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# PHYSICAL SCALE MODELING OF SMOKE CONTAMINATION IN UPPER BALCONIES BY A CHANNELED BALCONY SPILL PLUME IN AN ATRIUM

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## ABSTRACT

Whether the balcony spill plume will rise unhindered as a free plume or curl inwards and interact with the atrium structure is determinant upon a number of factors. Not all the factors are well investigated and wholly understood, resulting in limited guidance for fire engineers. This paper systematically investigates the effects of varying balcony breadths, plume widths and fire sizes on smoke contamination in upper balconies through a series of smoke flow experiments conducted using a one-tenth physical scale model representing a six-storey atrium building. The scale model simulated a fire in an adjacent compartment connecting to a fully open atrium. Visual observations and temperature measurements of the smoke flows were carried out. From the results, it was established that the extent of smoke contamination in upper balconies increased with decreasing balcony breadths, increasing plume widths and decreasing fire sizes. Analysis showed that the aspect ratio of plume width to balcony breadth can be used to determine whether smoke contamination of upper balconies will occur. Where contamination is likely, an empirical correlation was developed to determine the minimum height of contamination above the lowest balcony of smoke contamination.

**Keywords :** Balcony spill plume, atrium, scale modeling, smoke contamination

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# 1 INTRODUCTION

In the event of a fire, the atrium can present significant risks to building occupants due to the lack of floor-to-floor separations which can allow fire and smoke to spread from the origin of fire to adjacent spaces in the building. Past experience with atrium fires have shown that there is less concern with the spread of fire within the building, particularly when the building is fully sprinklered [1]. Instead, of greater concern is the spread of smoke to areas intended for the evacuation of building occupants.

The spread of smoke in an atrium may be dependant on the volume of smoke produced. The larger the volume of smoke produced, the greater the possibility of smoke spreading from the atrium space to the adjacent spaces. A large volume of smoke is produced when large amounts of air are entrained into a rising smoke plume. For different types of smoke plumes (e.g. axisymmetric plume, wall plume, corner plume, window plume and balcony spill plume), the amount of air being entrained varies [2].

The balcony spill plume involves a sequence of smoke flows [3]. When a fire occurs in an adjacent space that opens directly to an atrium, hot smoke from the fire will flow horizontally towards the opening. If the smoke is not contained within the adjacent space, it will flow out of the opening. If a higher projecting balcony extends from the opening, the smoke will rise from the opening and flow beneath the balcony towards the free edge of the balcony. The flow under the balcony may be channeled using screens or be unchanneled. The smoke will then 'rotate' about the balcony edge and rise vertically, entraining large amounts of air as it rises. The balcony spill plume is said to rise vertically as a free plume where the entrainment of air occurs on both sides of the spill plume as shown by the arrows in Figure 1a. This behavior is determinant upon a number of factors. The balcony has to be sufficiently broad to allow air to flow between the rising spill plume and the atrium structure, thereby enabling the entrainment of air on both sides of the spill plume [3]. Another factor will be the momentum of the balcony spill plume when 'rotating' about the balcony edge. If the momentum is sufficiently high, the spill plume will project beyond the balcony edge to allow air to flow between the rising spill plume and the atrium structure. In contrast, the balcony spill plume may curl inwards towards the atrium structure, as shown by the arrows in Figure 1b. Whether the spill plume curls inwards is determinant upon similar factors. A balcony that is very narrow will mean that air cannot flow between the rising spill plume and the atrium structure. Alternatively, the momentum of the balcony spill plume when 'rotating' about the balcony edge may be so low that the spill plume does not project out sufficiently to allow air to flow between the rising spill plume and the atrium structure. As a result, the spill plume will also curl inwards towards the atrium structure and contaminate the upper balconies. However, if the balcony is broader and the spill plume momentum is sufficient for entrainment of air to occur on the side of the plume nearest to the atrium structure, this can cause a region of 'warm' air to develop between the spill plume and atrium structure and the static pressure to fall. This low-pressure region will cause the spill plume to curl inwards towards the atrium structure and contaminate the upper balconies. This is known as the Coanda effect [4]. For very broad balconies, the Coanda effect is unlikely to occur due to the fresh air at ambient temperature existing in the region between the plume and the atrium structure.

The factors affecting the behavior of the balcony spill plume are not limited to the balcony breadth and the momentum of the spill plume, but not all of the factors are well investigated and wholly understood. Whether the balcony spill plume will rise as a free plume or curl inwards towards the atrium structure is of concern to fire engineers in atrium design given that areas within the atrium may need to be kept tenable for safe evacuation of building occupants. In addition, it is expected that a spill plume that curls inwards towards the atrium structure will entrain less air compared to a free plume. As such, another interest to fire engineers is the design of smoke management systems that are directly related to the rate of air entrainment in an atrium.

A number of standards and engineering guides on smoke management in atria have been developed [2, 3, 5]. However, most of the guidance on the balcony spill plume is concentrated on smoke mass flow rate calculations. There exists limited guidance on the behavior of the balcony spill plume in an atrium with respect to upper balconies. The only relevant guidance is made available by Morgan *et al.* [3], that states "*balconies which are shallow ($<$2 m) will cause the rising spill plume to curl inwards towards the structure*…… *smoke-logging the balcony levels above the fire floor*". This guidance is based on a limited number of smoke flow experiments conducted by Hansell *et al.* [6] in a model atrium. That work concluded that for the balconies in an atrium to be kept clear of smoke, the balconies must be broader than 1.25 m (full scale) but not necessary to be broader than 2.5 m (full scale), which lead to 2 m as the appropriate minimum balcony breadth. Hansell *et al.* [6] also suggested that the extent of smoke contamination was also dependent on the 'length of the line plume' (i.e. plume width), though no experiments were conducted to investigate this which resulted in the authors stating that the 2 m criterion may not apply for openings wider than were possible in the original experiments.

This paper systematically investigates the effects of varying balcony breadths, plume widths and fire sizes on smoke contamination in upper balconies through experimental work. Guidance on the behavior of the channeled balcony spill plume in a fully open atrium with respect to smoke contamination in upper balconies is presented.

## 2 METHODOLOGY

The methodology used was similar to complementary research work on entrainment mechanisms of the thermal spill plume by Harrison [7] and some results have already been reported by Harrison and Spearpoint [8]. In particular, the approach and experiment apparatus were kept generally the same, so that the calibration and experimental results (e.g. fire heat release rates and compartment flows) could be used in this research work.

The approach of physical scale modeling in the form of burning fires in a reduced physical scale model was adopted. In order for the experiment results to be extrapolated from model scale to full scale, the scaling laws set out by Thomas *et al.* [9] had to be met. Essentially, this was a modified Froude number scaling and required the equivalent flows on both the full and model scales to be fully turbulent, i.e. the Reynolds number of significant flows should exceed the critical value of 4000 [10]. In the experiments by Harrison [7], the Reynolds number for the typical flows from the fire compartment were calculated to range between 8,100 and 20,400. Identical compartment flows were used in this work and it was established that the flows were fully turbulent and that any scaling laws could be applied with confidence.

