the term transducer.
the air state. The pressure drop inside the Hilton rig is used to calculate the airflow rate, which is necessary to study the energy transfer rate in the different air conditioning processes. In the environmental chamber the pressure drop is used to check for icing on the evaporator which can cause blockage in the supply duct.

**The atmospheric pressure sensor**

The atmospheric pressure is measured using a SenSym® pressure transducer type ASCX15AN. This transducer had been chosen during previous work on the project. It has internal vacuum reference and an output voltage proportional to the absolute pressure. It doesn’t need any further signal conditioning because its signal is already amplified. The supply voltage may range between +5V and +16V. An external +12V power supply has been used in this application.

The absolute pressure transducer ASCX15AN has an operating pressure range from 0 to 103.4214 kPa and it is factory calibrated to ±0.1% of full scale. Hence the uncertainty in the acquired atmospheric pressure will be ± 0.1034 kPa. In fact this value of uncertainty will have a small effect on the calculated value of the humidity ratio (W). For example, at a dry-bulb temperature of 25°C and a wet-bulb temperature of 19.5°C, the humidity ratio is obtained as 0.01193 kg<sub>W</sub>/kg<sub>a</sub> at the standard atmospheric pressure of 101.325kPa. But at an atmospheric pressure of 101.428 kPa, the value obtained for the humidity ratio became 0.01197 kg<sub>W</sub>/kg<sub>a</sub> which means that the uncertainty in the obtained humidity ratio is ± 0.3%.
The airflow sensor in the Hilton rig:

Previously, a Setra® pressure transducer model 264 with range 0 to 12.5mm water gauge (0.125kPa) had been moved around the facility to measure the airflow at different points. This transducer can sense 0.5mm WG differential pressure reliably. Pressure drops of interest were; across the return duct orifice plate; across the inlet duct orifice plate; and in the environmental chamber’s supply duct. The cost of three equally sensitive and expensive pressure transducers was unsustainable for this project. And so, because frequent sampling of the three differential pressures was not necessary, it was decided to use the Setra® 264 transducer for the first two measurements with computer-controlled switching solenoid valves to achieve the necessary connections as shown in Fig.4.4.

One solenoid has been connected to the upstream taps and the second one has been connected to the down stream taps on the inlet and the return ducts. The pressure connections have been made using clear plastic tubes with diameter 4.5mm.

As shown in Fig.4.4(a) the default position of the solenoids (unactuated) has been set to pass air samples from the return duct to the pressure transducer. When a control output signal is sent from the data acquisition card it switches on a relay switch, which in its turn supplies the solenoids with ~24 Volts needed for actuation. When the solenoids are actuated as shown in Fig.4.4(b) air samples pass from the inlet duct to the pressure transducer.

These solenoids have been checked during sustained actuation and they showed a very reliable performance without any tendency for overheating or leakage. However, a minimum delay
time of seven seconds at least should be allowed after every switching to permit the sampled pressure in the transducer to build up or to be relieved.

(a) Unactuated solenoids
picking up the pressure drop at the return duct

(b) Actuated solenoids
picking up the pressure drop at the inlet duct

Fig. 4.4: Switching solenoids actions
The pressure transducer’s base plate has been mounted in a vertical position. This gives the best performance because it reduces the effect of the vibrations. The electric connection of the pressure transducer is very simple. An excitation voltage of 12 to 24V DC is supplied to the “exc” and ground to “com” terminals. Then the output signal from terminal “out” is connected to the assigned analog channel on the data acquisition card.

**The airflow sensor in the environmental chamber:**

Another pressure transducer has been installed to measure the pressure drop in the supply duct of the environmental chamber. Another Setra® pressure transducer of the same model but with a measuring range from 0 to 125mm WG (1.25kPa) which is considered as being satisfactory for its role which is just checking the pressure in the duct, rather than giving a precise measure of the pressure drop. It has been connected in a way that gives the maximum usage of its function. As shown in Fig.4.5 the ‘LOW’ inlet has been connected to a tap in between the evaporator and the fan while the ‘HIGH’ inlet has been left open to the atmospheric pressure. By setting up this connection the pressure transducer can check for two different problems that can arise.

If the pressure drop increases above the normal working pressure this will be an indication that the duct is blocked upstream where ice builds up on the evaporator coil. And if the pressure decreased, this gives an indication that the fan is partially blocked downstream. The software performs this check over different periods of time and alerts the user by displaying the specific problem.
4.2.3 Electric power sensors

There are two heating stations in the Hilton rig used for preheating and reheating of the airflow. Each station consists of two extended fin electric heating elements; 0.5 and 1.0 kW nominally at 230V. The project provides an automated utility to compare the heat output with the electric power input in each station.

The heat output is calculated from enthalpy difference on each heating station (using the acquired dry and wet bulb temperatures) and the mass airflow rate (from pressure drop signal). The electric power input is calculated from the acquired current and voltage signals from each heating element. Simply, the power is the result of multiplication of the current by the voltage, with power factor equals unity (Hilton user’s manual 1987).
To implement this technique the Hilton rig’s electric circuit has been modified to supply both heating stations from the same line phase in order to use a single voltage sensor for both of them. Consequently connection changes have been made to distribute the total rig load over all the three phases. This way has not only saved the cost of another voltage sensor, but also has saved a free channel on the data acquisition card for future work. A current sensor LEM® model LTA50P/SP1 has been installed for each heating station.

**The Voltage Sensor:**

A voltage transducer LEM® model LV25-P, with overall accuracy ±0.6% of the nominal input current, has been installed on each phase to measure the real time mains voltage. A typical output signal would be equivalent to 230±1.3 volt. This value is used together with the acquired current value to get the real time electric power input. The calibration result has been included in Appendix D.

**The Current Sensors:**

The current sensor LEM® model LTA50P/SP1, shown in Fig.4.6, is a miniature current transducer which can accurately measure an instantaneous value of AC current up to 50±1% A of the full range in total isolation from the circuit being monitored. The output is linearly related to the primary current flowing through the centre core and equals to 100mV/A.

The calibration accuracy of this sensor as found originally was ±1% of the full range (±0.5A for a range of 50A). But by passing the conductor through the sensor five times rather than once, its
sensitivity has been increased because the range has been dropped from 50 to 10A which resulted in a new calibration accuracy of total ±0.1A.

A typical output current of 6.5±0.1 A using a mains voltage value of 230±1.3 V will result in a power input value of 1495±31.5 watt. This value declares an accuracy of ±2% of the input electrical power due to the uncertainty of measurements. As will be discussed in Chapter 6, these uncertainties in measuring the input electrical power are less than those associated with the air temperature measurements. So, in determining the percentage of discrepancy in the heating processes, the value of the electrical power deposited to the airflow will be chosen as the “correct” value for determining the percentage of discrepancy. The calibration data of these sensors have been included in Appendix D.

4.2.4 Refrigeration cycle sensors

Measuring the refrigerant condensation and evaporation pressures in addition to the flow rate gives the necessary parameters needed for the energy balance analysis on the
cooling coil of the Hilton rig. The sensors used on the refrigerant cycle are explained in the following two paragraphs:

**Refrigerant Pressure Transducers**

Two SenSym® pressure transducers models ST2300G1 and ST2100G1 selected in previous work had been fitted into the Hilton rig refrigeration unit to measure the condensation and the evaporation pressures respectively. The designated ST2000 series transducers produce a linear voltage output between 1 and 6 volt over their operating pressure ranges, which are nominally 0 to 2068 kPa for the ST2300G1 transducer and 0 to 689.5 kPa for the ST2100G1 transducer.

These transducers have claimed accuracy of 0.5% of full scale i.e. ±10 kPa for the transducer ST2300G1, and ±3.5 kPa for the transducer ST2100G1.

In this project, the transducer ST2300G1 is used just to indicate the compressor outlet pressure, while the transducer ST2100G1 has been used to measure the pressure at the evaporator outlet, from which the refrigerant superheated vapour enthalpy can be determined. It has been found that the accuracy in measuring the refrigerant pressure has an insignificant impact on the calculated enthalpy. For example, as shown in Fig. 4.7, for a typical superheated vapour state at 35°C and 261 kPa, an uncertainty in the pressure measurement will result in an uncertainty of ±0.051 kJ/kg in the enthalpy at that point which is 207.5 kJ/kg, i.e. ±0.02%. The enthalpy at the evaporator inlet is based on the saturated liquid temperature at the point 11 (see Fig.1.1) assuming the throttling process is completely adiabatic.
As will be discussed in Chapter 6, these uncertainties in measuring the refrigerant pressures, hence calculating the enthalpy, are less than those associated with the air temperature measurements. So, in determining the percentage of discrepancy in the cooling process, the value of the power withdrawn via the refrigerant will be chosen as the “correct” value for determining the percentage of discrepancy.

They also feature internal voltage regulation and accept supply voltages from 12V to 30V DC (SenSym® pressure sensors handbook). The voltage has been set to 20V DC to serve this project.

**Refrigerant Flow Meter**

In previous work (Duff 1994), a litre-meter type LM24/SS/20 flowmeter had been fitted into the refrigeration unit in the liquid line. This meter is a volumetric measurement device using a positive displacement principle in the form of a straight bladed...
Pelton wheel. When the Pelton wheel rotates, a small sensing coil detects the ferrite pieces mounted on the blade tips as they pass resulting in a pulse output. By calibration the frequency of the pulse output can be converted to mass flow rate.

More information is available in the fact sheet of the litre-meter LM24/SS/20 flowmeter.

### 4.2.5 Water level sensors

When the environmental chamber was being set up, two floatless level sensors had been installed in its steam generator as shown in Fig.4.8. These sensor probes have been set to give signals if the water level is not enough to cover the heating elements, or becomes too high. The output signals of these probes switch electro-mechanical relays for digital output signals, which have been connected to the digital input of the data acquisition card.

The high or low water level signals have been used in the software to display an alert message to the user showing the specific problem and, controlled by the software, the power will be switched off from the heating elements until the problem has been checked and rectified.

![Fig.4.8: Water level sensors in the steam generator](image-url)
It should be noted that this system is only activated while the software is running. So it is important in the future (as will be discussed later in the recommendations in Chapter 7) to install a safety relay which connects the power to the heating elements only if the water level is high enough regardless of whether the software is running or not.

4.3 Signal conditioners

Although the signal, which comes from the sensor, is electrical, it may not necessarily be in a suitable form for the next block of the data acquisition system.

Most of the time the signal produced by the sensor is very weak. Because of this it is vulnerable to distortion by any surrounding noise. Thus the signal needs to be properly conditioned before entering the next block of the data acquisition system.

4.3.1 Amplifier/multiplexing board PCLD-789D

The number of thermocouples used in the project is relatively high. There are 16 thermocouples connected into the Hilton rig and another 15 thermocouples connected into the environment chamber and the model building. In fact one multiplexer board has been used in one previous stage of the facility’s development.
to multiplex the Hilton rig thermocouples and in another stage to multiplex the environmental chamber thermocouples. After integrating the Hilton rig with the environment chamber in one project, adding a new multiplexer board became essential. The intention was to buy a board identical to the existing type PCLD-889 but the manufacturer (Advantech®) has superseded this model with a type PCLD-789D board.

The PCLD-789D like the existing PCLD-889, is a powerful front-end signal conditioning and channel multiplexing daughter board. This board has the capability to amplify and multiplex 16 differential input channels into one analog output channel. Up to 10 PCLD-789Ds can be cascaded to expand the analog inputs of a single data acquisition card to 160 channels.

The board has a high-grade instrumentation amplifier to provide switch selectable gains of 1, 2, 10, 50, 100, 200, 500, 1000 or user definable gain. This function allows users to perform accurate low level analog signal-measurement especially those who are using thermocouples.

**Cold Junction Compensation**

The PCLD-789D provides on-board cold-junction compensation circuitry to support thermocouple measurement. This circuitry generates a +24.4 V/°C compensation signal with a zero volt output at 0°C. Although the CJC circuitry is calibrated as prescribed in the manufacturer’s manual, it can be expected that it will not provide the proper compensation for two reasons:

1. The thermistor that transmits the temperature of the second junction is located very close to one end of the thermocouples
connection terminal block on the board. Consequently, it may not transmit the actual temperature of the connectors located at the far end of this block, particularly due to the temperature gradient generated from the different electronic components on this board and the transformers located in the near vicinity to it as shown in Fig.4.9.

Fig.4.9: The layout of the multiplexer board showing the CJC sensor’s position relative to the thermocouples connectors blocks

2. The terminal block connectors on the board used to connect the second junction of the thermocouples are all made from the same material. Ideally, any connector should be compatible with the material of thermocouple wire it is connected to, either chromel or alumel. Omitting to do this will result in an erroneous indicated EMF if the terminal block is not truly isothermal (as is likely for the reason explained in 1 above)

3. In addition to that, the noise introduced by the different electronic components placed adjacent to the board, may be a significant source of error for the thermocouple measurements.
**Thermocouple connection onto the multiplexer board**

The following explains the nature of floating and non-floating sources and how to properly connect the input signals.

**Floating Source Connection:**

Since the PCLD-789D has only differential input channels, each input channel must have two signal wires. The differential input responds only to the voltage difference between the high and low inputs. If the signal source has no connection to ground, it is called a ‘floating source’.

A connection must exist between Low and Ground to define a common input voltage for a floating signal source. To measure a floating source, the input channel should be connected as shown in Fig.4.10.

![Fig.4.10: Floating source connection](image)

**Non-Floating Source Connection**

If the signal source has one side connected to local ground, the signal source ground and the PCLD-789D ground will not be at exactly the same voltage as they are connected through the ground return of the equipment and building wiring.
The difference between the ground voltages forms a common mode voltage\(^1\).

To avoid ground loop noise effects, the signal ground should be connected to the low input signal. The low input should not be connected to the PCLD-789D ground directly. For better grounding, a wire connection between the PCLD-789D ground and signal source ground is necessary as shown in Fig.4.11(a).

![Diagram of Correct Connection](image1)

(a) Correct connection

![Diagram of Incorrect Connection](image2)

(b) Incorrect connection

Fig.4.11: Non-floating source connection

Figure 4.11 illustrates in (a) the correct connection and in (b) the incorrect connection of a differential input with local ground.

**Gain Selection**

\(^1\) For non-floating thermocouples, the A.GND must not be connected to LO. Jumpers JP21~JP36 (one for each channel) should be shorted to satisfy isolation requirements.
Chapter 4: Data acquisition system

The user’s manual suggests setting the gain to 50 for K-type thermocouples, however in this application it has been set to 1000. Since no temperature in this project exceeds 100°C, which is very low compared to the K-type thermocouple maximum range, the gain value suggested in the user’s manual would be insufficient. Therefore, the gain switch has been set to 1000 to obtain the maximum available resolution.

Switch and jumper setting

The PCLD-789D needs to be configured manually by the users to suit a particular application. Simply inserting or removing the appropriate jumpers can do this. Also changing components on the board can alter some of the filter’s characteristics. All the details on how the PCLD-789D board is configured to serve the particular needs of this project are included in Appendix B.

4.3.2 Amplifier/ multiplexer board type PCLD-889

This board is the old multiplexer/amplifier board that had been used before in the previous stages. It almost has the same features as the new board PCLD-789D with relatively unimportant little differences. The approach to the CJC connection is essentially identical.

Appendix B includes the details on how the PCLD-889 board is configured to serve the particular needs of this project.