Dimensional relationships between fluid dynamics variables were derived from first principles by Morgan *et al.* [11]. By holding certain variables constant, the relationships can be simplified to obtain the required scaling laws. For this research, when the temperature above ambient was kept constant, the scaling laws become $\dot{Q}_c \propto L^{5/2}$; $\dot{m} \propto L^{5/2}$; $\dot{V} \propto L^{5/2}$; $u \propto L^{1/2}$. As the scaling laws do not apply to conductive and radiative heat transfer processes, it is assumed that the heat transfer mechanisms in this research work were pre-dominantly convective.

## 2.1 Physical Scale Model

A one-tenth physical scale model representing a six-storey atrium building was designed and constructed (Figure 2). The scale model simulated a fire in an adjacent compartment connecting a fully open atrium. It consisted of two main compartments, namely the fire compartment (as an adjacent compartment) and the atrium.

The fire compartment of internal dimensions 1 m by 1 m by 0.5 m high was constructed from 1 mm thick steel sheets. The internal surfaces were protected by 25 mm thick Ceramic Fiber Insulation (CFI) boards. The width of the compartment opening could be varied using 'inserts' that were constructed similarly.

The fire was generated by supplying and burning Industrial Methylated Spirit (IMS) fuel at a steady rate in a steel tray. The fuel was supplied to the tray from a fuel reservoir via a flowmeter. The steel tray, measuring 0.25 m by 0.25 m by 0.015 m high, was positioned at the rear of the fire compartment. Since the fuel did not occupy the full area of the tray, the tray was tilted slightly toward the back of the compartment and positioned at an angle of 45 degrees to the walls of the compartment. Hence, the sides of the fire tray channeled the fuel such that its surface remained reasonably uniform and automatically adjusted to match the burning rate to the inflow of fuel. Based on the properties of the IMS fuel, the total fire heat release rate was calculated from heat of combustion, density and volume flow rate through the flowmeter.

The atrium was of internal dimensions 2 m by 2 m by 2.5 m high. The main supporting frame of the atrium was constructed using steel sections. Three out of the four vertical faces of the atrium were side walls constructed from 2 mm thick steel sheets and affixed to the supporting steel frame. The internal surfaces of the side walls were protected by 10 mm thick CFI boards. The side walls were constructed such that they could move freely in the vertical direction along the supporting steel frame. The fourth vertical face of the atrium was kept free of obstructions to allow for visual observations. However, due to the need to contain and exhaust the hot smoke properly, the top portion of this vertical face was partially covered by a side wall constructed from 12 mm thick clear acrylic sheet. This created an exhaust hood that enabled the hot smoke to be contained and exhausted via a mechanical fan. The mechanical fan was a 0.44 m diameter bifurcated fan attached to the exhaust hood vent using temperature resistant flexible ducting. The fan speed was controllable, enabling different exhaust rates to be selected.

The atrium housed five levels of balconies above the opening of the fire compartment. The balconies were designed with 0.1 m high upstands and were constructed from 1 mm thick steel sheets. The height of 0.1 m represented a typical height for safety barriers. In order to minimize heat losses and enable scaling, the underside of Balcony 1 was further protected with 10 mm thick CFI boards. This was consistent with the research work of Harrison [7].

The underside of Balcony 1 was flush with the top of the opening of the fire compartment. The subsequent balconies above were positioned 0.4 m vertically apart (from floor to floor) chosen as an appropriate typical representation of a full scale balcony spacing of 4 m. The balconies occupied the full 2 m width of the atrium, while the balcony breadth was made adjustable.

Channeling screens were constructed from 1 mm thick steel sheets and protected with 10 mm thick CFI boards. The screens were 0.2 m deep and occupied the full breadth of Balcony 1. The screens were designed such that the smoke flowing beneath Balcony 1 was contained within the depth of the screens. The screens were butted to the underside of Balcony 1 and the atrium wall (that the balconies were attached to), and were aligned with the width of the opening of the fire compartment. This ensured that the plume width that is parallel to the edge of Balcony 1 followed the width of the opening.

## 2.2 Instrumentation

Visual observations and photography of the experiments were carried out. The primary interests were the behavior of the balcony spill plume and the extent of smoke contamination in upper balconies. As the IMS fuel burns with no visible smoke, commercial oil-mist smoke was introduced into the hot fire gases to enable visual observations and photography of the buoyant smoke flows. The oil-mist smoke was produced from a smoke generator and supplied through pipes. The amount of oil-mist smoke to be introduced into the hot fire gases was manually controlled so that the visual observations would not be affected by any excessive oil-mist smoke.

Smoke temperatures were measured to support the visual observations. The smoke temperatures were measured using 0.5 mm diameter exposed chromel/alumel (K-type) thermocouples, and the temperature readings were scanned at a rate of 1 reading/s and recorded using a data logging software. Two thermocouple columns were set up and positioned as shown in Figure 2. Column A was a 9-thermocouple column running vertically from the edge of Balcony 1 to the base of the atrium. The column was centrally positioned along the balcony length and the thermocouples were spaced in accordance with Table 1. The thermocouples measured the smoke temperatures flowing out of the opening of the fire compartment and were monitored to determine when steady state conditions had been achieved during the experiments.

Column B was 15-thermocouple column running vertically from the edge of Balcony 1 to the ceiling of the atrium. The column was centrally positioned along the balcony length and the thermocouples were spaced in accordance to Table 2, whereby a set of three thermocouples were assigned to each balcony. The thermocouples measured the smoke temperatures flowing into the balconies. The temperature readings were analyzed to determine the temperature profiles of any hot smoke flowing into the balconies.

## 2.3 Experimental Variables

Four balcony breadths, *b* of 0.15 m, 0.2 m, 0.3 m and 0.5 m were used, and were equivalent to 1.5 m, 2 m, 3 m and 5 m on a full scale respectively. The range of 0.15 – 0.5 m was chosen in relation to real balcony designs, where a balcony breadth of less than 0.15 m is not practical and a balcony breadth of more than 5 m might be considered large enough to be a separate space or an intermediate floor. The balcony breadths were specifically selected so that some form of comparison could possibly be made with the findings from Hansell *et al.* [6] that 2 m would be the appropriate minimum balcony breadth to prevent smoke contamination.

Five plume widths, *w* of 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0 m measured as the distance between the channeling screens consistent with Harrison [7] were used, and were equivalent to 2 m, 4 m, 6 m, 8 m and 10 m on a full scale respectively. These widths were considered typical of compartment openings, such as for shops and offices.

Three steady state fire sizes of heat release rates 5 kW, 10 kW and 15 kW were used, and were approximately equivalent to 1.6 MW, 3.2 MW and 4.8 MW on a full scale respectively. The fire heat release rates were consistent with the range of design fires in an atrium recommended by Morgan *et al.* [3] and corresponded to those used by Harrison [7].

Varying the plume width and heat release rate of the fire in turn varied the momentum of the plume from the fire compartment opening. By configuring the balcony breadth, plume width and heat release rate, a total of 60 combinations to characterize the behavior of the balcony spill plume are obtained of which 50 were investigated by experiment.

## 3 RESULTS

The presentation of experiment results for visual observations and temperature readings is limited to Balconies 1, 2 and 3. The reason for this limitation is the interference caused by a smoke layer within the exhaust hood of the atrium. As there was a need to contain and exhaust the hot smoke properly for health and safety reasons, the top portion of the atrium was enclosed by side walls to form an exhaust hood. During the experiments, the smoke would be contained within the exhaust hood and exhausted via a mechanical fan. At steady state conditions, a smoke layer would develop within the exhaust hood. As Balconies 4 and 5 were also enclosed within the exhaust hood, the smoke layer would contaminate Balconies 4 and 5, and affect the temperature readings.

Three generic types of plume behavior were observed and described here as: free plume; 're-attached' plume; and upstand 'adhered' plume.

It was generally observed that for experiments with a low aspect ratio of *w* / *b* (i.e. narrow plume widths and broad balconies), the balcony spill plume flowing beneath Balcony 1 projected horizontally far enough out such that the spill plume rose unhindered as a free plume and did not curl inwards towards the balconies. There was no smoke contamination on Balconies 1 to 3 for this type of plume behavior, as shown in Figure 3a.

For experiments with intermediate balcony breadths and plume widths, the horizontal projection of the balcony spill plume was not far enough to rise unhindered into the atrium. The spill plume then behaved as a 're-attached' plume. This was when the spill plume curled inwards and impinged with one of the upper balconies, resulting in smoke contamination on that particular balcony and subsequent balconies above (Figure 3b). The extent of smoke contamination on the balconies (i.e. the locations and depths of smoke layers) depended on the experiment setup.

For experiments with narrow balconies and wide plume widths, the balcony spill plume had little or no horizontal projection. The balcony spill plume would 'rotate' about the edge and 'adhere' to the upstand of Balcony 1, and subsequently 'spill' into Balcony 1 (Figure 3c). There was smoke contamination in all balconies. It is recognized that the term 'adhered plume' is conventionally used in cases where a balcony is absent and the spill plume adheres to a vertical surface above the compartment opening. However, in this paper, the 'adhered' plume is different and refers to the spill plume 'adhering' to the upstand.

In the event that there was smoke contamination in a balcony, the phenomenon of a 'secondary' balcony spill plume would manifest. This 'secondary' spill plume was the result of the smoke layer from a lower balcony re-entering the atrium space and spilling back into the balcony above. There would be an accumulative effect of smoke contamination in upper balconies, resulting in deeper smoke layers. The same observation was made by Hansell *et al.* [6] in their smoke flow experiments. Also during some experiments, there were 'secondary' balcony spill plumes occurring at the open ends of the balconies (where the acrylic side wall was located) due to lateral smoke spread under the balconies. This was not desirable as these spill plumes would affect the extent of smoke contamination in upper balconies and thus the observations but was a limitation of the scale model due to space constraints. Enclosing the ends of the balconies would have led to layer deepening and further ‘secondary’ balcony spill plumes along the front edge of a balcony. Wider balconies would have reduced the occurrence of lateral ‘secondary’ balcony spill plumes at the open ends of the balconies but would have been beyond the extent of the collecting hood.

For a common understanding of the experiment results for visual observations, the various extents of smoke contamination in the balconies are broadly classified as follows:

- Clear - No smoke was visually observed between balconies (Figure 4a).
- Shallow smoke layer - Smoke contamination occurred (Figure 4b) such that a smoke layer was visually observed in upper half of balcony height (floor to ceiling).
- Deep smoke layer - Smoke contamination occurred (Figure 4c) such that a smoke layer was visually observed in lower half of balcony height (floor to ceiling).

The model scale half height of 0.2 m is equivalent to 2 m full-scale which is a typical design criterion for smoke layer depth [12].

Table 3 shows the results from the experiments in which it indicates the extent of any layer obtained on each balcony using the criteria discussed. Results were inferred where it was obvious from experiments already completed that smoke contamination would not occur.

## 4 ANALYSIS

The temperature readings from Thermocouple Column B were averaged over the period of 60 s for each experiment. The distances of the thermocouples above the edge of Balcony 1 were plotted against the averaged temperatures above ambient. This provided a temperature profile across the balcony edge in the vertical axis. Using Experiment 1 as an illustration, the temperature profile with error bars of one standard deviation is shown in Figure 5.

From all the temperature profiles across the balcony edge, it was found that where the smoke temperatures were significantly above the ambient temperature, smoke was visually observed in the balconies. To establish this relationship clearly, a simple method of a temperature marker of 10 °C above ambient temperature was used to relate the temperature readings to the visual observations. That is, where the temperature reading was less than 10 °C above ambient temperature, smoke was not expected to be visually observed; where the temperature reading was more than 10 °C above ambient temperature, smoke was expected to be visually observed. The temperature marker of 10 °C above ambient temperature was used for all four balcony breadths as it best-fitted the visual observations.

From the temperature profile of Experiment 1, smoke was expected to be visually observed at the level of Thermocouple B3 in Balcony 1 (i.e. a shallow smoke layer was expected). A deep smoke layer was expected to be visually observed in Balconies 2 and 3. This was consistent with the visual observations for Experiment 1. In this analysis, the temperature reading of Thermocouple B1 was ignored, as it tended to record higher temperatures due to the initial 'adherence' of the balcony spill plume to the upstand of Balcony 1.

Using this approach further analysis was conducted to relate the effect of the experiment variables to the extent of smoke contamination in upper balconies.

## 4.1 Effects of Experiment Variables on Smoke Contamination

The extent of smoke contamination in upper balconies increased as the balcony breadth decreased and this finding is consistent with the findings by Hansell *et al*. [6]. For all four balcony breadths in this work, the extent of smoke contamination in the balconies increased as the plume width increased. One possible reason for this finding lies with the aspect ratio of plume width to depth of the smoke layer (of the balcony spill plume) flowing beneath Balcony 1. For a given fire heat release rate and smoke volume produced, the aspect ratio of the smoke layer would change so that as the plume width increased, the depth of the smoke layer beneath Balcony 1 decreased. Similar to the findings by Yokoi [13], the balcony spill plume would project horizontally further for a narrow width and deep smoke layer, in comparison to a wide width and shallow smoke layer. For the latter, the spill plume would curl inwards towards the balconies.

Generally, for experiments with the same geometrical variables (i.e. balcony breadth and plume width), the differences in the extent of smoke contamination were not significant for the various fire heat release rates. For the few cases where the differences were noticeably significant, the extent of smoke contamination was more severe for a lower fire heat release rate as compared to a higher fire heat release rate (e.g. Experiments 34 to 36 and Experiments 52 to 54). This is expected given that a higher fire heat release rate would lead to an increase in the momentum of the fire gases and in turn, a further horizontal projection of the balcony spill plume and these findings are again consistent with Hansell *et al*. [6].

## 4.2 Aspect Ratio of Plume Width to Balcony Breadth

Since the effect of fire size was relatively less significant compared to those of balcony breadth and plume width, an analysis involving the aspect ratio of plume width to balcony breadth was performed. The purpose of this analysis is to determine whether this aspect ratio can be used to provide generic guidance to fire engineers. The aspect ratios for the experiments are shown in Table 3, where it is shown that the extent of smoke contamination increased as the aspect ratio increased. By plotting the aspect ratio to the number of balconies with smoke contamination (Figure 6), it is shown that there was no smoke contamination in Balconies 1 to 3 where the aspect ratio $w / b \leq 1$, while there was smoke contamination in more than one upper balcony where the aspect ratio $w / b \geq 3$.