4.4 Data acquisition card PCL-812PG
Chapter 4: Data acquisition system

An Advantech® PC data acquisition card type PCL–812PG had been used from previous work (Eaton, 1992). It is physically located inside the PC, plugged into the expansion bus.

The PCL–812PG is a multi-function analog and digital I/O card that features the five most desired measurement and control functions for PC/AT and compatible systems: A/D conversion, D/A conversion, digital input, digital output and counter/timer.

This card neatly packages 16 12-bit analog input channels, two 12-bit analog output channels, 16 digital input channels, 16 digital output channels and a programmable counter/timer.

In addition to that, it features a programmable sampling rate of up to 30kHz, A/D with DMA or interrupt, and programmable A/D ranges (gains).

4.4.1 Analog to Digital Conversion

The A/D converter is a device on the data acquisition card, which converts analog voltage levels into digital form. In the real world, almost all parameters that we want to measure exist in analog form; ie they are continuous with respect to time. The relation between the input magnitude and the output magnitude has to be linear. Analog-to-digital converter, or A/D converter, is one of the most important data acquisition components. It can be considered the heart of any data acquisition system. Because of its importance, some detailed features of the A/D converter will be focused on in this section giving an idea of the basis by which a data acquisition card can be chosen.

Fig. 4.12: Start and End of Conversion pulses
The analog to digital conversion process takes a finite amount of time and the conversion process is initiated by sending a start-conversion pulse into the A/D converter as shown in Fig.4.12. When the A/D converter finishes the conversion process, it informs the peripheral components outside by giving an end-of-conversion pulse. The time it takes for converting the analog signal into digital form is a crucially important parameter, called conversion time. Typical values for conversion time are from 5 to 50 microseconds (Ozkul, 1996).

On the other hand, the digital output of the A/D converter can be of different sizes depending on the quality of the A/D converter. Typical values for resolution of the A/D converters are 8 bit, 12 bit, 14 bit, 16 bit, and 18 bits. But there is always a trade-off between the speed and the resolution. Higher resolution always requires longer conversion time. The conversion time of the PCL-812PG is 30 microseconds, which is suitable for essentially steady state psychrometric processes.

The K-type thermocouple typically generates 0.789 mV at 20°C, and 1.196 mV at 30°C, which represents 0.040 mV/°C. Using a channel set up to an input gain 1000, the maximum input voltage range will be ±10 mV. Hence, the maximum resolution
for that channel using 12 bits is $20\text{mV} / 2^{12} = 0.004\text{mV}$ which is equivalent to a temperature value of $0.01\degree\text{C}$\textsuperscript{1}.

### 4.4.2 Card configuration

The configuration of the PCL-812PG card includes jumpers and Dip switch positioning appropriately selected for the specific purposes of the card. The different jumper settings required to perform the specific data acquisition and control processes in this project are described in detail in Appendix B.

### 4.5 Variable power controllers

The environmental chamber from previous work (Lewes, 1994) has been equipped with 3 electronic circuit boards to control the power level of the two air heating elements (a preheater and a reheater 3kW each) and a water heating element (1.5kW) in the steam generator. The power can be controlled into 265 different levels proportionally via the analogue output from channel no. 1 of the data acquisition card. So, the higher the analogue output (extending from 0 to 5 volts), the higher is the power level of the heating element (extending from 0 to 3kW for the air heaters). Three TRIACs on these circuits have been replaced with higher power rating ones, which eliminated frequent breakdowns occurred when switching on the heating elements to full load. Even so, more enhancements are still required to be done on these variable power controllers. A suggestion about that has been included in the recommendation section in Chapter 7.

\textsuperscript{1} It should be noted that this is the resolution possible through the 12-bit A/D converter, not the accuracy of the temperature.
4.6 The computer

In 1997 when this project started the computer attached to the facility had an Intel 486 processor but it has been significantly upgraded as will be described in the next chapter. As a result of widespread availability, computer prices have been driven down and performance up. In addition to the high performance, the reliability of the computers has also been increased which significantly helped in developing this project.

Closure
In this chapter, all data acquisition electronics installed in this project have been described. All input and output channels assignment have been summarised in Appendix C. It should be noted that the measuring devices and sensors should be calibrated regularly to ensure the integrity of measuring results. Appendix D contains the calibration data for different sensing and measuring devices.

In the next chapter, the software that has been developed to control this data acquisition system will be explained.
Chapter 5

SOFTWARE DEVELOPMENT

5.1 Introduction

The application program that controls this project has been developed using structured system design. Structured design is a disciplined approach to computer software design which historically has been a haphazard activity. Computer system design is defined as the activity of transforming a statement of what is required to be accomplished into a plan for implementing that requirement by means of an electronic automation. This definition (Meiler, 1988) indicates that the software design is the bridge between system requirements and implementation.

In this chapter, through a closer look at the “traditional software development phases of analysis, design, implementation, testing and maintenance” (Sommerville, 1993), aspects such as programming technique, programming language, program architecture, files structure, relationships between functions, data structures, and the internal qualities of the completed software are discussed.
5.2 Requirements analysis

Analysis is considered the first step in moving programming from an ad-hoc intuitive art to an engineering-like discipline. What most importantly have been produced from this stage are the system specifications. The analysis has covered what the previous system did, what extra features were needed in the new system, and what constraints the new system would need to satisfy.

Different systems had been developed in previous stages on the facility. One of them had been used to monitor the Hilton rig refrigeration unit. That system had been developed for Disk Operating System (DOS) using QBasic language. Another system developed for MS-DOS® in the C language had been used to control the environmental chamber by Lewes in 1994. Although those systems had fulfilled their specific tasks at the time they had been developed, they had become incompatible for running the integrated facility as one unit. Moreover, they were designed for specific channels’ assignment, which had been changed due to the new arrangement. Because channel assignment can be changed at any time, the new system specifications has added an extra feature which allows changing assignment and the gain code for each channel simply from the user interface. This utility has no impact on the program structure and it can be executed even while the program is running which adds significant flexibility to the system. Other important features have been added in the system’s specifications such as displaying the air conditioning processes on a software version of the psychrometric chart\(^2\) (Tucker 1998). This feature has been

\(^2\)Beta version developed in Mechanical Engineering Dept., University of Canterbury.
implemented by using Object Linking and Embedding Automation OLE. Other features such as using the standard Windows® messages and dialogues in the Application Program Interface (API) were not available in previous applications because they were developed in a DOS environment. Windows® API contains a rich library of tools available for programmers to use in their applications. Printer set-up, Save dialogue, Open file dialogue, Font dialogue, warning or confirmation messages are all examples of Windows® API functions that have been included in the new system specifications.

Since the project is primarily used to educate and demonstrate the different aspects of air conditioning processes, building the graphical user interface (GUI) using 3D objects was highly desirable. Because 3D graphics give the live touch of the real world it emphasises the different actions, and motivates students for better understanding. Interactive applications communicate information powerfully; hence, small moving arrows have been used to show airflow direction in the ducts.

At the time this project was begun, Windows3.11 was running on the majority of the Department’s workstations; consequently, fast data processing as an essential constraint was not going to be satisfied due to the large graphics overhead in the new system. But after installing Windows95 on the facility, the system has overcome this difficulty.

The output from this analysis is not only to define the new software specifications but also the hardware specifications.

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3 Industry standard used to manipulate an object’s properties in an application from within another application.
Almost all of the system hardware has been significantly upgraded. The new hardware specifications are a Pentium 60MHz processor, 32 Megabytes RAM, 2 Gigabytes hard disk, and a 17-inch monitor.

Since the nature of the computer industry is fast changing, the Internet has become the major resource for developing this system. The data acquisition hardware manufacturer has made help online and software drivers available to be downloaded from the web site ‘www.advantech.com’ and many other third parties have made some of their products available for shareware as well. In addition, many software developers and programmers share problem-solving in different news groups.

5.3 System design

Like other mechanical engineering disciplines, computer system development requires the use of the right tools to save effort and time. One of the earliest programming tools was the flowchart, which didn’t survive as systems grew. It has been difficult to use the flowchart since it provides no organisational insight except for small systems. Instead, an entity relationship diagram has been used as the right design tool for the most modern systems.

5.3.1 Entities relationships

The entity relationship analysis diagram is a standard programming design tool. It breaks down the application into meaningful entities and relationships. Figure 5.1 shows the different entities that have been modelled in the system and the relations among them.
### Environmental Chamber

- Current temperatures (DB, WB)
- Target temperatures (DB, WB)
- Airflow rate
- Sensible heat requirement
- Latent heat requirement

<table>
<thead>
<tr>
<th>Fan</th>
<th>Model building</th>
<th>Cooler</th>
<th>Humidifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow pressure drop (Fan speed)</td>
<td>Inlet temperatures (DBT, WBT)</td>
<td>Evaporator Temperature</td>
<td>Water temperature</td>
</tr>
<tr>
<td></td>
<td>Outlet temperatures (DBT, WBT)</td>
<td>Airflow pressure drop (Ice formation)</td>
<td>Water High level</td>
</tr>
<tr>
<td></td>
<td>Air flow rate</td>
<td></td>
<td>Water low level</td>
</tr>
</tbody>
</table>

### Hilton rig

- Preheater Energy balance
- Reheater Energy balance
- Duct pressure drop
- Inlet pressure drop
- Solenoid actuation time

<table>
<thead>
<tr>
<th>Reheater station</th>
<th>Solenoid</th>
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<tbody>
<tr>
<td>Inlet temperatures (DBT, WBT)</td>
<td>Pressure relief time</td>
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<tr>
<td>Outlet temperatures (DBT, WBT)</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
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<tr>
<td>Fan power</td>
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<table>
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<th>Preheater station</th>
<th>Fan</th>
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<td>Inlet temperatures (DB, WB)</td>
<td>Power factor</td>
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<tr>
<td>Outlet temperatures (DB, WB)</td>
<td>Current</td>
</tr>
<tr>
<td>Current</td>
<td>Voltage</td>
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<table>
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<th>Refrigeration unit</th>
<th>Boiler</th>
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<td>Condensation pressure</td>
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<tr>
<td>Evaporating temperature</td>
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<tr>
<td>Evaporating pressure</td>
<td></td>
</tr>
<tr>
<td>Refrigerant flow rate</td>
<td></td>
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</tbody>
</table>

**Fig.5.1: Entities relationship diagram**
5.3.2 Object oriented approach

At the time of this application being developed, the object-oriented programming was an emerging technology promising to make systems and software designers more productive and make software development activities accessible to more people. This section defines the basic concepts of using objects in software programming.

The world in which we live is full of objects, and each type of object has characteristics that separate it from other types of objects, such as height, width, colour, name and caption. The computer world is really not very different; in Windows® for instance, virtually everything on the screen makes up a different object. Some common Windows objects we use every day are buttons, check boxes, scroll bars, images, tool bars, labels, and edit boxes. All these objects are different but have one thing in common: Objects have properties (or attributes) and methods that control their appearance and behaviour. Example of these properties and methods can be shown if any object on Windows95® desktop is right clicked. A so-called verb list will appear with “Properties” option at its end. These verbs are not the same for all objects, because every object has its own specific method, which suits its nature. The Properties item, in turn, reveals a sub-list containing the specific properties of the selected object. Each object has its own specific properties. They can be customised during development to control the way they look and respond. Many different programming objects are already existing on-the-shelf and ready to use. So the programmer is no longer required to write a code that creates a text box, button, label and many other objects.
Thus, object oriented programming encourages code reuse and prototyping rather than invention. Object oriented programming (OOP) is superior to top-down programming in its capability to create reusable code and to better model real-world situations.

The arrival of Microsoft Windows made moving to OOP languages a more rational decision. This is because OOP and graphical user interface (GUI) development complement each other and have grown to the point where one cannot be used without the other. Programming Windows applications using a non-OOP language such as C, is not a trivial task; yet this was how Microsoft® Windows was originally built and how Windows applications were most often built in the early days of Windows. Excessive amounts of C code have to be written just to show a simple message window. OOP allows complex tasks to be made easier by encapsulating complex functions into objects.

### 5.3.3 Visual programming tools

Although OOP programming allows complex tasks to be made easier, a considerable amount of code still has to be written to get objects to behave as desired. Although early OOP environments had true object oriented features they didn’t provide visual tools. Consequently they lacked the capability of easily drawing visual objects and manage the interaction with the external events. Filling the need for an easy-to-use visual Windows development tool, Microsoft introduced Visual Basic, a visual programming environment based on BASIC (Beginners All-purpose Symbolic Instruction Code).

By introducing Visual Basic, the importance of the visual side of application development has been clearly stated.
In summary, this combination is revolutionary, bringing visual programming together with an extremely powerful object-oriented development framework. It lets users put more effort into solving particular problems rather than learning about complex programming syntax. This way, an engineer does not have to be a programmer to simulate a complex control system. Future programming may look less like writing down words and more like assembling together bolts and nuts.

5.3.4 Programming language

Although Microsoft Visual Basic is no doubt the most popular object–based development tool for Windows programming, and the author had experience with it, Delphi® has been considered as an alternative choice. A careful study had been made to decide which language is most convenient to develop the program in order to avoid the large time and effort that could be invested in learning another language. The result of this study has shown that Delphi® has many advantages over Visual Basic®. Although Visual Basic implements a number of essential OOP tools, it lacks pointers and formal OOP language extensions. Visual Basic relies on a run-time interpreter that is found in Microsoft Office. Besides, interpreted Visual Basic programs generally are not as fast as programs created with Delphi’s optimising compiler. Unlike Visual Basic, Delphi has pure OOP extensions beside pointers. Underlying Delphi is Object Pascal, which even non-Pascal programmers will find easy to pick up by just knowing object-programming principles. Unlike Visual Basic, Delphi can compile an entire application into a single executable file. This file may be rather large, but it eliminates the need to distribute a number of run-time files with the application such as “VBRUN.dll”.
5.3.5 Program architecture

The application that has been developed communicates with the data acquisition electronics using a device driver. The purpose of the driver is to represent the hardware input and output (I/O) capabilities of the data acquisition card in software form. Figure 5.2 shows an overview on the application program interface and the driver system architecture.

The application denotes the program that has been developed in Delphi®, which utilises the services that the driver system provides. According to the request from the application, the driver provides different services or function calls for it. As an
example for temperature data acquisition with expansion boards
the following function is called:

**TCMuxRead** (DeviceHandle, DasChan, DasGain, ExpChan, TCType, TempScale, Temp)

**Function input parameters are:**
- **DeviceHandle:** variable contains device configuration data
- **DasChan:** The sampled channel on the data acquisition card
- **DasGain:** Gain code of the sampled channel
- **ExpChan:** The thermocouple channel on the expansion board
- **TCType:** Thermocouple type (J, K, S, T, B, R, and E)
- **TempScale:** Temperature unit (Celsius, Fahrenheit, Rankine, Kelvin)

**Function return (output) is:**
- **Temp:** Acquired temperature value

All function calls are listed in details in Advantech® driver manual.

**Driver configuration file**

---

![Driver function flow](image)
The configuration file stores the configuration data about hardware settings in Windows95 Registry. Opening the driver means creating a reference to this data for I/O access. Figure 5.3 shows the relation between the configuration data and the function flow.

**Driver architecture**

This driver system decomposes into three layers: uniform driver, device-specific driver, and low level driver, which fill the following roles:

- The uniform driver layer (adapi32.dll) provides a uniform interface between the applications and device-specific drivers. It handles the management of the different device-specific drivers in the case of using more than one data acquisition card. Thus, the application doesn’t care about the underlying drivers. In this project only one data acquisition card has been used so there is no need for a uniform driver layer.