For $1 < w / b < 3$, smoke contamination may or may not occur on one or more balconies. There is a desire to provide further guidance to establish the extent of smoke contamination in the balconies. An analysis involving non-dimensional correlation of related experiment variables was performed in which two new variables were introduced, namely the height of smoke contamination above Balcony 1, $H$ (i.e. the height above Balcony 1 at which the balcony spill plume curls inwards and crosses the vertical axis of the balcony edge) and the depth of smoke layer, $d$ of the balcony spill plume flowing beneath Balcony 1.

The height $H$ is obtained by locating the intersection point between the temperature profile across the balcony edge and the temperature marker (10 °C above ambient temperature). Using the temperature profile of Experiment 1 as an illustration (Figure 5), $H$ is found to be 0.24 m. If the method of a temperature marker was not suitable (for example, there was no point of intersection for Experiment 6), $H$ was approximated from the visual observations. The values for $H$ for the experiments are shown in Table 4.

The depth of smoke layer $d$ was dependent on the fire heat release rate and since the plume widths and fire sizes were the same as those used by Harrison [7], the values as shown in Table 5 were referenced from his work. Although the work by Harrison used a fixed balcony breadth of 0.3 m it is reasonable to assume that the values for $d$ were similar for all four balcony breadths investigated in this research given that the smoke layer flowing beneath Balcony 1 was well contained within the channeling screens.

In view of the findings by Yokoi [13], the term $w/d$ was found suitable to relate to the behavior/trajectory of the balcony spill plume. It was found that by plotting $H/b$ against $w/d$, ignoring experiments without smoke contamination (i.e. those with no value for $H$), the relationship shown in Figure 7 was obtained with a best-fit correlation of $\frac{H}{b} = 20\left(\frac{w}{d}\right)^{-1.5}$ or $H = 20\,b\left(\frac{d}{w}\right)^{1.5}$. As the correlation was empirically obtained, the limits applicable to the equation shall follow the range of experiment variables as $0.15 \le b \le 0.50$ $(1.5 \le b \le 5.0$ at full scale) and $0.10 \le \frac{d}{w} \le 0.85$. In design practice the smoke layer depth, $d$ can be obtained using the established methods given in Morgan *et al.* [3] or from any other suitable methods.

## 5 DISCUSSION

It is appropriate to compare the results from this work with those from Hansell *et al.* [6] however of those experiments which considered smoke contamination of balconies only the 0.125 m balcony breadth involving 0.525 m wide channeled flow (resulting in a ratio of 4.2) gave re-attachment of the rising spill plume to the atrium wall. This would suggest that there would be smoke contamination in upper balconies, had there been balconies above the fire compartment, and would be in agreement that smoke contamination in more than one upper balcony is likely for $w$ / $b$ ≥ 3.0 proposed in this work. Unfortunately the findings by Hansell *et al.* [6] were given as the re-attachment height of the balcony spill plume at the atrium wall, whereas $H$ has been defined here as the minimum height above Balcony 1 at which the balcony spill plume curls inwards and crosses the vertical axis of the balcony edge so that a comparison of the correlation equation for smoke contamination height to Hansell *et al*. is not possible. If the 2 m criterion specified by Morgan *et al.* [3] is considered then this work would suggest upper level smoke contamination will not occur if $w$ ≤ 2 m but would become an issue if the plume width increased until at $w$ ≥ 6 m when contamination would affect all levels.

The research work presented in this paper is limited in that it only provides an assessment of whether smoke contamination may occur on the balconies close to the spill edge and where this occurs, an assessment of the contamination height. The work does not quantify what the tenability effects might be should smoke contaminate upper balconies and whether those effects might significantly compromise occupant escape. Experiments were limited to three balconies due to space constraints, and the need to contain and exhaust the hot smoke properly. It is recognized that in very tall buildings, it is possible for the smoke plume to project away from the lower balconies and eventually contaminate the upper balconies due to the entrainment of sufficient air and the resulting increase in the plume cross-section area. This can be further complicated by stratification of the smoke plume as it cools. For such cases, the height at which the upper balconies are contaminated may be difficult to determine experimentally. Numerical modeling could be used to further investigate the issues of higher balcony levels and the effects on tenability.

The correlation equation should be used with caution for narrow balcony breadths (i.e. 0.15 m) as the deviations from the experiment results were significant. Additionally, for atrium designs with geometries that are very different from that of the experiments, caution should also be exercised when using the correlation equation. The presence of balconies and upstands can either cause the balcony spill plume to either move further from or curl inwards towards the atrium wall. This was also noted by Hansell *et al.* [6] in one of their experiments involving two balconies. The experiments used a fixed balcony vertical separation distance and a fixed balcony upstand height. It would be useful to investigate if varying these distances over a range of practical values has any significant effect on the correlation equation.

## 6 CONCLUSION

The research described in this paper shows that for channeled balcony spill plumes the extent of smoke contamination in upper balconies increased as the balcony breadth decreased and as the plume width increased. The differences in the extent of smoke contamination were not significant for different fire sizes. Where the differences were noticeably significant, the extent of smoke contamination was more severe for a lower fire heat release rate as compared to a higher fire heat release rate.

The aspect ratio of plume width to balcony breadth can be used to provide guidance in atrium design with respect to smoke contamination in upper balconies. For $w / b \leq 1.0$ smoke contamination in upper balconies is unlikely; whereas for $w / b \geq 3.0$, smoke contamination in more than one upper balcony is likely. This guidance broadly agrees with previous 2 m requirement but accounts for both the width of the balcony and the size of the fire rather than just be a fixed criterion.

For $1.0 < w / b < 3.0$, an empirical correlation was developed to provide further guidance on the extent of smoke contamination in upper balconies. The height of smoke contamination above Balcony 1, $H$ is calculated as $H = 20\, b \left( \frac{d}{w} \right)^{1.5}$ with the limits at full-scale being $1.5 \leq b \leq 5.0$ and $0.10 \leq \frac{d}{w} \leq 0.85$.

Further experimental and numerical work would be advantageous to investigate the likelihood of contamination on higher level balconies; the effects of different balcony upstand heights and vertical separation distances; unchanneled smoke flows from the compartment and the tenability conditions on contaminated balconies. Some work is already underway at the University of Canterbury to investigate these issues.