- Device-specific driver layer (ad812.dll) which provides board-specific functionality. The format of the driver is standard Windows dynamic link library (DLL) format.

- Low-level driver layer (wrtdev0.vxd) performs physical hardware access operations. The format of this driver is standard Windows virtual device (VXD). This technique of using a virtual device in Windows95 creates an entity that appears to the application as if it is a real hardware device. This virtualisation introduces a certain level of separation that “insulates” the data acquisition card from being directly manipulated by the application. For example if two programs simultaneously
requested access to the hardware, the VXD captures these requests and only one is honoured.

### 5.3.6 Program files structure

The complete software suite for this project has been built up from a related collection of files. These files are mainly text files with extension “PAS” where code instructions have been written, and graphical files with extension “DFM” where forms have been designed. The Delphi project file has the extension “DPR”. As shown in Fig.5.4 the software project has been called “hilton.dpr” and has been assembled from the following major and auxiliary collections of files:

**The major files**

- **Hilton.dpr**: This file declares all units that have been used in building up this application. In fact the software project file is not a container for these units physically, but it contains information about them. It also contains information about the sequence of the application execution.

- **Main.pas**: is the main unit, where all objects in Main.dfm and the static global data have been declared such as the atmospheric pressure, temperatures, airflow rate, equipment’s flags (statuses) to make them visible to all other files. It pays most attention to data displaying, although other files are responsible for data acquisition. It provides the different tools (buttons) that manually control the equipment, and shows its running status. It provides file creation and saving service in MS Excel spreadsheet format, printing services, and OLE automation procedure to create the psychrometric chart in MS Excel.
Fig. 5.4: Program files structure

The Project Files

- HILTON.DPR

The Major Files

- Main.dfm
  - Main.pas
- Control.dfm
  - Control.pas
- Alarm.dfm
  - Alarm.pas
- Psychrometrics.pas
- R12.pas
- Ad812.pas
- Ad812.pas

The Auxiliary Files

- About.dfm
  - About.pas
- Spmainu.dfm
  - Spmainu.pas
- Spsplsh.dfm
  - Spsplsh.pas
- Ad812.hlp
  - The help file
- Ad812.dll
  - The Driver

Splash screen files
Main.dfm: is the associated form with the unit Main.pas. Figure 5.5 shows the environmental chamber hosting the model building and to the left is a sliding switch to set the chamber to the required environmental condition. To the right are the supply and the return ducts representing the Hilton rig. The tabbed panel shows the energy balance chart for Hilton rig heating elements and the energy level of the sensible air heaters and the humidifying boiler.

Control.pas: contains all functions that convert the acquired signal to its equivalent in physical units i.e. from volt to kPa, Amp, or °C. It contains also the equipment switching on/off routines. It checks the water level in the boiler and the airflow in the environmental chamber and creates Alert.frm in case of warning to display the problem to the user.

Control.dfm: is the associated form with Control.pas. It provides the tools which allow the user to change the channel assignment and the gain code and to carry out a diagnostic check on the data acquisition card by testing the input analogue channels voltage as shown in Fig.5.6.

It also provides the utility to configure the data acquisition card driver as shown in Fig.5.7 and any expansion daughter boards as shown in Fig.5.8.

Alarm.pas:

Alarm.pas makes the screen blink and generates an alert sound from the PC speaker to draw the user’s attention to the warning. It is created if control.pas find any problem during system checks.
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Fig. 5.5: The main graphical user interface (GUI)

Fig. 5.6: Hardware Settings Screen
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Fig. 5.7: Driver configuration windows for data acquisition card

Fig. 5.8: Driver configuration window for the expansion boards PCLD-889, and PCLD-789D
**Alarm.dfm:**
This is the associated form with the unit Alarm.pas. It is a blinking alert screen containing a message about the water level status in the boiler and is accompanied by an alarm sound. The same form is used to show other alerts such as “ICE FORMATION ON THE COOLER” and “FAN SLOW DOWN”.

**Psychrometrics.pas:**
This module is responsible for performing the necessary psychrometric calculations. Results such as specific enthalpy, relative humidity, absolute humidity are passed to any other module on calling.

**R12.pas:**
This module calculates the refrigerant’s properties such as vapour pressure, density and enthalpy, which are required for calculating the energy balance of the refrigeration unit.

**Ad812.pas:**
This module declares all the driver’s functions that have been used in this project. It is also the legal transport of the functions’ parameters and returns to the driver file “ad812.dll”.

**The Auxiliary Files:**

**Splash screen:** Spmainu.pas, spmainu.dfm, spsplshu.pas, and spsplsh.dfm are used to show a splash screen while the program is being loaded in the background. It asks the user to wait until program finishes loading. Once the main user interface is fully created, this splash screen is destroyed and freed from the memory.
About box: and about.dfm are used to display information about the program’s version and author’s name.

Ad812.hlp: is a help document that provides information about the data acquisition card in a hypertext format. To run this file properly it must be physically installed in the same area (folder) where the program is installed or in the standard help folder: `\Windows\help`. Figure 5.9 shows the help file “ad812.hlp” when opened.

Fig. 5.9: The contents of the help file

Ad812.dll: is the data acquisition card driver file. It can be installed in the same folder where the program is installed or in the standard system folder `\Windows\system` where all driver files are normally stored.
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Main
InitializeVariables;
updateDisplay;
displayHiltonPower;
switchOffAll;
ExcelOut;
autoScan;

Result

Ad812.pas

The driver functions needed to access the hardware.

Psychrometrics.pas

The driver functions that are needed in this program have been declared and included as prototypes.
RelativeHumidity;
MoistureContent;
SpecificEnthalpy;
MoistureContentRH;
specificEnthalpyRH;
controlChamber;
process1;
process2;
process3;
Procedure
displayHiltonPower;

Control
getVoltage;
getAtmPressure;
getCJCTemperature;
getHiltonCondensatingPressure;
getHiltonEvaporatingPressure;
getHiltonFlowmeter;
switchOnSolenoid;
switchOffSolenoid;
getAirFlow;
getTempArray;
setPreheater;
setReheater;
setHumidifier1;
switchOnPreheater;
switchOffPreheater;
switchOnReheater;
switchOffReheater;
switchOnHumidifier1;
switchOffHumidifier1;
switchOnHumidifier2;
switchOffHumidifier2;
switchOnHumidifier3;
switchOffHumidifier3;
switchOnHumidifier4;
switchOffHumidifier4;
switchOnHumidifier5;
switchOffHumidifier5;
switchOnCooler;
switchOffCooler;
switchOnFan;
switchOffFan;
getWaterLevel;
boilerCheck;
warning(s:string);

Alarm

R12
R12 properties

Fig. 5.10: Functions and procedures
5.3.7 Functions and procedures

Each module has one-problem-related group of functions and procedures as described above. However, a function or a procedure in one module can be called from another module to perform its job. The major functions and procedures are shown in Fig.5.10.

5.4 Implementation

In the implementation phase, alias programming or coding that was produced during design has been turned into code. In this section some important data structures and coding technique will be discussed.

Data structure

Different data structures have been chosen according to their nature and role. Some of the major data structures that have been declared globally⁴ are:

“DsaVoltageArray: array [0..15] of singles⁵” is a one-dimensional array that stores the 16 floating values acquired from all analogue input channels in the data acquisition card. All stored values are in voltage units.

“DasGainArray” is an array [0..15] of words⁶ which is a one-dimensional array that stores the 16 integer values representing the gain codes of every analogue input channel in the data acquisition card.

⁴ Global data are accessible to all functions in the module, but local data can be accessed only by the function that uses it (protected from being accessed by other functions). In addition, local data are cleared from the memory once the function is executed.
⁵ Numbers with a fractional part. Requires four bytes of memory.
⁶ Numbers without a fractional part. Requires two bytes of memory.
“TempArray” is an array \([0..1, 0..15]\) of singles which is a two-dimensional array that stores temperatures acquired from two expansion boards (from 0 to 1) with 16 thermocouples on each board (from 0 to 15). All the stored values are in Celsius units; however this scale can be changed to other units\(^7\). This array is loaded with the average of 20 sequential readings to minimise the effect of any spurious readings.

“DigitalOutput, DigitalInput” are of type word. These two variables are of great importance. They store the current 16-bit digital input and output in order to specify which bits of data will be sent to the digital output port and which bits remains unchanged. “Driver, Cooler, Solenoid, Fan, Preheater, Reheater, Humidifier” are of a type Boolean\(^8\). These stored data are working like flags to declare the equipment status not only for the user but also among themselves. For example the fan will not be switched on unless the Driver is ON, and the Preheater will not be set to any power level over zero unless the Fan is ON.

**Program coding**

Unlike many traditional systems this program application uses event driven coding. Being event driven means that it doesn’t simply execute the code one line at a time until it runs out of instructions. Instead, it waits for events to occur in the program and then executes the code associated with those events. Virtually any action initiated by the user or by the operating system creates an event. For example, some events are: clicking on a button, moving the mouse pointer over an object, selecting an item from a menu and retrieving a file.

---

\(^7\) Kelvin, Rankine, or Fahrenheit

\(^8\) Logic type: True or False, occupies one byte of memory
The code associated with those events is included in the “event handler” which is like any normal procedure but linked to a specific object. A procedure is a subprogram that can be called from another part of the program to perform a particular task. When the button1 is clicked at run-time any code written between: ‘begin’ and ‘end’ in the procedure will execute. User-defined procedures or functions execute within an event handler. The event handler shown in Fig.5.11 executes when the button “ButFan” is clicked. The function “OpenDriver” executes and the returned value is assigned to the variable S. Then if the value of S equals one which means success, the procedure “switchFanOn” will execute; otherwise an error message will be displayed on the screen.

```pascal
Procedure Tform1.ButFan1Click (Sender: TObject):
Begin
  S := OpenDriver;
  If S = 1 then switchFanOn else ShowMessage( Error );
End;
```

Fig.5.11: Example for an event handler

### 5.5 Testing and maintenance

In fact, the system-testing phase began at the first step in the design phase and has been carried out during the implementation phase itself. Interweaving of the testing phase with the implementation phase ensures that the system quality is built-in rather than added-on.

Since the system has become operable, anything that happens to it from then on is called maintenance. Because this system

---

9 The difference between a procedure and a function is that a function returns a value and a procedure does not.
has been created in an object environment it is normally easy to maintain because object coding is written in simple language structures easy to understand and maintain. For example a line of code “FormMain.LabelPressure.caption.font.size:=10” explains its content even to non-programmers. In addition, partitioning the system into a number of manageable black boxes represented by the different modules has reduced system complexity.

5.6 Internal quality factors

The quality of this software design has been evaluated using the following criteria (Meiler, 1988):

a) Correctness & Verifiability:

This program is able to perform its basic tasks as follows:

1. Monitoring the psychrometric conditions inside the Hilton rig, the model building, and the environmental chamber.
2. Controlling the environmental chamber equipment to achieve and maintain a predefined psychrometric condition
3. Performing energy balance analyses in the preheater, cooling coil and the reheater stations in the Hilton rig.
4. Showing the different air conditioning processes on an on-screen psychrometric chart.
5. Providing file saving and printing services for the all acquired data.
b) Modularity:

Modularity is one of the fundamental principles of a good structured design. In this project, the system is partitioned in a way that keeps each module as independent as possible. As discussed above, each module has one-problem-related functions. Although this way increased the number of files used it has increased the maintainability and the extendibility of the system.

c) Robustness:

Although this application is not quite a commercial product, it has significant ability to function even in abnormal circumstances. If it were a fully commercial application, more attention would be paid to such issues as more error trapping. However this would increase the size of the listing and make it more difficult to document.

d) Extendibility:

This application is easy to adapt to any changes in the facility in the future just by creating the virtual additional objects that represent the new extension. Possible additional objects might be expansion data acquisition boards or new air conditioning equipment.

e) Reusability:

Many functions and objects in this application can be reused in whole or in part, for new applications. The module “Alarm” can be reused in other programs to display an alert message that
can be customised. Also, the modules “Psychrometrics” and “R12 can be reused easily in any other related application.

f) Portability:

This program is easy to transfer to other platforms such as Windows NT. It can be transferred to other hardware taking into consideration that it has been written to a specific data acquisition card which is PCL-812PG. A data acquisition card should be installed and configured with the right base address.

5.7 Additional features of the programming approach

In addition to the above quality factors an attempt has been made to achieve a programming style which could be used as guidelines in future studies on the facility. Steps that have been taken include:

a) Objects are created at run time to decrease memory overhead, however it takes more time to be created. Freeing objects after finishing work with it is also considered a good programming practice. It avoids running the risk of memory leaks and the associated problems that can be produced.

b) Functions and data variables have been given meaningful names.

c) Windows API messaging has been used effectively rather than creating new message boxes and forms.

d) The energy balance charts are linked to the acquired data to show dynamically the energy change in the heating stations.

e) The result file is saved in a standard MS Excel format; however data are first acquired and loaded in an embedded (not linked) spreadsheet component. This component is a
third party product (Formula One®, Visualcomp, Inc.) that has been added to Delphi’s visual components library.

f) Printing service has been provided using standard page set-up, printer options, and printing dialogues. This utility allows choosing different printers on the network at run time.

g) OLE automation technology has been implemented effectively to create a psychrometric chart, which can be edited, printed or saved from within MS Excel environment.

h) Minimising the number of the global variables because they are static and occupy memory locations during program run time. Also, because they are accessible for more than one function, they are unprotected.

i) Many functions and modules have been created and are available to be used in other future applications.

Closure

In this chapter, the development of the software to control the data acquisition system has been described. The whole software project including the execution program and the source files with all the necessary explanatory comments have been included in the accompanied CD-ROM. The contents of this CD-ROM are listed in Appendix E.

It should be noted that although this application is a ‘stand alone’ program it has been developed to communicate with a specific electronic hardware components which means that it might not run properly unless the data acquisition card is fitted in the computer.

In the next chapter, some sample results from different experimentation runs will be presented.
Chapter 6

RESULTS AND SPECIMEN CALCULATIONS

6.1 Introduction

An air conditioning process determines the change in thermodynamic properties of moist air between its initial and final states. It also determines the corresponding energy and mass transfer between the moist air and a medium (such as a refrigerant or the moist air itself) during this change.

In this chapter, different air conditioning processes are highlighted and some experimental results and specimen calculations are presented after fixing the airflow rate value in the following section.

6.2 Mass airflow rate measurement

In order to study energy transfer processes, it is necessary to get the right value of the airflow rate. In its original
configuration, the Hilton rig was operating alone as shown in Fig.6.1. In order to keep the Hilton rig as compact as possible, it was not possible to provide the necessary length of straight duct before the inlet orifice for a standard flow rate formula to apply. Hence, the calculation of inlet airflow rate used the inlet orifice pressure drop in a formula provided by the Hilton rig’s operating manual.

Later, due to the modifications made to the Hilton rig, the original formula in Hilton rig operating manual was no longer valid. This section shows the different methods used to determine the new airflow rate after the modifications.

a) Orifice flow measurement

In the first modification made to the Hilton rig air intake, a supply duct was built to connect between the environmental chamber and the Hilton intake orifice as shown in Fig.6.2.
With the inlet orifice formula in Hilton rig operating manual no longer valid, calculation of inlet orifice flow was obtained using the return duct orifice which had been calibrated against the inlet orifice before modification. Because the nature of the air entering the return duct orifice was expected to be in a vigorous turbulent state as a result of the fan and bends located directly upstream, effects on the calibration by the modification at the inlet orifice are assumed negligible (Duff, 1996). So, the inlet airflow rate was determined using the return duct orifice as a reference datum.

b) Airflow rate using anemometer traverse method

After the addition of the model building and the associated ducts as shown in Fig.6.3, it became necessary to re-calibrate the return duct orifice.

To obtain the value of the airflow rate, a velocity traverse across the duct cross-section was plotted. Because the velocity varied from point to point over the cross-section of the duct, it was measured at a number of points, so distributed as to give an unbiased average over the rectangular duct cross-section. The rectangular duct cross-section was divided into at least 25
rectangular areas (5 divisions each side). The accuracy is likely to be slightly better when a large number of points are taken.

The simple average of all velocities in the locations shown in Fig.6.4 multiplied by the total duct area, gives the volume airflow rate (Daly, 1985). The flow at the test plane for the measurement was chosen to be as steady and symmetrical as possible. The calibration result has been included in Appendix D.

A TRISENSE® anemometer was used in this calibration process because the airflow velocity in that duct can be as low as 0.5 m/s which is insufficient for a standard Pitot-static tube to sense. A calibration check on this anemometer has been set up in the test section of the recirculating wind tunnel in the laboratories of the Department of Mechanical Engineering, University of Canterbury, and its accuracy has been found as 5% (Tucker, 2000).
6.3 Energy and mass transfer balance

The energy balance and the mass conservation are the two principles most often used equations in the analysis and calculation of the change of thermodynamic properties in air conditioning processes. Since moist air consists of two components (dry air and water), two mass conservation equations can be used in addition to the conservation of energy equation.

In the generalised analysis approach (Tucker, 1994), the principal airflow enters the control volume at right (State 1) and leaves at left (State 2) as shown in Fig.6.5. In between, there may or may not be transfers of heat (or the heat equivalent of work, such as results from a fan in the air stream) either into or out of the system ($\dot{q}_{1,2}$); and/or transfers of water ($\dot{m}_w$); and/or transfers of air via infiltration/ exfiltration ($\dot{m}_{ai}$) into or out of the system. In this approach, the so-called acquisitive sign convention has been adopted in which any of these additional transfers which are deposits into the system are taken as being
positive. Under the steady flow conditions being considered, conservation of dry air mass requires that:
\[ \dot{m}_{a1} + \dot{m}_{ai} = \dot{m}_{a2} \] ......................................................... (6.1)

Conservation of water mass requires that:
\[ \dot{m}_{a1} W_1 + \dot{m}_{ai} W_i + \dot{m}_w = \dot{m}_{a2} W_2 \] ........................................... (6.2)

The steady flow energy equation, neglecting kinetic and potential energy changes, conservation of energy requires that:
\[ \dot{m}_{a1} h_1 + \dot{m}_{ai} h_i + \dot{m}_w h_w + q_{1,2} - P = \dot{m}_{a2} h_2 \] ............ (6.3)

### 6.4 Experimental results and specimen calculations

All the processes in the Hilton rig are treated as steady flow processes with insignificant change of kinetic and potential energy. Each station of the Hilton rig is treated as an open system. The order of the air conditioning processes is shown in Fig.6.7.

---

**Fig.6.6: The different air conditioning processes in the Hilton rig**

1. Adiabatic mixing zone o-r-m
2. Sensible preheating m-sh
3. Humidifying m-sh
4. Sensible cooling and/or dehumidifying sh-sc
5. Sensible Reheating and mechanical work done by fan sc-sf
6. Space conditioning process s-r.
6.4.1 Adiabatic mixing of two moist air streams

The process of mixing two moist airstreams (having different air states) occurs frequently in air conditioning systems. Common examples include: the mixing of hot and cold airstreams just prior to room entry to achieve the desired supply state suitable for the prevailing loads on the space; the mixing of fresh outside air (for ventilation purposes) with a flow of air re-circulated from the conditioned space. In such instances the great bulk of the energy exchange occurs between the two airstreams rather than by heat transfer through the ducts walls so that the mixing process may be treated overall as being adiabatic (Tucker, 1994). In a two-stream adiabatic mixing process shown in Fig.6.6, two moist airstreams are mixed together, forming a uniform mixture in a mixing chamber.

Applying the three conservation principles on Eq.6.1, Eq.6.2, and Eq.6.3, requires that:

\[
\begin{align*}
\dot{m}_{a1} + \dot{m}_{a2} &= \dot{m}_{a1} \\
\dot{m}_{a1} W_1 + \dot{m}_{a2} W_2 &= \dot{m}_{a3} W_3 \\
\dot{m}_{a1} h_1 + \dot{m}_{a2} h_2 &= \dot{m}_{a3} h_3
\end{align*}
\]

Fig.6.7: Adiabatic mixing of two airstreams
Adiabatic mixing occurs in Hilton rig when the inlet fresh air measured at the inlet orifice is mixed with the re-circulated airflow.

**Acquired data:**

\[
\begin{align*}
\dot{m}_{a3} &= 0.144 \text{ kg/s} \\
\dot{m}_{a1} &= 0.087 \text{ kg/s} \\
t_1 &= 19.9^\circ\text{C} \\
t_{w1} &= 12.4^\circ\text{C} \quad \text{1} \\
t_2 &= 29.3^\circ\text{C} \\
t_{w2} &= 21.2^\circ\text{C} \\
t_3 &= 23.5^\circ\text{C} \\
t_{w3} &= 16.2^\circ\text{C}
\end{align*}
\]

From \( t_1, t_{w1} \rightarrow h_1 = 34.92 \text{ kJ/kg} \)

From \( t_2, t_{w2} \rightarrow h_2 = 61.24 \text{ kJ/kg} \)

From \( t_3, t_{w3} \rightarrow h_3 = 45.20 \text{ kJ/kg} \)

**Calculated results**

\[
\begin{align*}
\dot{m}_{a2} &= \dot{m}_{a3} - \dot{m}_{a1} \\
&= 0.144 - 0.087 \\
&= 0.057 \text{ kg/s}
\end{align*}
\]

The ratio between the two air streams:

\[
\left( \frac{\dot{m}_{a1}}{\dot{m}_{a2}} \right)_{\text{mass-based}} = \frac{0.087}{0.057} = 1.526 : 1
\]

This ratio is based on the direct measurement of the air mass flow rate quantities in each duct.

---

1 All wet bulb values include correction, as per Appendix D
On the psychrometric chart generated from the corresponding measurements of dry and wet bulb temperatures:

\[
\left( \frac{m_{a1}}{m_{a2}} \right)_{\text{state-based}} = \frac{23}{13} = \frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1}
\]

Thus \( \frac{\Delta h_{23}}{\Delta W_{23}} = \frac{\Delta h_{31}}{\Delta W_{31}} \)

But \( \frac{\Delta h_{23}}{\Delta W_{23}} \) is the slope of the condition line \( 23 \)

While \( \frac{\Delta h_{31}}{\Delta W_{31}} \) is the slope of the condition line \( 31 \)

i.e. the lines \( 23 \) and \( 31 \) have the same slope and, since the Point 3 is common to both, it follows that \( 132 \) should be a straight line. Hence, the Point 3 (the resultant mixed state) should lie on the straight line which joins the two initial air states 1 and 2.

The air mass flow rate ratio based on the air state measurements then can be calculated as follows:

\[
\left( \frac{m_{a1}}{m_{a2}} \right)_{\text{state-based}} = \frac{23}{13} = \frac{h_2 - h_3}{h_3 - h_1}
\]

\[
= \frac{61.24 - 45.2}{45.2 - 34.92} = \frac{16.02}{10.28} = 1.657 : 1
\]

This ratio is derived from psychrometric calculations based on measurements of six temperatures (dry and wet-bulb temperatures of all three air states) whereas the earlier
calculations of the same ratio was derived from measurements of two air mass flow rates.

Purely on the basis of the number of the errors associated with each case, the earlier value for the ratio (1.526:1) has been chosen as the “correct” value because it is associated primarily with the TRISENSE calibration error (in measuring the airflow rate). But the other ratio is based on accumulated errors from six different temperatures measurement.

\[
\text{Percentage of discrepancy} = \frac{1.657 - 1.526}{1.526} \times 100\% = 8.6\%
\]

Fig.6.8: Adiabatic mixing of two moist air streams

It should be noted that the three measured air states, when transposed into the h-W co-ordinate system of the psychrometric chart, appear to be on a straight line (see Fig.6.8). Since this should be the case for true adiabatic mixing, this gives
confidence in the accuracy of the data acquisition system and the psychrometric calculations which lie behind the representation of the measured states on the chart.

### 6.4.2 Sensible heating process

A sensible heating process occurs when the moist air flows through the electric heating element in the preheating station, in which heat is transferred from the heating element to the moist air resulting in an increase in its temperature, while its humidity ratio remains constant as illustrated in Fig.6.9. Application of the three conservation principles in Eq.6.1, Eq.6.2, and Eq.6.3 requires that:

\[
\begin{align*}
\dot{m}_{a1} &= \dot{m}_{a2} = \dot{m}_a \\
W_1 &= W_2 = W \\
\dot{m}_a h_1 + q_{1,2} &= \dot{m}_a h_2
\end{align*}
\]

**Acquired data:**

\[
\begin{align*}
\dot{m}_a &= 0.146 \text{ kg/s} \\
I &= 4.7 \text{ A} \\
E &= 232 \text{ V}
\end{align*}
\]
\[ t_1 = 16.5^\circ C \]
\[ t_{w1} = 11.0^\circ C \]
\[ t_2 = 23.5^\circ C \]
\[ t_{w2} = 13.8^\circ C \]

From \( t_1, t_{w1} \rightarrow h_1 = 31.56 \text{ kJ/kg} \)

From \( t_2, t_{w2} \rightarrow h_2 = 38.5 \text{ kJ/kg} \)

**Calculated results**

Air enthalpy change rate \( \dot{H} \)

\[
\dot{H} = \dot{m}_a (h_2 - h_1) \\
= 0.146 (38.5 - 31.5) \\
= 1.022 \text{ kW}
\]

Heat transfer rate \( \dot{q}_{1,2} = E \times I \)

\[
\dot{q}_{1,2} = 232 \times 4.7 \\
= 1.090 \text{ kW}
\]

Power discrepancy

\[
\dot{q}_{1,2} - \dot{H} \\
= 1.090 - 1.022 \\
= 0.068 \text{ kW}
\]

The percentage of the discrepancy:

\[
\frac{0.068}{1.090} \times 100 \% \\
= 6.2 \%
\]

The value for the deposited power (1.090 kW) has been chosen as the “correct” value for determining the percentage of discrepancy based on the fact that the uncertainties associated with the current and voltage measurements (see section 4.2.3) are less than the uncertainties associated with the temperature measurements. For example, an uncertainty value of ±0.5°C in
measuring a single temperature value can result in ±1kJ/kg uncertainty of the airflow enthalpy.

6.4.3 Humidifying process

Humidification is used in winter in cold climates where the outside air would have unacceptably low relative humidity by the time it has been heated up to an indoor dry bulb temperature. Water vapour is added to increase the humidity ratio of the initial moist air-state using different systems such as dry saturated steam injection; direct injection of liquid water; or using an air washer with directly recirculated water.

The humidifying process in this project is performed using the dry saturated steam injection method, where steam is supplied from a boiler to a pipe grid where it is injected directly into the air through small nozzles as shown in Fig.6.11.
The three conservation principles in Eq.6.1, Eq.6.2, and Eq.6.3 require that:

\[ m_{a1} = m_{a2} = m_a \]
\[ m_w = m_a (W_2 - W_1) \]
\[ m_w h_w = m_a (h_2 - h_1) \]

The change in enthalpy between the initial state and the final state \((h_2 - h_1)\) divided by the corresponding change in humidity ratio \((W_2 - W_1)\) is called the **enthalpy-moisture ratio**:

\[ \frac{\Delta h}{\Delta W} = \frac{h_2 - h_1}{W_2 - W_1} = h_w \]

This enthalpy-moisture ratio \(h_w\) represents the slope \((q')\) of the process line connecting states 1 and 2 on the psychrometric chart (since the psychrometric chart is constructed in an \(h-W\) coordinate system).

When air is humidified at constant dry bulb temperature, the steam added must have a specific enthalpy equal to that of
saturated steam at the air dry-bulb temperature. If water at the air thermodynamic wet-bulb temperature is added, the entering and leaving air wet-bulb temperatures must be identical.

The following are the three basic humidification condition lines as shown in Fig.6.12:

1) The process exactly follows the dry-bulb temperature line 1\(\rightarrow\) 2 if \(h_w\) of the injected steam equals to \(h_g\) corresponding to the DBT of the air.

2) If \(h_w > h_g\) the process line inclines to the right side, as the air will be heated as well as humidified, as represented by the line 1\(\rightarrow\) 2\(^*\).

3) If \(h_w < h_g\), the air will be cooled during the process of humidification as represented by the line 1\(\rightarrow\) 2\(^*\).
Acquired data:  \[ \dot{m}_a = 0.144 \text{ kg/s} \]
\[ I = 8.0 \text{ A} \]
\[ E = 230 \text{ V} \]
\[ t_1 = 22.7^\circ\text{C} \]
\[ t_{w1} = 15.4^\circ\text{C} \]
\[ t_2 = 24.6^\circ\text{C} \]
\[ t_{w2} = 19.2^\circ\text{C} \]

From \( t_1, \ t_{w1} \rightarrow \)  \[ h_1 = 43.25 \text{ kJ/kg} \]
\[ W_1 = 0.0080 \text{ kg}_w/\text{kg}_a \]

From \( t_2, \ t_{w2} \rightarrow \)  \[ h_2 = 54.80 \text{ kJ/kg} \]
\[ W_2 = 0.0118 \text{ kg}_w/\text{kg}_a \]

Assuming saturated steam at 100°C, 101.3kPa is generated from water feed at 10°C gives the following:

Saturated steam enthalpy  \( h_s = 2675.8 \text{ kJ/kg} \)
Saturated water enthalpy  \( h_w = 42 \text{ kJ/kg} \)

Calculated results

Air enthalpy change rate  \( \dot{H} \)
\[ = \dot{m}_a (h_2 - h_1) \]
\[ = 0.144 (55.0 - 43.25) \]
\[ = 1.692 \text{ kW} \]

Heat transfer rate into the boiler  \( \dot{q}_s \)
\[ = E \times I \]
\[ = 1.840 \text{ kW} \]

Deduced heat losses (\( \dot{q}_{loss} = \dot{q}_s - \dot{H} \))
\[ = 0.148 \text{ kW} \]
Moisture mass balance:

Moisture increase in the airflow \( \dot{m}_v \)
\[
\dot{m}_v = m_a (W_2 - W_1)
\]
\[
= 0.144 (0.0118 - 0.0080)
\]
\[
= 0.0005472 \text{ kg/s}
\]

Evaporation rate at the boiler \( \dot{m}_w \)
\[
\dot{m}_w = \frac{\text{Net heat input rate into the boiler}}{\text{Enthalpy increase of the water}}
\]
\[
= \frac{\dot{q}_s - \dot{q}_{\text{loss}}}{h_s - h_w}
\]
\[
= \frac{1.840 - 0.148}{2675.8 - 42}
\]
\[
= 0.0006424 \text{ kg/s}
\]

Mass flow discrepancy = \( \dot{m}_w - \dot{m}_v \)
\[
= 0.0006424 - 0.0005472
\]
\[
= 0.0000952 \text{ kg/s}
\]

The percentage of the discrepancy:
\[
= \frac{0.0000952}{0.0006424} \times 100 \%
\]
\[
= 14.8 \%
\]

In the same manner, the value for the deposited water mass flow rate (0.0006424 kg/s) has been chosen as the “correct” value for determining the percentage of discrepancy, again because the uncertainties associated with it are less than the uncertainties associated with the air temperature measurements. The line 12 on the generated psychrometric chart shown in Fig.6.13 represents this humidifying process.
6.4.4 Cooling/dehumidifying process

Fig. 6.14: Illustration of cooling/dehumidifying device

Fig. 6.13: Humidifying and heating process on a psychrometric chart generated by the software
In this project, a direct expansion DX-coil in which refrigerant evaporates directly inside the coil’s tubes is used in cooling/dehumidification process. If the airflow is cooled below its dew point, condensation of moisture will occur. The numerical value of the quantity $q_{1,2}$ will be negative since heat is removed from the air as shown in Fig.6.14. The conservation principles in Eq.6.1, Eq.6.2, and Eq.6.3 require that:

$$
\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a $$

$$
\dot{m}_w = \dot{m}_a (W_2-W_1) $$

$$
\dot{m}_w h_w + \dot{q}_{1,2} = \dot{m}_a (h_2-h_1) $$

Neglecting energy of condensate ($\dot{m}_w h_w = 0$) gives:

$$
\dot{q}_{1,2} = \dot{m}_a (h_2-h_1) $$

**Assumptions for simplification:**

1) The throttling process is adiabatic.