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## NOMENCLATURE

| **Symbol** | **Description** |
|---|---|
| $b$ | Breadth of balcony (m) |
| $d$ | Depth of smoke layer beneath edge of Balcony 1 (m) |
| $H$ | Height of smoke contamination (m) |
| $L$ | Characteristic length of scale model (m) |
| $\dot{m}$ | Mass flow rate (kg/s) |
| $\dot{Q}_c$ | Convective heat release rate (kW) |
| $u$ | Velocity (m/s) |
| $\dot{V}$ | Volume flow rate ($m^3$/s) |
| $w$ | Width of plume (m) |

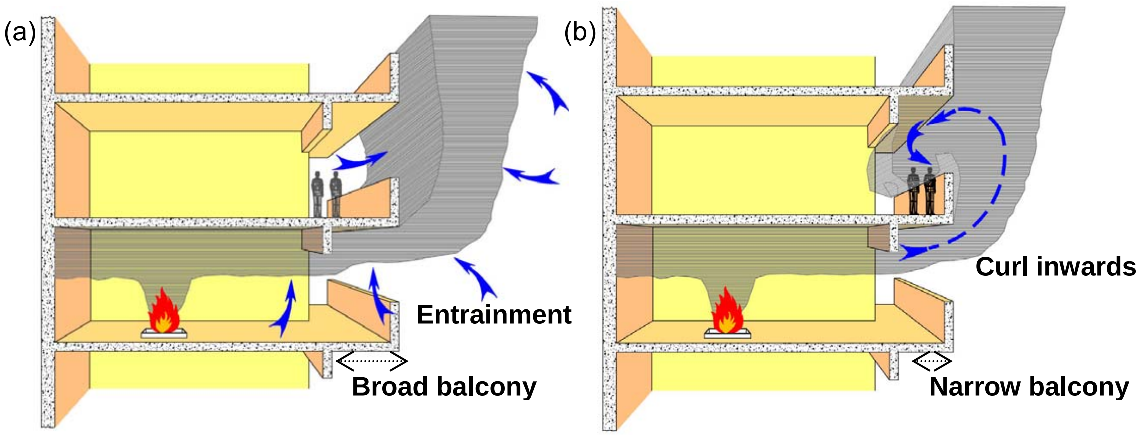


**Figure 1.** Spill plume behavior (a) Rises as free plume; (b) Plume curls inwards (adapted from Morgan *et al.* [3])

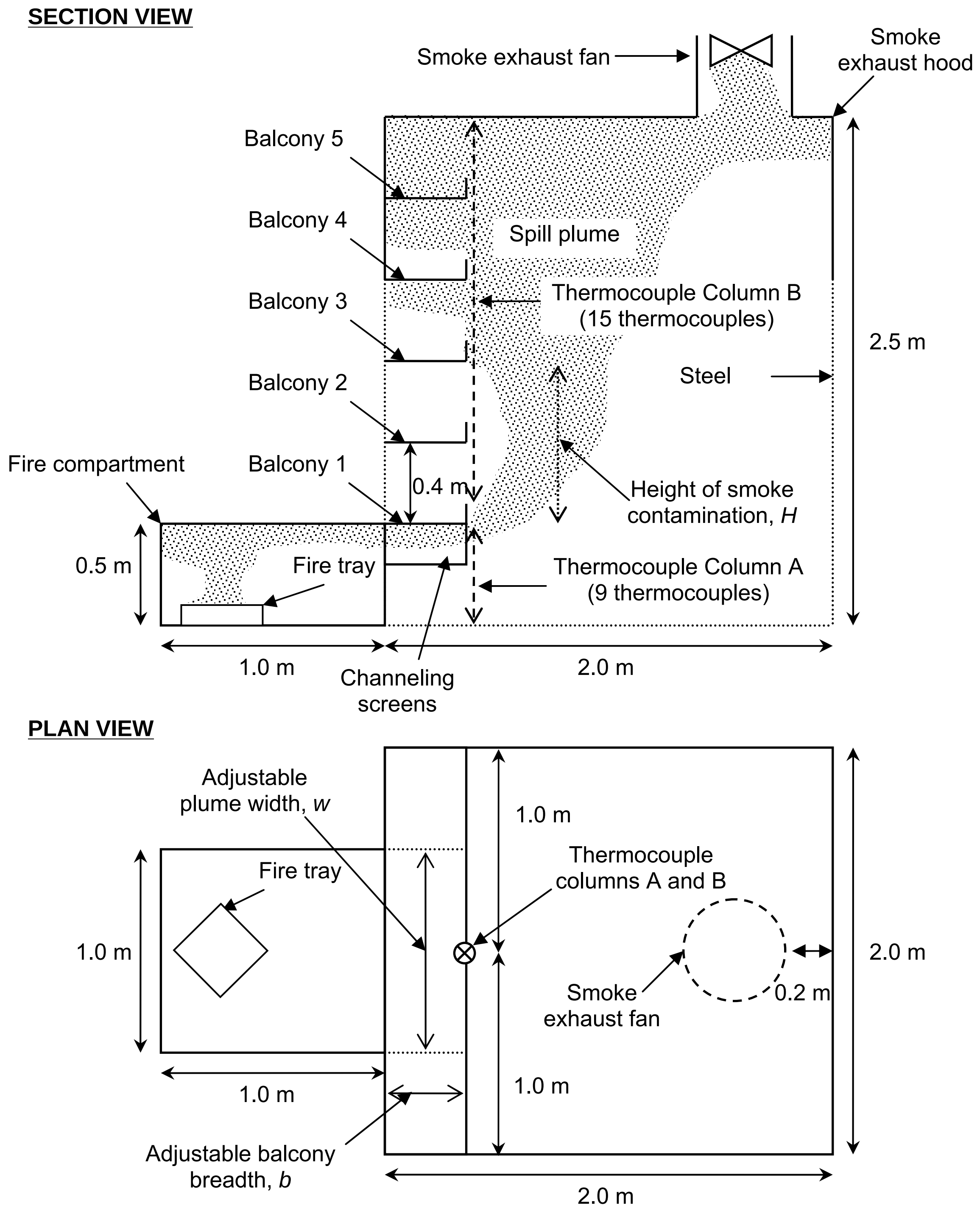