2) The enthalpy of sub-cooled liquid refrigerant entering the expansion valve equals $h_f$ at saturation liquid temperature $\theta$.

3) The isotherms in the liquid region are close to vertical lines as shown in Fig.6.15 on the p-h diagram for R12.

![Fig.6.15: Illustration of a simplified p-h diagram for R12](image-url)
Acquired data:
Atmospheric pressure \( \dot{m}_a \) = 101.3 kPa
Air mass flow rate \( \dot{m}_a \) = 0.146 kg/s
Refrigerant flow rate \( \dot{m}_r \) = 0.0128 kg/s
Water condensate rate \( \dot{m}_w \) = immeasurably small

\[
\begin{align*}
  t_1 & = 23.5 ^\circ C \\
  t_{w1} & = 13.8 ^\circ C \\
  t_2 & = 13.1 ^\circ C \\
  t_{w2} & = 9.5 ^\circ C
\end{align*}
\]

From \( t_1, t_{w1} \rightarrow h_1 \) = 38.5 kJ/kg
From \( t_2, t_{w2} \rightarrow h_2 \) = 28.0 kJ/kg

Superheated vapour refrigerant enthalpy at \( \Theta = 191.97 \) kJ/kg
Saturated liquid refrigerant enthalpy at \( \Theta = 62.93 \) kJ/kg

Calculated results
Air enthalpy change rate \( \dot{H} \) = \( \dot{m}_a (h_2 - h_1) \)
\[
\begin{align*}
  & = 0.146 (28 - 38.5) \\
  & = -1.53 \text{ kW}
\end{align*}
\]

Heat transfer rate via refrigerant \( \dot{q}_{1,2} \)
\[
\begin{align*}
  & = -\dot{m}_r (h_{r1} - h_{r3}) \\
  & = -0.0128 (191.97 - 62.94) \\
  & = -1.65 \text{ kW}
\end{align*}
\]

\footnote{The fact that there was no measurable condensate flow from the coil indicates that the process was one of sensible cooling. This implies that the dew-point temperature of the on-coil air state was below the surface temperature of the cooling coil. In almost all typical cooling coil applications some dehumidification would occur.}
Power discrepancy \( = \dot{q}_{1,2} - \dot{H} \)
\( = -0.12 \text{ kW} \)

The percentage of the power discrepancy:
\( = \frac{0.12}{1.65} \times 100 \% \)
\( = 7.27 \% \)

The value of the power withdrawn via the refrigerant (1.65kW) has been chosen as the “correct” value for determining the percentage of discrepancy because the uncertainties in measuring the refrigerant pressures (see Section 4.2.4), hence the refrigerant enthalpy, are less than those associated with the air temperature measurements.

The line \( \overline{12} \) on the generated psychrometric chart shown in Fig.6.13 represents this cooling process.

![Psychrometric Chart](image-url)

**Fig.6.16: Cooling process on a psychrometric chart generated by the software**
Chapter 6: Results and specimen calculations

The previous calculations of the thermodynamic properties for the refrigerant are based on the thermodynamic formulation presented by Stewart et al. (1986). The file “R12.pas” contains the functions necessary to automate the calculations of the refrigerant thermodynamic properties.

The datum state used in ASHRAE formulations is +200 kJ/kg at 0°C. This datum has been changed in the software to the value 0 kJ/kg at temperature –40°C. Thus, properties values have been kept consistent with the “Tables of Thermodynamic Properties of Fluids” prepared by the Department of Mechanical Engineering, University of Canterbury 1996.

6.4.5 Sensible reheating and mechanical work input

In this process work is transferred by the fan into the system and a sensible heating process occurs as well in the same way as in the preheating station. The result is an increase in the airflow temperature, while its humidity ratio remains constant.

![Diagram of sensible heating and work transfer](image)

Fig.6.17: Illustration of sensible heating and work transfer
The conservation equations require that:

\[ \dot{m}_{a1} + \dot{m}_{a2} = \dot{m}_a \]

\[ W_1 = W_2 = W \]

By the steady flow energy equation (using Engineering Thermodynamics Sign convention),

\[ \dot{q} - ( - P ) = \dot{m}_a (h_2 - h_1) \]

**Acquired data:**

- \( \dot{m}_a = 0.144 \text{ kg/s} \)
- \( I_f = 0.6 \text{ A} \)
- \( I_r = 7.1 \text{ A} \)
- \( E = 230 \text{ V} \)
- \( t_1 = 24.5^\circ\text{C} \)
- \( t_{w1} = 19.8^\circ\text{C} \)
- \( t_2 = 36.2^\circ\text{C} \)

from \( t_1, t_{w1} \rightarrow W = 0.0105 \)

thus from \( W \rightarrow C_p = 1.005 +1.84 \text{ W} \)

\[ = 1.0243 \text{ kJ/kg}_a \text{ K} \]

where \( C_p \) is the specific heat of moist air.

**Calculated results**

Air enthalpy change rate \( \dot{H} \)

\[ = m (h_2 - h_1) \]

\[ = m C_p (t_2 - t_1) \]

\[ = 0.144 \times 1.0285 \times (36.2 - 24.5) \]

\[ = 1.733 \text{ kW} \]
Chapter 6: Results and specimen calculations

Total energy transfer rate $\dot{q}_t$

$$\dot{q}_t = \dot{q} - (-P)$$
$$= E I_r - (- E I_f)$$
$$= E (I_r + I_f)$$
$$= 230 \times 7.7$$
$$= 1.771 \text{ kW}$$

Power discrepancy

$$\dot{q}_t - \dot{H}$$
$$= 1.771 - 1.733$$
$$= 0.038 \text{ kW}$$

The percentage of the discrepancy:

$$= \frac{0.038}{1.771} \times 100 \%$$
$$= 2.14 \% \text{ of the power deposited.}$$

The bar graph shown in Fig.6.18 can be printed out while the program is running to show the energy balance in both the preheater and the reheater components. 

Fig.6.18: Illustration chart of the air enthalpy change rate compared to the energy deposit rate in the preheater and the reheater components – generated at run-time.
6.5 Discussion on discrepancies

The discrepancies that have been introduced in the above results can be attributed to different factors. They can be attributed in part to heat losses to the surroundings because the Hilton rig duct and the steam generator are not completely insulated which disturb the adiabatic assumption.

In the cooling process, the discrepancy is also attributed to the non-adiabatic throttling process in the refrigerant circuit which creates some difference of the enthalpy before and after the expansion. Also, the refrigerant entering the expansion valve has been assumed to be at saturation condition, but actually it is at sub-cooled state. The sign of the discrepancy in this cooling process is negative because the change in refrigerant enthalpy is higher than the change in the enthalpy of the air.

Almost certainly, however, the principle source of discrepancy is the accuracy of the measurements, which depends on the accuracy of the calibration of the sensors and the resolution of the measuring devices.

6.6 Space ventilation process

![Diagram of space ventilation process](image)

Fig.6.19: Schematic illustration of space ventilation
Any combination of the previous processes may be made to represent a practical space air conditioning process. Moreover, simulation of ventilation of a room with sensible and latent heat gains can be established as shown in Fig. 6.19.

Adding a heating element can also represent the sensible heat gain in the room, and the latent heat gain can be represented using a simple steam injector such as a kettle for example.

Closure:
In this chapter the results and the specimen calculations have shown how accurately the air-state can be determined at each station. The energy and mass transfer balance have been presented and analysed. Also, the processes have been demonstrated on psychrometric charts.

Following this chapter are the final conclusions about this project, and a discussion about some recommendations for further development.
Chapter 7

CONCLUSIONS & RECOMMENDATIONS

7.1 Introduction:

The primary objective was to set up a computer-controlled monitoring system able to monitor the psychrometric conditions inside the Hilton rig, the model building, and the environmental chamber with a ‘hoped-for’ accuracy of ±0.2°C. This was not fully achieved because the actual accuracy is only up to ±0.5°C. The errors associated with the complete temperature measuring system are the main cause of why this primary objective was not fully achieved. It could not be possible to carry out a calibration process for all the thermocouples mounted in the rig using a standard method until the noise and the CJC temperature errors have been eliminated first. While an accuracy of ±0.5°C would be considered reasonable in normal building services applications, it falls short of what is desirable in this particular experimental and research facility. At the end of this chapter, there is a detailed discussion about these errors and possible remedies.
The environmental chamber equipment can be controlled using the same computer program to achieve and maintain a predefined psychrometric condition to an accuracy of ±1°C. Again, this falls short of the planned ±0.5°C but this is almost entirely due to temperature measurement inaccuracies referred to already. With improvement in temperature measurement accuracy, improvement in achieving desired psychrometric conditions would follow as a consequence.

Also, the system can carry out energy balance analyses on the preheater, cooling coil and the re heater stations in the Hilton rig showing the different air conditioning processes on an electronic psychrometric chart and providing file saving and printing services for all the acquired data.

A laboratory experimental air conditioning system has been built up to model processes likely to be met in an air conditioning plant where psychrometric conditions are monitored and controlled, and the energy transfers are evaluated.

As a means of providing a complete and realistic air processing environment, and as a secondary objective of this project, a model building has been built up within the environmental control chamber and has been connected to the Hilton rig, which then acts as an air conditioning system for the model building. Thus, the model building is “externally” exposed to a controlled environment representing a desired outdoor air-state. This same “outdoor air-state” would be the fresh air-state utilised by the Hilton system for ventilation purposes. Overall, then, the facility is capable of representing, on a much-reduced scale, a building and its air conditioning system operating within an artificially created and controlled outdoor environment. The necessary
modifications and extensions to the hardware electronics, and the software required to run and control the integrated system have been developed.

Following are general conclusions about this project, a discussion about the associated errors, and recommendations for future work.

7.2 Conclusions

a) The model building

The model building, which simulates the conditioned space, has been equipped with changeable walls to allow different wall constructions and insulation materials to be studied. Its bottom surface has been extended using an attached convoluted surface to increase the amount of heat transfer and consequently creates a significant air conditioning load. At this stage the model building has no internal heat gains but in a future stage sensible and a latent internal heat gains could be added and controlled digitally.

Because the airflow rate inside the Hilton rig is considered low, it has been taken into consideration during the design of the model building to keep the air pressure drop through it as low as possible. The pressure drop in the return duct before adding the model building was 3.5 mm Water Gauge, and now after adding the model building 3.2 mm Water Gauge which indicates that the effect is very small.

Modifications to the environmental control chamber (which controls the outside air state around the model building) have
made its operation more reliable and safer, especially the new electrical arrangement which ensures that the fan is running before switching on the two air heater banks (3 kW each). Furthermore, the airflow pattern within the chamber has been enhanced to enable efficient heat transfer between the air and the model building.

b) The data acquisition electronics

The data acquisition system has been increased to a large extent. Therefore, a new panel has been built up to hold all data acquisition electronics in one appropriate compartment. It has sixteen LED’s fitted on its lid to display the status of the sixteen digital output channels. These LED’s have been very useful in not only learning about digital control but also provide helpful fault diagnosis. The additional sensors for the voltage and the current acknowledge the real-time power consumption, and hence have allowed accurate energy balance analysis. The two multiplexer expansion boards have been used to host 30 thermocouples, thus utilising only two channels on the data acquisition card (compared to thirty).

The solenoid switching system, which is used to alternate pressure measurements from the duct and the inlet orifice using one differential pressure transducer, has proved its functionality. It had been recommended in previous stages to use this technique, and it has been implemented successfully in this project. However the pressure reading needs 6 seconds at least to settle down after each switching but this has no adverse effect on this application. This delay time may be decreased if vented type solenoids were used.
c) The software

More than half of the research time of this project was invested in developing the software program. At the time when this project started, there were some reservations about how such a data acquisition program could be developed in a Windows environment. All software applications that had been developed in the Department were based on a DOS environment. Moreover, at that time, Windows 95 was just released and there were no available examples to follow or to learn from. Nevertheless, the software program has been finally developed in a Windows environment and successfully put into operation. The results have been so encouraging that other researchers in the Department have started seriously to follow this technique.

The software program that has been developed is capable of fulfilling the initial requirements and the intent of its use as follows:

1. Monitoring the different air states in the Hilton rig, the outside air-state (in the environmental control chamber), and the inside air-state (in the model building). This has been achieved through acquiring coincident dry and wet-bulb temperature readings and automatically calculating the values of the other moist air parameters (such as relative humidity and specific enthalpy) by appropriate conversion algorithms.

2. The outside air state can be controlled to be one of three different pre-set conditions (winter, summer, and moderate condition) or, alternatively, any custom condition specified by the user.
Performing heat transfer evaluation and energy balance analysis of the different air conditioning components in the Hilton rig by comparing the air enthalpy change rate against the deposited/withdrawn energy transfer rate to/from the system, and calculating any discrepancy between them. The comparison can be printed out on a bar graph showing the power comparison.

Showing the different psychrometric processes on an on-screen version of psychrometric chart. This has been accomplished by plotting the initial and final air-states (dry, and wet-bulb temperatures) onto a linked Microsoft® Excel file containing the psychrometric chart (Tucker, 1998).

Providing file saving and printing services for the psychrometric chart, energy chart, and all data acquired in an ordinary Microsoft® Excel spread sheet.

The program has the capability of being expanded if new components and data acquisition hardware are added in the future.

d) The associated errors

In experimental work one strives to measure true values and to compute true results from these values. Recognising that rarely, if ever, are true values measured it is necessary to anticipate the uncertainties, which are associated with the measured values and hence the error associated with a computed result. The two fundamental errors associated with the measured data are fixed, and accidental or random errors.
The fixed errors are characteristics of the instruments used (eg. a biased voltmeter, or thermometer) and the operator (eg. parallax in reading the scale). However, although these systematic errors can be eliminated by calibration it is necessary to examine the data for accidental or random errors. The latter often are mistakes while the former often constitute errors inherent in the instruments or the operator. During data sampling several readings are taken at each point and averaged to obtain a best estimate.