**Figure 2.** Schematic diagram of physical scale model and locations of thermocouple columns.

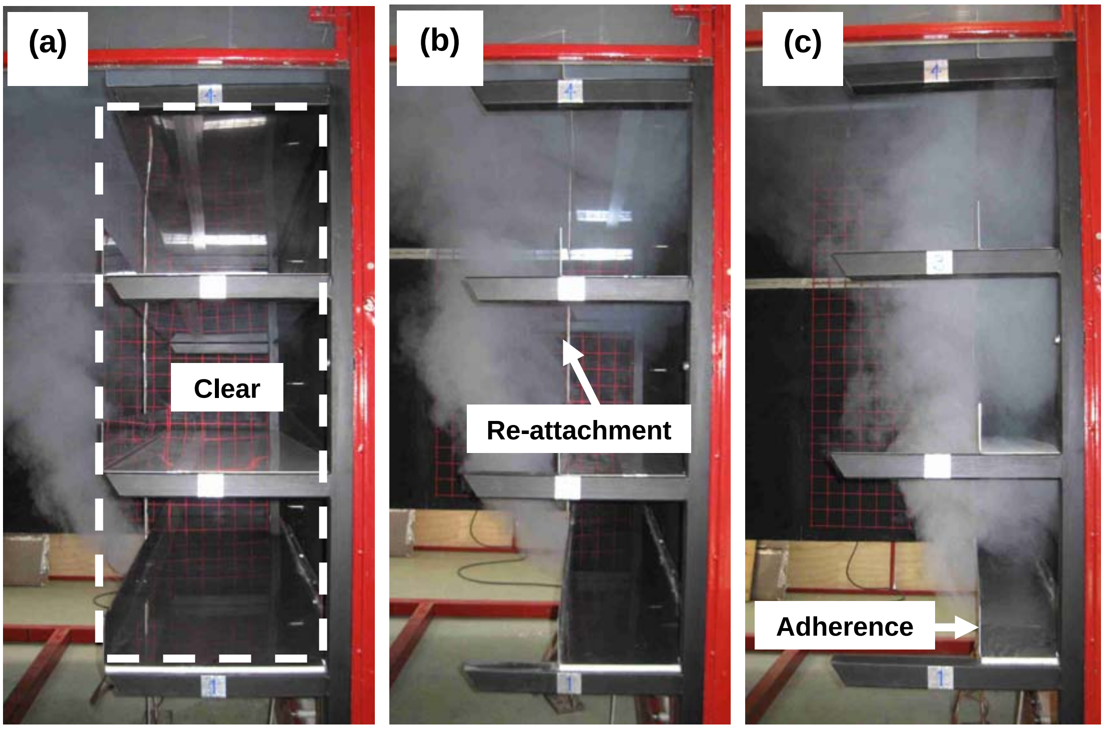


**Figure 3.** Plume behaviour observed in experiments (a) Free plume; (b) ‘Re-attached’ plume; (c) ‘Adhered’ plume.

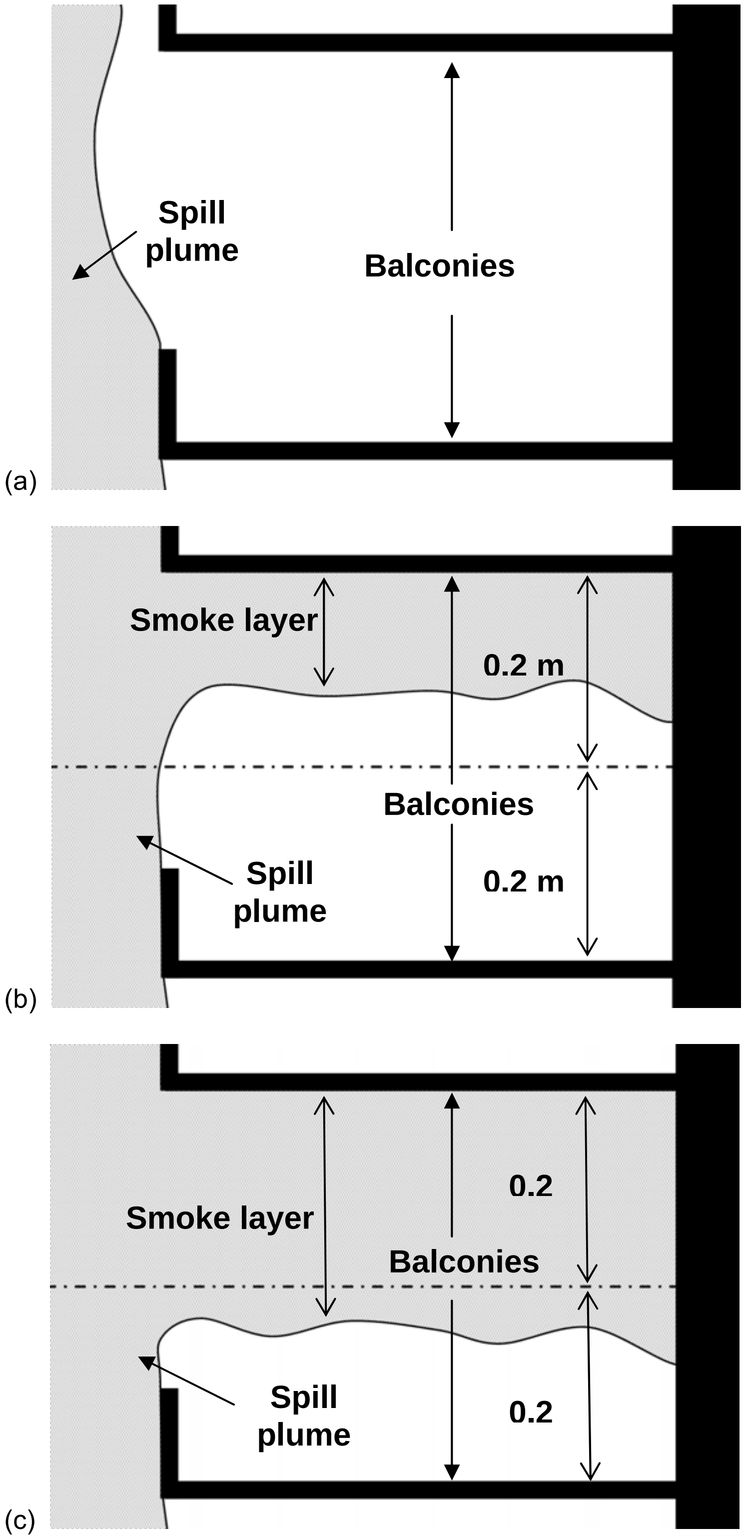


**Figure 4.** Classification of visual observations (a) Clear – no smoke observed visually between balconies; (b) Shallow smoke layer – smoke layer visually observed in upper half of balcony height; (c) Deep smoke layer – smoke layer visually observed in lower half of balcony height.