In this way the influence of the random errors associated with the sampling are reduced. Also software checking and validation of the data before averaging has been used to eliminate any influence of large random errors.

**7.3 Recommendations**

There is still a lot of work that could be done on this facility. This section outlines some possible future developments.

A cyclic condition profile for modelling the daily or annual condition variations could be added. This would allow tests to be carried out to study the transient thermal behaviour of some building insulating or thermal storage materials.

Further work should be done to develop variable internal sensible and latent heat gains in the model building.

As mentioned before in Chapter 4, further improvement modifications can be done on the variable power controllers of the environmental control chamber. Controlling three 1kW
heating elements will be more reliable and efficient than controlling one 3kW element.

As shown in Fig. 7.1 the range from 0 to 1000 W could be set using the variable power controller alone. When switching on the other relays of the heating elements, variable ranges from 1001 to 2000 W or from 2001 to 3000 W could be achieved. This approach would make the control more smooth and reliable because it would protect the controller TRIAC from high current overheating.

As shown in Fig. 7.1 the range from 0 to 1000 W could be set using the variable power controller alone. When switching on the other relays of the heating elements, variable ranges from 1001 to 2000 W or from 2001 to 3000 W could be achieved. This approach would make the control more smooth and reliable because it would protect the controller TRIAC from high current overheating.

Also, as noted in Chapter 4, the steam generator of the environmental chamber needs to be protected by a circuit breaker which connects the power to the heating elements only if the water level is high enough regardless of whether the software is running or not. The present protection is only activated if the software is running.
In fact, the wet-bulb temperature measurements in the Hilton rig need more attention and investigation. When examining the deviations of the wet-bulb temperature measurements shown in Table D.3, it has been found that those errors can be attributed to different factors. First, the airflow speed in the Hilton rig is not adequately high to obtain a realistic wet-bulb temperature value. Second, although the airflow speed in station ‘A’ shown in Fig.D.11 is higher than 3.5m/s because it is located just after the Vena Contracta, there is still an error. This could be attributed to the large wet-bulb depression (the difference between the dry and the wet-bulb temperatures). Also, those errors can originate where surrounding surfaces are at temperature substantially different from the air dry-bulb temperature such as the water reservoirs of the wet-bulb thermocouples.

Moreover, it has been noticed that the errors are significantly higher in stations ‘B’ and ‘C’. This could be attributed to substantial temperature variation in those regions because the flow is not uniform in those stations which are located just after a sharp bend in the Hilton rig duct.

Because of the underlying principles of wet-bulb thermometer operation there is likely to be a complex dependence of error on:

- Local air velocity
- Wet-bulb temperature depression (i.e. the difference between dry and wet-bulb values)
- The mean radiant temperature of surrounding surfaces which the wet-bulb sensors can “see”.

These influencing factors would be true for any form of wet-bulb sensor in any location.
Additionally, in this particular experimental set-up there has been a significant uncertainty in the indicated wet-bulb temperature due to the manner in which the cold junction reference temperature has been measured (see Section 4.3.1).

Thus, although it might appear to be worthwhile to carry out an experimental mapping of the dependence of the wet-bulb temperature on the three factors listed above, there would be a little point in doing so until the existing CJC problem has been largely overcome.

As well as its benefits for improving wet-bulb temperature measurement accuracy, reducing the CJC problems on the PCLD-889 and PCLD-789D boards would bring about improved accuracy in all the dry-bulb temperature measurements. The ideal approach to terminating the thermocouple connections to the data acquisition system, and knowing the prevailing temperature there, would be to have the terminal block alone in an isothermal enclosure with an accurate temperature sensor (but no other electronic components) within the enclosure. However this might be difficult to achieve in practice if all the other functional capabilities of the existing multiplexer/amplifier boards are to be retained. More practical suggestions are either to place these multiplexer boards into a thermally insulated box or to install an air-circulating fan after re-positioning the transformers to a remote place. This will minimise the effect of the temperature gradient and keep the compartment at a relatively more uniform temperature.

The fixed set of correction factors to the wet-bulb temperatures that the present software utilises are an admittedly crude attempt to overcome that net effect of all the possible error
contributing factors (including the CJC errors). How much each factor contributes to the error cannot be simply resolved and it is possible that if the CJC problem can be largely overcome it may, by itself, result in acceptably small discrepancies in the indicated wet-bulb temperatures. If this were to prove to be the case, the suggested experimental mapping of the sensors characteristics as a function of air velocity, wet-bulb depression and mean radiant temperature would become unnecessary.
REFERENCES

Advantech® User’s Manuals for the following PC Lab Cards:
The Data Acquisition PC Lab Card: PCL-812PG.
The Amplifier Multiplexer Daughter Board: PCLD-789D.
The Amplifier Multiplexer Daughter Board: PCLD-889.

AIRAH HANDBOOK (1995)
The Australian Institute of Refrigeration Air Conditioning and Heating (Inc.) Handbook, 2/e, p1.2.

ASHRAE (1997)
“Handbook of Fundamentals”

“Fundamentals of Temperature, Pressure, and Flow Measurements”
Wiley, N.Y., p71.

Daly, B.B. (1985)
“Woods Practical Guide to Fan Engineering”
**Devasahayam, J.P. Walter (1977)**

“Elements of Comfort Air Conditioning”

**Duff, C.W. (1996)**

“Data Acquisition System for the Refrigeration Unit on the Hilton A770 Air Conditioning Rig”
Final Year Research Project report, Department of Mechanical Engineering, University of Canterbury.


“Data Acquisition System for the Hilton A770 Air Conditioning Unit”
Final Year Research Project report, Department of Mechanical Engineering, University of Canterbury.


“Experimental Operating & Maintenance Manual for Recirculating Air Conditioning Unit A770”

**IRHACE (1999)**

Industry Directory & Yearbook August 1999, p80.
The official journal of Institute of Refrigeration, Heating, and Air Conditioning of New Zealand Inc. (IRHACE) and refrigeration air conditioning companies association (RACCA).

**Irvin, T.F. & Lily, P.E (1972)**

“Steam and Gas Tables with Computer Equations”


“Thermal Environmental Engineering”
“Design and Control of an Environmental Control Chamber for Air Conditioning Experimentation”
Master Thesis, Department of Mechanical Engineering, University of Canterbury.

Meiler, P. J. (1988)
Yourdon Press Computing Series, New Jersey, 2/e, p57.

NZS 4214 (1977)
“Methods of Determining the Total Thermal Resistance of Parts of Buildings”
New Zealand Standard, p19,
Standards Association of New Zealand, Wellington, NZ.

“Data Acquisition and Process Control Using Personal Computers”
Marcel Dekker, Inc. N.Y., p180.

“Data Acquisition System for the Refrigeration Unit on the Hilton A770 Air Conditioning Rig”
Final Year Research Project report, Department of Mechanical Engineering, University of Canterbury.

Rogers, Paul (1997)
“Optimisation of Air Conditioning Systems in Commercial Buildings”

Sensym® (1994)
“Solid State Pressure Sensors Handbook”
Sensym Inc., Milpitas, California.
Sommerville, I. (1992)
“Software Engineering”

“Thermodynamic Properties of refrigerants”

Tables of Thermodynamic Properties of Fluids (1996)
Thermo-fluid Group, Department of Mechanical Engineering,
University of Canterbury.

Threlkeld, J.L. (1970)
“Thermal Environmental Engineering”
Prentice-Hall, New Jersey, 2/e, p171.

“Heat and Mass Transfer”
Course Notes ENME435, Department of Mechanical Engineering,
University of Canterbury.

“On-Screen Psychrometric Chart”
Psychrometric Software developed in the Department of Mechanical Engineering, University of Canterbury.

Personal communication.
APPENDIX A

PSYCHROMETRIC CALCULATIONS

This Appendix includes the calculation steps followed to obtain some of the moist air properties such as the humidity ratio, relative humidity, and the specific enthalpy, providing that the dry and wet bulb temperatures are determined.

The amount of water vapour in moist air varies from zero to a maximum, which depends on temperature and pressure. The maximum condition refers to saturation, a state of neutral equilibrium between moist air and the condensed water phase. Principally the water vapour saturation pressure is required to calculate the saturation humidity ratio as a first step in determining the moist air properties.

The value of the water vapour saturation pressure can be calculated from the following formula (Irvine & Liley 1972), noticing that starred quantities are evaluated at wet bulb temperature ($T_s = t^*$):

$$\text{LOG}(p_{ws}^*) = \sum_{N=0}^{9} A(N)T_s^N + \frac{A(10)}{T_s - A(11)} \quad \text{........................ (A.1)}$$

where

\[ p_{ws}^* \text{ Water vapour pressure at saturation for WBT.} \]
\[ A(N) \text{ Constants} \]
\[ T_s \text{ Saturation temperature} \]
The defining equation for wet-bulb temperature is obtained from an energy balance (Threlkeld, 1970) based on unit mass of dry air:

\[ h + (W_s^* - W) h_f^* = h_s^* \] .......................... (A.2)

where \((W_s^* - W)\) kilograms of water, having specific enthalpy \(h_f^*\) evaporate into the air to produce a saturated air state at the same temperature.

Under ideal gas assumptions, equation (A.2) can be re-written in the alternative form:

\[ W (h_g - h_f^*) = W_s^* h_{fg}^* - c_p (t - t^*) \] ................. (A.3)

Now the second step is to determine the humidity ratio \(W\) from the equation (A.3) given that:

\[
W_s^* = 0.622 \frac{p_w^*}{p_{at} - p_{w_s}} \\
h_f^* = c_{pw} t^* \\
h_f = c_{pw} t \\
h_g^* = 2501 + 1.84 t^* \\
h_g = 2501 + 1.84 t \\
h_{fg}^* = (h_g^* - h_f^*)
\]

where

\(W\) and \(h_g\) (from steam tables) correspond to the dry bulb temperature \(t\).
\(c_p\) is the specific heat of dry air.
\(c_{pw}\) is the specific heat of water.
The relative humidity $\phi$, then can be calculated as follows:

$$\phi = \frac{p_w}{p_{ws}}$$

where

$$p_{ws}$$ is calculated from equation A.1 at $(T_s = t)$

$$p_w = p_{at} \frac{W}{W + 0.622}$$

Then the specific enthalpy $h$ can be calculated from the direct relation:

$$h = h_a + W h_w$$

where

$h_a$ is the specific enthalpy of the dry air component [kJ/kg$_a$].

$h_w$ is the specific enthalpy of the water vapour component [kJ/kg$_w$].
APPENDIX B
Data Acquisition Boards

Switches and Jumper Settings

To perform the specific data acquisition and control tasks, switches on the data acquisition boards are positioned appropriately and jumpers are selected for the specific purposes of this project.

This appendix gives a detailed description of the configuration settings of the data acquisition card PCL-812PG and the two daughter boards PCLD-789D, and PCLD-889.

1. The data acquisition card PCL-812PG

Base Address Selection:
Switch SW1

The I/O port base address for the PCL-812PG is selectable via an eight-positions switch. The PCL-812PG requires 16 consecutive address locations in I/O space.

Table B.1: Base address selection switch SW1 on board PLC-812PG

<table>
<thead>
<tr>
<th>I/O Address</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 – 20F</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>x</td>
</tr>
<tr>
<td>210 – 21F</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>x</td>
</tr>
<tr>
<td>220 – 22F</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>x</td>
</tr>
<tr>
<td>220 – 23F</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>x</td>
</tr>
<tr>
<td>300 – 30F</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>x</td>
</tr>
<tr>
<td>3F0 – 3FF</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>X</td>
</tr>
</tbody>
</table>
The switch settings for various base addresses are illustrated as above in Table B.1. The default base address has been set to hex220 and this setting (highlighted in the table) is what has been used in the project.

**Wait State Selection:**

**Switch SW1**

High speed PC may require wait states to be added to the bus I/O to achieve a stable data transfer. The PCL-812PG can be configured with different wait state delays. The length of the wait state can be selected with the positions 7 and 8 on the base address selection switch SW1 as shown below in Table B.2:

Table B.2: Wait state selection on board PCL-812PG

<table>
<thead>
<tr>
<th>Time Delay</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Since the used PC in the project is high speed, the wait state has been set to the maximum delay time.

**Data Transfer Method Selection:**

The PCL-812PG has the capability to transfer data using direct memory access (DMA), interrupt control (IRQ), or program control. For simplicity and ease of programming, NO DMA has been selected as shown in Fig.B.1.
**Appendix B**

**IRQ Level Selection:**

**Jumper JP5**

The IRQ level has been set to no interrupt as shown in Fig.B.2.

**Trigger Source Selection:**

**Jumper JP1**

The A/D conversion trigger source has been set to internal on-board programmable pacer trigger as shown in Fig.B.3.
User’s Counter Input Clock Selection:
Jumper JP2

The PCL-812PG has a programmable timer/counter. This timer/counter has 3 channels 16 bit counters. Channel 1 and channel 2 are configured as internal pacer. Channel 0 is left for user’s applications. The clock input of channel 0 can be internal 2MHz clock or external clock signal from connector CN5 pin8. As shown in Fig.B.4, the jumper JP2 has been set to external clock signal to count the outside signals from the refrigerant flow meter in the Hilton rig.

D/A Reference Source Selection:
Jumpers JP3, JP4

The reference voltage of D/A converters can be the internal generated −5 or −10 volts or an external reference voltage from connector CN2 pin 17 or pin19. As shown in Fig.B.5, the D/A channels no.1 and no.2 have been respectively set via jumpers JP3 and JP4 on internal source reference.
**D/A Internal Reference Selection:**

**Jumper JP8**

The internal reference voltage can be –5V or –10V. The reference voltage is –5V when the D/A range is 0 to +5V. When the reference voltage is set to –10 Volt the D/A range is 0 to +10V. As shown in Fig.B.6, the jumper JP8 has been set to 5 volts.

![Fig.B.6: D/A reference value selection JP8 on board PCL-812PG](image)

**A/D Maximum Input voltage Selection:**

**Jumper JP9**

The A/D converter range can be set to +/-5V or +/- 10V as shown in Fig.B.7.

![Fig.B.7: A/D converter input voltage range in PCL-812PG](image)

Although the input range can be doubled from 5v to 10V, it is not advisable. Some PC power supplies offer the bias voltage with a voltage less than +12V, eg +11.5V.

![Fig.B.8: D/A input voltage selection JP9 on board PCL-812PG](image)
In this case, the output voltage swing range of the programmable amplifier can not reach +10V and the A/D converter will not be able to make correct measurement if JP9 is set to +/-10V. Therefore the jumper JP9 has been set to +/-5V as shown up in Fig.B.8.

2. The Daughter Board PCLD-789D

This board has been allocated to host the entire environmental chamber and the model building multiplexed thermocouples. The following details describe how it has been configured to serve the particular needs of this project.

**Gain Selection:**

**Switch SW1**

Table B.3: Gain selection switch - SW1 on board PCLD-789D

<table>
<thead>
<tr>
<th>Gain</th>
<th>Switch position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>● ○ ○ ○ ○ ○ ○ ○</td>
</tr>
<tr>
<td>2</td>
<td>○ ● ○ ○ ○ ○ ○ ○</td>
</tr>
<tr>
<td>50</td>
<td>○ ○ ○ ● ○ ○ ○ ○</td>
</tr>
<tr>
<td>100</td>
<td>○ ○ ○ ○ ● ○ ○ ○</td>
</tr>
<tr>
<td>200</td>
<td>○ ○ ○ ○ ○ ● ○ ○</td>
</tr>
<tr>
<td>500</td>
<td>○ ○ ○ ○ ○ ○ ● ○</td>
</tr>
<tr>
<td>1000</td>
<td>○ ○ ○ ○ ○ ○ ○ ●</td>
</tr>
</tbody>
</table>

● = ON  ○ = OFF
The specific amplifier’s gain is selected through an eight-position switch (SW1) called “GAIN”. Table B.3 shows the switch setting and corresponding gain.

Although the user’s manual suggests setting the gain to 50 for K-type thermocouples, it has been set to 1000. Since no one temperature in the project exceeds 100°C, which is considerably low compared to the K-type thermocouple maximum range, using the suggested gain value doesn’t help the signal to be sensed. Therefore the gain value has been set to 1000 to obtain the maximum available resolution.

**CJC Output Channel Selection:**

**Jumper JP1**

The PCLD-789D board provides cold junction compensation (CJC) for the thermocouples by placing a shorting link in JP1. As shown in Fig.B.9, JP1 consists of 10 channels 0 through 9 and an unused position marked “X”. The CJC channel has been chosen as number 8.

![Fig.B.9: CJC output channel selection JP1 on board PCLD-789D](image)

**Analog Output Channel Selection:**

**Jumper JP2**

The PCLD-789D board supports 10 separate jumper-selectable analogue output channels by placing a short link in jumper JP2. The jumper JP2 consists of 10 channels 0 through 9 and an
unused position marked “X”. The assigned channel is number 1 as shown in Fig.B.10.

![Fig.B.10: Analogue output channel selection JP2 on board PCLD-789D](image)

**Low Pass Filter Selection:**

**Jumpers JP5 to JP20**

To reject the unwanted high frequency noise from the low frequency input signals, the PCLD-789 provides low pass filtering on each of the input channels. The Jumpers JP5 through JP20 control the use of the filtering function on different input channels with cut off frequency is 66Hz. As thermocouple signals have low frequencies, all jumpers have been left ON as shown in Fig.B.11.

![Filter ON Filter OFF](image)

**Fig.B.11: Jumpers (JP5 to JP20) on board PCLD-789D**

The low pass filter is constructed with a $1\mu$F capacitor and two $1.2k\Omega$ resistors. The time constant is 2.4msec, ie. the cutoff frequency is 66Hz. This cutoff frequency can be changed by changing the resistors and/or the capacitor. The cutoff frequency ($f$) can be calculated from the equation B.1:

$$f = \frac{1}{2\pi CR} \quad (B.1)$$
where C and R are the values of the capacitor and resistors in the filter network. The easiest way to change the cutoff frequency is to change the resistors. To find the resistor value, the equation B.2 can be used after deciding the required cutoff frequency. It should be noted that resistors values are added together when more than one are used.

\[
R = \frac{1}{2 \times \pi \times C \times f} \quad \text{(B.2)}
\]

**2nd Stage Low Pass Filter Selection:**

**Jumper JP3**

JP3 is a second stage low pass filter to reject the output noise from the PCLD-789D’s amplifier with a cut-off frequency of 310Hz. As the low pass filter has been set to 66Hz, this filter has no effect.

**Power Supply Selection:**

**Jumper JP4**

The PCLD-789D requires both +5V and +12V power supplies for operation. Power can be supplied either from the PC or an external source. In this project, the PC power supply has been used to supply the multiplexer board. The jumper connection JP4 has been set to “Internal” as shown in Fig.B.12.

![Power supply selection jumper JP4](image)

Fig.B.12: Power supply selection jumper JP4
On board PCLD-789D
3. The Daughter Board PCLD-889

This board has been allocated to host the environmental chamber and the model building multiplexed thermocouples. It has almost the same features as the board PCLD-789D with only some small differences. The following details describe how the PCLD-889 board is configured to serve the particular needs of this project.

**Gain Selection:**

**Switch SW2**

Table B.4: Gain selection switch – SW2

<table>
<thead>
<tr>
<th>Switch position</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>● ● ● ○</td>
<td>0.5</td>
</tr>
<tr>
<td>● ● ○ ○</td>
<td>1</td>
</tr>
<tr>
<td>● ○ ● ○</td>
<td>2</td>
</tr>
<tr>
<td>● ○ ○ ○</td>
<td>10</td>
</tr>
<tr>
<td>○ ● ● ○</td>
<td>50</td>
</tr>
<tr>
<td>○ ● ○ ○</td>
<td>100</td>
</tr>
<tr>
<td>○ ○ ● ○</td>
<td>200</td>
</tr>
<tr>
<td>○ ○ ○ ○</td>
<td>1000</td>
</tr>
</tbody>
</table>

The specific amplifier’s gain is selected through a four-position switch (SW2) labelled as “GAIN”. Table B.4 above, illustrates the switch setting and corresponding gain. The gain value has been set to 1000 to obtain the maximum available resolution.
CJC Output Channel Selection:
Jumper JP17

Since one cold junction compensating temperature can be used for both of the expansion boards PCLD-889 and PCLD-789D, then the jumper JP17 on the PCLD-889 has been set to “X” as shown in Fig.B.13.

Analog Output Channel Selection:
Jumper JP16

The PCLD-889 board supports 10 separate jumper-selectable analog output channels by placing a short link in jumper JP16.

Filter Selection:
Jumpers JP0 to JP15

To reject the unwanted high frequency noise from the low frequency input signals, the PCLD-889 provides low pass filtering
on each of the input channels. The Jumpers JP0 through JP15 control the use of the filtering function on different input channels. As thermocouples’ signals have low frequency, all jumpers have been placed ON as shown in Fig.B.15.

![Filter ON and Filter OFF](image)

*Fig.B.15: Filter selection JP0 to JP15 on board PCLD-889*

The low pass filter is constructed with one microfarad capacitor and two 1.2k ohm resistors. The time constant is 2.4msec, ie. the cutoff frequency is 66Hz. This cutoff frequency can be changed by changing the resistors and/or the capacitor.

**Power Supply Selection:**

**Jumper JP18**

![External and PC](image)

*Fig.B.16: Power selection jumper JP18 on board PCLD-889*

The PCLD-889 requires both +5V and +12V power supplies for operation. Power can be supplied either from the PC or an external source. In this project, as shown in Fig.B.16, the PC power supply has been used and the jumper connection JP18 has been set to “PC”.
APPENDIX C
Data Acquisition Boards

Input and Output Channels

The following tables include the assignment of the data acquisition boards channels inputs and outputs.

1. The Data Acquisition Card PCL-812PG

Table C.1: Analogue input channels into the board PCL-812PG

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Daughter board PCLD-889, Multiplexed thermocouples</td>
</tr>
<tr>
<td>1</td>
<td>Daughter board PCLD-789D, Multiplexed thermocouples</td>
</tr>
<tr>
<td>2</td>
<td>Evaporative pressure, Hilton rig cooling unit</td>
</tr>
<tr>
<td>3</td>
<td>Condensing pressure, Hilton rig cooling unit</td>
</tr>
<tr>
<td>4</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td>5</td>
<td>Airflow pressure drop, Hilton rig</td>
</tr>
<tr>
<td>6</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>--</td>
</tr>
<tr>
<td>8</td>
<td>Cold junction temperature</td>
</tr>
<tr>
<td>9</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>Voltage sensor, Hilton rig preheater and reheater</td>
</tr>
<tr>
<td>11</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>Airflow pressure drop, Environmental chamber</td>
</tr>
<tr>
<td>14</td>
<td>Current sensor, Hilton rig preheater</td>
</tr>
<tr>
<td>15</td>
<td>Current sensor, Hilton rig reheater</td>
</tr>
</tbody>
</table>

Table C.2: Analogue output channels from the board PCL-812PG

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Variable power controller boards</td>
</tr>
<tr>
<td>1</td>
<td>--</td>
</tr>
</tbody>
</table>
### Table C.3: Digital output channels
Into the board PCL-812PG

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reserved for controlling the multiplexers of the daughter boards</td>
</tr>
<tr>
<td>1</td>
<td>1.5kW heating element, environmental chamber humidifier 1</td>
</tr>
<tr>
<td>2</td>
<td>3kW heating element, environmental chamber preheater</td>
</tr>
<tr>
<td>3</td>
<td>3kW heating element, environmental chamber reheater</td>
</tr>
<tr>
<td>4</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>Switching solenoids, Hilton rig airflow sampling</td>
</tr>
<tr>
<td>6</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>3kW heating element, environmental chamber humidifier (2)</td>
</tr>
<tr>
<td>8</td>
<td>1.5kW heating element, environmental chamber humidifier (3)</td>
</tr>
<tr>
<td>9</td>
<td>1.5kW heating element, environmental chamber humidifier (4)</td>
</tr>
<tr>
<td>10</td>
<td>3kW heating element, environmental chamber humidifier (5)</td>
</tr>
<tr>
<td>11</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>1.5kW heating element, environmental chamber humidifier (6)</td>
</tr>
<tr>
<td>13</td>
<td>3kW heating element, environmental chamber humidifier (7)</td>
</tr>
<tr>
<td>14</td>
<td>Fan, environmental chamber</td>
</tr>
<tr>
<td>15</td>
<td>Evaporative cooling unit, environmental chamber</td>
</tr>
</tbody>
</table>

### Table C.4: Digital input channels
Into the board PCL-812PG

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>‘High’ water level, environmental chamber steam generator</td>
</tr>
<tr>
<td>2</td>
<td>‘Low’ water level, environmental chamber steam generator</td>
</tr>
<tr>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>--</td>
</tr>
<tr>
<td>6</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>--</td>
</tr>
<tr>
<td>8</td>
<td>Refrigerant flow metre, Hilton rig cooling unit</td>
</tr>
<tr>
<td>9</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>--</td>
</tr>
<tr>
<td>11</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>--</td>
</tr>
<tr>
<td>15</td>
<td>--</td>
</tr>
</tbody>
</table>
2. Thermocouple channels assignment of the daughter boards

The board PCLD-889 has been allocated to host the entire environmental chamber and the model building multiplexed thermocouples, and the board PCLD-789D hosts the entire Hilton rig thermocouples. All Thermocouples have been labelled with the letter T appended by three digits in the form (T###). The first digit after the letter T represents the Board number (from 0 to 1), and the next two digits represent the channel number (from 0 to 15). Therefore, the thermocouples hosted by the board PCLD-889 are from T000 to T015, and the thermocouples hosted by the board PCLD-789D are from T100 to T115 as shown in Fig.C.1. Tables C.5 and C.6 include the channels assignment of the daughter boards PCLD-889 and PCLD-789D respectively.

Table C.5: Multiplexed thermocouples hosted by the board PCLD-889

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>T000, chamber top DBT</td>
</tr>
<tr>
<td>1</td>
<td>T001, chamber top WBT</td>
</tr>
<tr>
<td>2</td>
<td>T002, chamber bottom DBT</td>
</tr>
<tr>
<td>3</td>
<td>T003, chamber bottom WBT</td>
</tr>
<tr>
<td>4</td>
<td>T004, chamber mixed air (recirculated/fresh) DBT</td>
</tr>
<tr>
<td>5</td>
<td>T005, chamber mixed air (recirculated/fresh) WBT</td>
</tr>
<tr>
<td>6</td>
<td>T006, chamber fresh air DBT</td>
</tr>
<tr>
<td>7</td>
<td>T007, chamber fresh air WBT</td>
</tr>
<tr>
<td>8</td>
<td>T008, chamber top DBT</td>
</tr>
<tr>
<td>9</td>
<td>T009, chamber top WBT</td>
</tr>
<tr>
<td>10</td>
<td>T010, chamber steam generator</td>
</tr>
<tr>
<td>11</td>
<td>T011, chamber evaporator coil</td>
</tr>
<tr>
<td>12</td>
<td>T012, model building inlet after mixing zone DBT</td>
</tr>
<tr>
<td>13</td>
<td>T013, model building inlet after mixing zone WBT</td>
</tr>
<tr>
<td>14</td>
<td>--</td>
</tr>
<tr>
<td>15</td>
<td>--</td>
</tr>
</tbody>
</table>
Table C.6: Multiplexed thermocouples hosted by the board PCLD-789D

<table>
<thead>
<tr>
<th>Channel</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td>T101, Hilton rig intake DBT</td>
</tr>
<tr>
<td>2</td>
<td>T102, Hilton rig intake WBT</td>
</tr>
<tr>
<td>3</td>
<td>T103, Hilton rig mixed (recirculated/fresh) DBT</td>
</tr>
<tr>
<td>4</td>
<td>T104, Hilton rig mixed (recirculated/fresh) WBT</td>
</tr>
<tr>
<td>5</td>
<td>T105, Hilton rig after preheating/humidifying DBT</td>
</tr>
<tr>
<td>6</td>
<td>T106, Hilton rig after preheating/humidifying WBT</td>
</tr>
<tr>
<td>7</td>
<td>T107, Hilton rig after cooling/dehumidifying DBT</td>
</tr>
<tr>
<td>8</td>
<td>T108, Hilton rig after cooling/dehumidifying WBT</td>
</tr>
<tr>
<td>9</td>
<td>T109, Hilton rig recirculated (out from the model building) DBT</td>
</tr>
<tr>
<td>10</td>
<td>T110, Hilton rig recirculated (out from the model building) WBT</td>
</tr>
<tr>
<td>11</td>
<td>T111, Hilton rig refrigerant before expansion</td>
</tr>
<tr>
<td>12</td>
<td>T112, Hilton rig refrigerant after expansion</td>
</tr>
<tr>
<td>13</td>
<td>T113, Hilton rig refrigerant after evaporation</td>
</tr>
<tr>
<td>14</td>
<td>T114, Hilton rig refrigerant after compression</td>
</tr>
<tr>
<td>15</td>
<td>T115, Model building inlet before mixing zone</td>
</tr>
</tbody>
</table>

Fig. C.1: Thermocouples connected on the facility
In data acquisition and control, it is important to calibrate the measuring devices so their accuracy is known. This appendix includes calibration data obtained from different devices used in this project.

1. **Data acquisition boards:**

Two calibration programs have been provided to calibrate the data acquisition boards from the manufacturer Advantech®. The first program ‘CAL812.exe’ is used to calibrate the data acquisition card PCL-812PG, and the second ‘CAL789.exe’ one is used to calibrate the daughter boards PCLD-789D and PCLD-889. Once the calibration program has been loaded and executed, it uses the graphic display and prompts to guide the user through the calibration process. These programs include calibration for the A/D offset, amplifier offset, amplifier gains, and the cold junction circuitry.