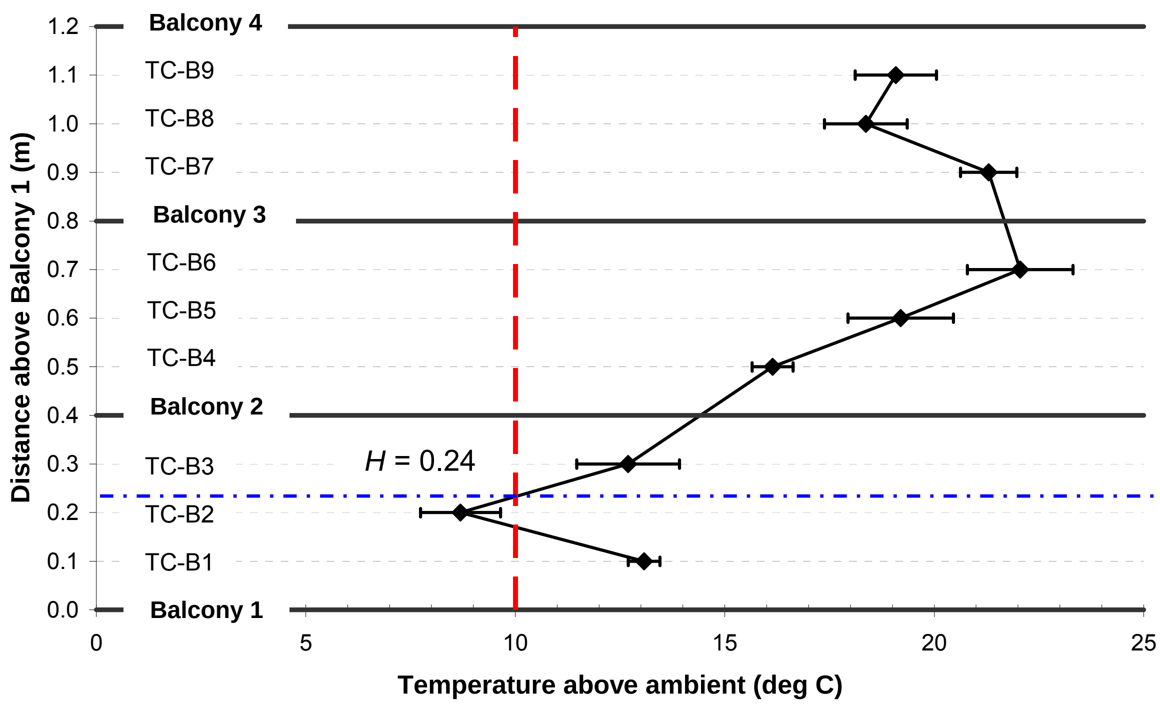


**Figure 5.** Temperature profile across balcony edges and determination of *H* for Experiment 1.

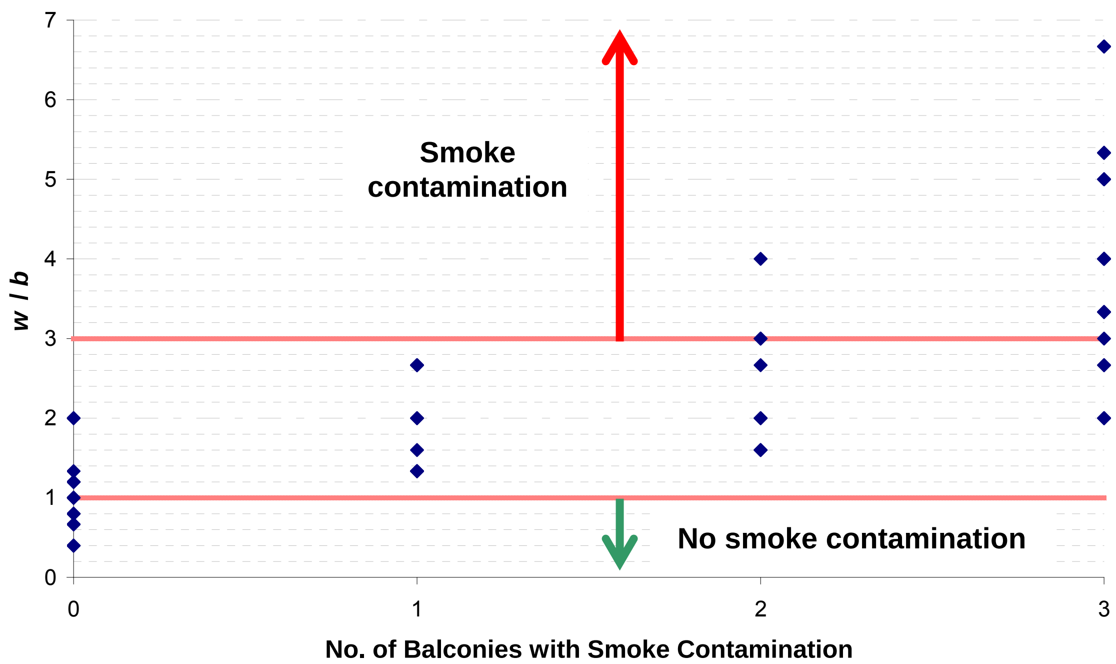


**Figure 6.** Plot of *w / b* against number of balconies with smoke contamination.

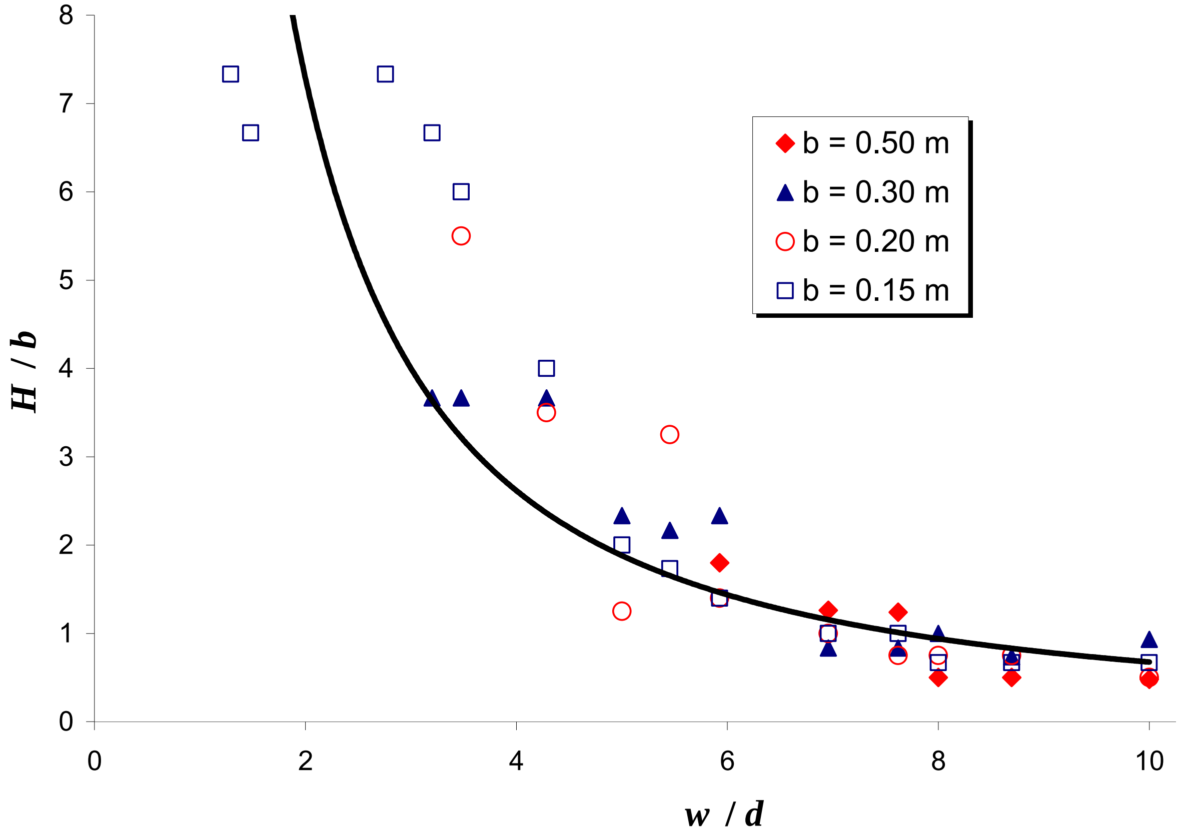


**Figure 7.** Non-dimensional correlation of *H* / *b* against *w* / *d*.

| Column | Number | Distance below edge of Balcony 1 (m) |
|---|---|---|
| A | 1 | 0.03 |
| | 2 | 0.07 |
| | 3 | 0.11 |
| | 4 | 0.15 |
| | 5 | 0.19 |
| | 6 | 0.23 |
| | 7 | 0.30 |
| | 8 | 0.40 |
| | 9 | 0.50 |

**Table 1.** Spacing of thermocouples along Column A.

| Column | Number | Balcony | Distance above edge of Balcony 1 (m) |
|---|---|---|---|
| B | 1 | 1 | 0.1 |
| | 2 | | 0.2 |
| | 3 | | 0.3 |
| | 4 | 2 | 0.5 |
| | 5 | | 0.6 |
| | 6 | | 0.7 |
| | 7 | 3 | 0.9 |
| | 8 | | 1.0 |
| | 9 | | 1.1 |
| | 10 | 4 | 1.3 |
| | 11 | | 1.4 |
| | 12 | | 1.5 |
| | 13 | 5 | 1.7 |
| | 14 | | 1.8 |
| | 15 | | 1.9 |