2. **Sensing devices:**

Sensors are calibrated to obtain an accurate relation between the sensor output signal (normally volt) and the physical quantity (such as pressure, current etc.) that it represents. Those relations have been obtained using a spreadsheet to generate the trend line equation of each device data series. This section includes the calibration charts for different devices with the trend lines equations printed on the top of each chart.
Current sensor of the Hilton rig preheater

\[ I = 1.9709 \text{ v} \]
\[ R^2 = 0.9999 \]

Fig.D.1: Preheater current sensor calibration data

Current sensor of the Hilton rig reheater

\[ I = 1.9688 \text{ v} \]
\[ R^2 = 1 \]

Fig.D.2: Reheater current sensor calibration data
Phase voltage sensor for the Hilton rig

\[ E = 53.904 \text{ v} \]

\[ R^2 = 0.9996 \]

![Phase voltage sensor calibration data](image)

Fig. D.3: Phase voltage sensor calibration data

Atmospheric pressure sensor

\[ P_{at} = 20.871 \text{ v} + 2.5652 \]

\[ R^2 = 0.9965 \]

![Atmospheric pressure sensor calibration data](image)

Fig. D.4: Atmospheric pressure sensor calibration data
Fig.D.5: Performance specifications of the pressure transducers:
ST2100G1 and ST2300G1

For the evaporating pressure (Transducer **ST2100G1**):
The pressure at 100% full-scale = 100psig\(^{†}\) = 689.5 kPa, which leads to the following relation:

\[ p_v = 137.9 \times v - 137.9 \]

where \( p_v \)........ Evaporating pressure [kPa]
\( v \)........ output signal [Volt]

For the condensation pressure (Transducer **ST2300G1**):
The pressure at 100% full-scale = 300psig\(^{†}\) = 2068.5 kPa, which leads to the following relation:

\[ P_c = 413.7 \times v - 413.7 \]

where \( P_c \)......... condensation pressure [kPa]
\( v \)........ output signal [Volt]

\(^{†}\) Source: SenSym ST2000 Series Pressure Transducers Data Sheet
3. Airflow measurement

To obtain the value of the airflow rate supplied to the model building, the velocity traverse method has been used across the duct cross-section. Because the velocity varies from point to point over the cross-section of the duct, it has been measured at a number of points, so distributed as to give an unbiased average over the rectangular duct cross-section.

The points for velocity measurement are determined here using the log-Tchebycheff rule (Daly, 1985). The flow at the test plane for the measurement has been chosen to be as steady and symmetrical as possible. This plane is substantially free from swirl, a condition, which has been checked by observing the...
direction taken by small flags of thread or wool moved over the section on the end of a stick.

At different fan speeds indicated by pressure drop measured in millimetre water gauge using a micro-manometer, a TRISENSE® anemometer has been used to measure the velocities at each point in [m/s].

Then, the simple average velocity at each pressure drop, multiplied by the total duct area, gives the volume airflow rate. Dividing the volume flow rate by the specific volume gives the mass flow rate at each pressure drop.
### Appendix D

#### Fig. D.8: Velocities [m/s] measured at different flow rates

(a): at 0.5 mm pressure drop

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
<td>0.580</td>
<td>0.580</td>
</tr>
<tr>
<td>0.880</td>
<td>0.930</td>
<td>0.870</td>
<td>0.880</td>
<td>0.880</td>
</tr>
<tr>
<td>0.920</td>
<td>0.960</td>
<td>0.880</td>
<td>0.860</td>
<td>0.880</td>
</tr>
<tr>
<td>0.870</td>
<td>0.950</td>
<td>0.880</td>
<td>0.800</td>
<td>0.780</td>
</tr>
<tr>
<td>0.870</td>
<td>0.920</td>
<td>0.880</td>
<td>0.790</td>
<td>0.700</td>
</tr>
</tbody>
</table>

(b): at 1 mm pressure drop

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.050</td>
<td>1.110</td>
<td>1.170</td>
<td>1.110</td>
<td>1.150</td>
</tr>
<tr>
<td>1.400</td>
<td>1.410</td>
<td>1.430</td>
<td>1.430</td>
<td>1.400</td>
</tr>
<tr>
<td>1.500</td>
<td>1.540</td>
<td>1.450</td>
<td>1.450</td>
<td>1.400</td>
</tr>
<tr>
<td>1.450</td>
<td>1.500</td>
<td>1.450</td>
<td>1.400</td>
<td>1.350</td>
</tr>
<tr>
<td>1.400</td>
<td>1.530</td>
<td>1.460</td>
<td>1.400</td>
<td>1.300</td>
</tr>
</tbody>
</table>

(c): at 1.5 mm pressure drop

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.360</td>
<td>1.500</td>
<td>1.575</td>
<td>1.450</td>
<td>1.305</td>
</tr>
<tr>
<td>1.780</td>
<td>1.830</td>
<td>1.815</td>
<td>1.830</td>
<td>1.665</td>
</tr>
<tr>
<td>1.950</td>
<td>1.950</td>
<td>1.875</td>
<td>1.765</td>
<td>1.810</td>
</tr>
<tr>
<td>1.940</td>
<td>1.960</td>
<td>1.865</td>
<td>1.750</td>
<td>1.745</td>
</tr>
<tr>
<td>1.915</td>
<td>1.980</td>
<td>1.935</td>
<td>1.825</td>
<td>1.700</td>
</tr>
</tbody>
</table>

(d): at 2 mm pressure drop

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.475</td>
<td>1.585</td>
<td>1.800</td>
<td>1.620</td>
<td>1.480</td>
</tr>
<tr>
<td>1.970</td>
<td>2.005</td>
<td>2.015</td>
<td>1.955</td>
<td>1.805</td>
</tr>
<tr>
<td>2.065</td>
<td>2.140</td>
<td>2.080</td>
<td>2.050</td>
<td>1.950</td>
</tr>
<tr>
<td>2.115</td>
<td>2.150</td>
<td>2.085</td>
<td>2.005</td>
<td>1.840</td>
</tr>
<tr>
<td>2.090</td>
<td>2.190</td>
<td>2.125</td>
<td>2.080</td>
<td>1.830</td>
</tr>
</tbody>
</table>

(e): at 2.5 mm pressure drop

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.880</td>
<td>0.920</td>
<td>1.000</td>
<td>0.950</td>
<td>0.860</td>
</tr>
<tr>
<td>1.180</td>
<td>1.190</td>
<td>1.220</td>
<td>1.180</td>
<td>1.170</td>
</tr>
<tr>
<td>1.260</td>
<td>1.240</td>
<td>1.210</td>
<td>1.210</td>
<td>1.170</td>
</tr>
<tr>
<td>1.220</td>
<td>1.250</td>
<td>1.200</td>
<td>1.180</td>
<td>1.110</td>
</tr>
<tr>
<td>1.220</td>
<td>1.250</td>
<td>1.210</td>
<td>1.170</td>
<td>1.190</td>
</tr>
</tbody>
</table>

(f): at 3 mm pressure drop

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.225</td>
<td>1.375</td>
<td>1.335</td>
<td>1.340</td>
<td>1.175</td>
</tr>
<tr>
<td>1.675</td>
<td>1.645</td>
<td>1.690</td>
<td>1.650</td>
<td>1.450</td>
</tr>
<tr>
<td>1.745</td>
<td>1.750</td>
<td>1.700</td>
<td>1.675</td>
<td>1.600</td>
</tr>
<tr>
<td>1.790</td>
<td>1.720</td>
<td>1.695</td>
<td>1.575</td>
<td>1.600</td>
</tr>
<tr>
<td>1.735</td>
<td>1.790</td>
<td>1.770</td>
<td>1.680</td>
<td>1.600</td>
</tr>
</tbody>
</table>

Note: Values are rounded for simplicity.
The mass flow rates calculated at different pressure drops are summarised in Table D.1.

<table>
<thead>
<tr>
<th>Pressure Drop [mmH₂O]</th>
<th>Average velocity [m/s]</th>
<th>Duct cross-section area [m²]</th>
<th>Volume Flow rate [m³/s]</th>
<th>Mass Flow rate [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.8244</td>
<td>0.06315</td>
<td>0.05206</td>
<td>0.061977</td>
</tr>
<tr>
<td>1.0</td>
<td>1.1456</td>
<td>0.06315</td>
<td>0.072345</td>
<td>0.086125</td>
</tr>
<tr>
<td>1.5</td>
<td>1.3696</td>
<td>0.06315</td>
<td>0.08649</td>
<td>0.102965</td>
</tr>
<tr>
<td>2.0</td>
<td>1.5994</td>
<td>0.06315</td>
<td>0.101002</td>
<td>0.120241</td>
</tr>
<tr>
<td>2.5</td>
<td>1.763</td>
<td>0.06315</td>
<td>0.111333</td>
<td>0.13254</td>
</tr>
<tr>
<td>3.0</td>
<td>1.9402</td>
<td>0.06315</td>
<td>0.122524</td>
<td>0.145861</td>
</tr>
</tbody>
</table>

A direct relation between the pressure drop and the mass airflow rate in the duct orifice can be obtained as shown in Fig.D.9:

\[ m = 0.0019 p^3 - 0.015 p^2 + 0.0659 p + 0.0327 \]

\[ R^2 = 0.9995 \]

Fig.D.9: Mass airflow rate at the duct orifice

After calibration of the Hilton duct orifice, the intake orifice has been calibrated with reference to the duct orifice. The relation
between the intake pressure drop and the duct pressure drop is shown in Table D.2.

### Table D.2: Calibration of Intake Orifice against Duct Orifice

<table>
<thead>
<tr>
<th>Intake Orifice Pressure Drop [mmH₂O]</th>
<th>Duct Orifice Pressure Drop [mmH₂O]</th>
<th>Mass Flow rate [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>1.20</td>
<td>0.0934</td>
</tr>
<tr>
<td>1.00</td>
<td>1.80</td>
<td>0.1138</td>
</tr>
<tr>
<td>1.30</td>
<td>2.10</td>
<td>0.1225</td>
</tr>
<tr>
<td>1.45</td>
<td>2.35</td>
<td>0.1294</td>
</tr>
<tr>
<td>1.70</td>
<td>2.70</td>
<td>0.1387</td>
</tr>
</tbody>
</table>

The relation between the fresh air intake pressure drop and the mass airflow rate is shown in Fig.D.10.

![Graph](image)

**Fig.D.10: Fresh air mass flow rate at the intake orifice**
4. **Wet-bulb sensor corrections:**

Apparent indications of inconsistency in the wet-bulb sensors readings in the Hilton rig have been checked and investigated during calibration of the temperature sensors.

While operating the Hilton rig with no recirculation, no humidification or dehumidification, the accuracy of the wet-bulb thermocouple at each station has been compared against the value obtained from the measured relative humidity at that station as shown in Fig.D.11. For direct measurement of the relative humidity of the air at each station, the portable device TriSense® meter\(^2\) has been used.

\[\text{Fig.D.11: Stations locations in the Hilton rig}\]

**Note:**
- T1, T3, T5, T7, and T9 are dry-bulb thermocouples
- T2, T4, T6, T8, and T10 are wet-bulb thermocouples

---

\(^2\) A solid state instrument used to measure air temperature, humidity, and velocity.
This TriSense® meter had been primarily calibrated against some known relative humidity states generated from different saturated water/salt solutions\(^3\) (Kuehin et al. 1998) to check its accuracy. The calibration results have been listed in Table D.3.

### Table D.3: Calibration results of the wet-bulb thermocouples in the Hilton rig at different airflow speed

<table>
<thead>
<tr>
<th>Station</th>
<th>Measured dry-bulb temperature [°C]</th>
<th>Airflow speed [m/s]</th>
<th>Measured(^4) relative humidity</th>
<th>Corrected(^5) relative humidity</th>
<th>Deduced(^6) wet-bulb temperature [°C]</th>
<th>Measured wet-bulb temperature [°C]</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>At low fan speed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>19.0</td>
<td>2.1</td>
<td>41.6</td>
<td>44.37</td>
<td>12.3</td>
<td>12.9</td>
<td>0.6</td>
</tr>
<tr>
<td>B</td>
<td>19.0</td>
<td>0.5</td>
<td>41.2</td>
<td>43.88</td>
<td>12.3</td>
<td>13.1</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>19.2</td>
<td>0.4</td>
<td>41.0</td>
<td>43.64</td>
<td>12.4</td>
<td>13.1</td>
<td>0.7</td>
</tr>
<tr>
<td>D</td>
<td>19.2</td>
<td>1.2</td>
<td>40.8</td>
<td>43.39</td>
<td>12.3</td>
<td>12.8</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>18.9</td>
<td>1.0</td>
<td>39.7</td>
<td>42.05</td>
<td>12.0</td>
<td>13.6</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>At high fan speed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>19.2</td>
<td>4.4</td>
<td>41.5</td>
<td>44.25</td>
<td>12.5</td>
<td>12.9</td>
<td>0.4</td>
</tr>
<tr>
<td>B</td>
<td>19.3</td>
<td>1.2</td>
<td>41.2</td>
<td>43.88</td>
<td>12.4</td>
<td>13.1</td>
<td>0.7</td>
</tr>
<tr>
<td>C</td>
<td>19.2</td>
<td>1.0</td>
<td>41.1</td>
<td>43.76</td>
<td>12.4</td>
<td>13.1</td>
<td>0.7</td>
</tr>
<tr>
<td>D</td>
<td>19.3</td>
<td>2.4</td>
<td>41.1</td>
<td>43.76</td>
<td>12.4</td>
<td>12.8</td>
<td>0.4</td>
</tr>
<tr>
<td>E</td>
<td>19.1</td>
<td>2.1</td>
<td>40.3</td>
<td>42.78</td>
<td>11.9</td>
<td>13.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

\(^3\) In closed chamber with no airflow at 20°C, magnesium chloride saturated water solution generates water vapour at 33.1% relative humidity, and potassium chloride solution generates 85.1%.

\(^4\) Using the TriSense meter

\(^5\) Corrected TriSense reading from the chart in Fig.D.12.

\(^6\) From the psychrometric chart using the corrected TriSense relative humidity reading, and the measured dry-bulb temperature.
The calibration results listed in Table D.3 do not show any consistent behaviour of the error. Although these errors are attributed to different predicted factors, as discussed in Chapter 7, there is no clear pattern which could be used as the basis for correcting these deviations. For simplicity, therefore, the corrections are taken as the arithmetic average of the deviations at each station as shown in Table D.4. These corrections have been embedded in the software. Further investigation into these sensors is required to get a clearer pattern of the error.

Table D.4: Correction values to the wet-bulb temperatures captured from the Hilton rig

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Correction °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>- 0.50</td>
</tr>
<tr>
<td>T4</td>
<td>- 0.75</td>
</tr>
<tr>
<td>T6</td>
<td>- 0.70</td>
</tr>
<tr>
<td>T8</td>
<td>- 0.45</td>
</tr>
<tr>
<td>T10</td>
<td>- 1.50</td>
</tr>
</tbody>
</table>

Fig.D.12: Two-point calibration check of the Tri-Sense (relative humidity sensor at 20°C)

\[ y = 1.2221x - 6.468 \]
APPENDIX E

CD-ROM Contents

The CD-ROM that accompanies this report contains the following folders:

1. Software Project:
   This folder contains all the source-code and project compiled files including the final execution program “hilton.exe”.

2. Thesis:
   This folder contains a software copy of this thesis as a collection of MS-Word™ documents.

3. Digital photos:
   This folder contains some digital photos taken for the facility including the Hilton rig, the environmental chamber, and the model building.

4. Test and Calibration:
   This folder contains a collection of programs delivered from Advantech® to test and calibrate the data acquisition electronic boards used in this project.

5. Driver:
   This folder contains the installation files necessary to install the Advantech® drivers, the help files, and the programmer’s manual of the driver in MS-Word™ format.