**Table 2.** Spacing of thermocouples along Column B.

| Experiment | Balcony breadth, *b* (m) | Plume width, *w* (m) | Balcony 1 | Balcony 2 | Balcony 3 | Aspect ratio, *w/b* |
|---|---|---|---|---|---|---|
| 1 | 0.50 | 1.0 | ✓ | ✓✓ | ✓✓ | 2.0 |
| 2 | | | ✓ | ✓✓ | ✓✓ | |
| 3 | | | ✓ | ✓✓ | ✓✓ | |
| 4 | | 0.8 | × | ✓ | ✓✓ | 1.6 |
| 5 | | | × | ✓ | ✓✓ | |
| 6 | | | × | × | ✓✓ | |
| 7 | | 0.6 | × | × | × | 1.2 |
| 8 | | | × | × | × | |
| 9 | | | (×) | (×) | (×) | |
| 10 | | 0.4 | × | × | × | 0.8 |
| 11 | | | (×) | (×) | (×) | |
| 12 | | | (×) | (×) | (×) | |
| 13 | | 0.2 | × | × | × | 0.4 |
| 14 | | | (×) | (×) | (×) | |
| 15 | | | (×) | (×) | (×) | |
| 16 | 0.30 | 1.0 | ✓ | ✓✓ | ✓✓ | 3.3 |
| 17 | | | ✓ | ✓✓ | ✓✓ | |
| 18 | | | ✓ | ✓✓ | ✓✓ | |
| 19 | | 0.8 | ✓ | ✓ | ✓✓ | 2.7 |
| 20 | | | ✓ | ✓✓ | ✓✓ | |
| 21 | | | × | ✓ | ✓✓ | |
| 22 | | 0.6 | × | ✓ | ✓✓ | 2.0 |
| 23 | | | × | ✓ | ✓✓ | |
| 24 | | | × | × | × | |
| 25 | | 0.4 | × | × | ✓ | 1.3 |
| 26 | | | × | × | ✓ | |
| 27 | | | × | × | × | |
| 28 | | 0.2 | × | × | × | 0.7 |
| 29 | | | (×) | (×) | (×) | |
| 30 | | | (×) | (×) | (×) | |
| 31 | 0.20 | 1.0 | ✓✓ | ✓✓ | ✓✓ | 5.0 |
| 32 | | | ✓ | ✓✓ | ✓✓ | |
| 33 | | | ✓✓ | ✓✓ | ✓✓ | |
| 34 | | 0.8 | ✓✓ | ✓✓ | ✓✓ | 4.0 |
| 35 | | | ✓ | ✓✓ | ✓✓ | |
| 36 | | | ✓ | ✓✓ | ✓✓ | |
| 37 | | 0.6 | × | ✓ | ✓✓ | 3.0 |
| 38 | | | ✓ | ✓ | ✓✓ | |
| 39 | | | × | ✓ | ✓✓ | |
| 40 | | 0.4 | × | × | ✓ | 2.0 |
| 41 | | | × | × | × | |
| 42 | | | (×) | (×) | (×) | |
| 43 | | 0.2 | × | × | × | 1.0 |
| 44 | | | (×) | (×) | (×) | |
| 45 | | | (×) | (×) | (×) | |
| 46 | 0.15 | 1.0 | ✓✓ | ✓✓ | ✓✓ | 6.7 |
| 47 | | | ✓✓ | ✓✓ | ✓✓ | |
| 48 | | | ✓✓ | ✓✓ | ✓✓ | |
| 49 | | 0.8 | ✓✓ | ✓✓ | ✓✓ | 5.3 |
| 50 | | | ✓✓ | ✓✓ | ✓✓ | |
| 51 | | | ✓ | ✓✓ | ✓✓ | |
| 52 | | 0.6 | ✓ | ✓✓ | ✓✓ | 4.0 |
| 53 | | | ✓ | ✓ | ✓✓ | |
| 54 | | | × | ✓ | ✓✓ | |
| 55 | | 0.4 | × | × | ✓✓ | 2.7 |
| 56 | | | × | × | ✓ | |
| 57 | | | × | × | ✓ | |
| 58 | | 0.2 | × | × | ✓ | 1.3 |
| 59 | | | × | × | ✓ | |
| 60 | | | × | × | ✓ | |

✓✓ : Deep smoke layer    ✓ : Shallow smoke layer    × : Clear    (×) : Clear - Inferred

**Table 3.** Observed and inferred extent of balcony smoke contamination.

| Experiment | Height of smoke contamination, *H* (m) | Experiment | Height of smoke contamination, *H* (m) |
|---|---|---|---|
| 1 | 0.24 | 31 | (0.10) |
| 2 | 0.25 | 32 | (0.15) |
| 3 | 0.25 | 33 | (0.15) |
| 4 | 0.62 | 34 | (0.15) |
| 5 | 0.63 | 35 | (0.20) |
| 6 | (0.90) | 36 | 0.28 |
| 7 | – | 37 | 0.65 |
| 8 | – | 38 | (0.25) |
| 9 | – | 39 | (0.70) |
| 10 | – | 40 | (1.10) |
| 11 | – | 41 | – |
| 12 | – | 42 | – |
| 13 | – | 43 | – |
| 14 | – | 44 | – |
| 15 | – | 45 | – |
| 16 | 0.28 | 46 | (0.10) |
| 17 | 0.22 | 47 | (0.10) |
| 18 | (0.30) | 48 | (0.10) |
| 19 | (0.25) | 49 | (0.15) |
| 20 | (0.25) | 50 | (0.15) |
| 21 | (0.70) | 51 | 0.21 |
| 22 | 0.65 | 52 | 0.26 |
| 23 | 0.70 | 53 | (0.30) |
| 24 | (1.10) | 54 | (0.60) |
| 25 | (1.10) | 55 | (0.90) |
| 26 | (1.10) | 56 | (1.00) |
| 27 | – | 57 | (1.10) |
| 28 | – | 58 | (1.00) |
| 29 | – | 59 | (1.10) |
| 30 | – | 60 | (1.10) |

(x.xx) : approximated value

– : no smoke contamination

**Table 4.** Values for *H* for the experiments.

| Plume width, *w* (m) | Heat release rate (kW) | Smoke layer depth, *d* (m) |
|---|---|---|
| 1.0 | 5 | 0.100 |
| | 10 | 0.115 |
| | 15 | 0.125 |
| 0.8 | 5 | 0.105 |
| | 10 | 0.115 |
| | 15 | 0.135 |
| 0.6 | 5 | 0.110 |
| | 10 | 0.120 |
| | 15 | 0.140 |
| 0.4 | 5 | 0.115 |
| | 10 | 0.125 |
| | 15 | 0.145 |
| 0.2 | 5 | 0.135 |
| | 10 | 0.155 |
| | 15 | 0.170 |

**Table 5.** Values for depth of smoke layer, *d* taken from Harrison [7].