

## EVALUATION OF THERMAL RADIATION MODELS FOR FIRE SPREAD BETWEEN OBJECTS

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### **ABSTRACT**

A current research initiative aims to produce a quantitative risk assessment tool, in the form of a probabilistic fire zone model for use in fire safety engineering design of buildings. In order to estimate if or when a remote object from a burning item will ignite, a radiation sub-model has been developed – part of which determines the thermal radiation received by the secondary object directly from the fire. There are a variety of methods presented in the literature that attempt to calculate the thermal radiation to a target from a flame. The performance of six of these methods: a spherical model, a simple correlation, three different cylindrical models and a planar model is investigated in this research. The predictions made by the models are compared with actual measurements of radiant heat flux around a propane gas burner. Different fire scenarios are represented by varying the burner geometry and heat release rate, with heat flux measurements being recorded in different locations around the fire. After comparing the measured data with predictions made by the theoretical radiation methods, the spherical (or point source) model was found to be the best performing method on average. This was unexpected given the relative simplicity of the model in comparison to some of its counterparts. Additionally, the point source model proved to be the most robust of the six methods investigated, being least affected by the experimental variables. Due to its performance and ease of implementation, the point source model has been recommended for use in the radiation sub-model within the probabilistic fire zone model software.

### **INTRODUCTION**

#### **Context and Motivation**

The dominant mechanism for the spread of fire within buildings is direct thermal radiation from the existing flames (Karlsson & Quintiere, 2000). In order to determine if or when certain objects adjacent to the fire may ignite or be damaged, one must be

able to predict the thermal radiation field surrounding the fire. This requires the radiant heat flux to be determined at various points in space.

The motivation for this research is that a thermal radiation model is desired to be input into an existing computer program named BRANZFIRE (Wade, 2008). This comprises part of a larger project being carried out between the Building Research Association of New Zealand Ltd (BRANZ Ltd) and the University of Canterbury, New Zealand. The overall project is being funded by the Foundation for Research, Science and Technology (FRST) and aims to include risk-based modelling in the forthcoming version of BRANZFIRE, thus creating a quantitative risk assessment (QRA) tool. This tool will address the inherent uncertainty in design fires by applying Monte Carlo sampling techniques to the likely fuel load within a compartment, and generating a range of design fire curves for the given occupancy class. The BRANZFIRE model will then perform deterministic calculations using each of the design fire curves as input, thus producing a range of zone model outputs. This should provide the user with a probabilistic overview of the compartment conditions, which captures the uncertainty that exists in real fires.

#### **Aim**

The specific part of the project explained in this paper relates to the thermal radiation and ignition sub-model that forms part of the design fire generator within the QRA tool. The purpose of the radiation and ignition sub-model is to determine if or when secondary fuel objects will ignite due to thermal radiation, given an initial burning item. The sub-model has three components: direct radiation from flaming objects, radiant exchange within a compartment and ignition of secondary fuel items. This paper deals exclusively with the first component (direct radiation from the flame), whilst the latter two components are described elsewhere by Baker et al. (2011).

This research involves evaluating the performance of six thermal radiation models of varying complexity

under a range of conditions. Models that are evaluated consist of a simple correlation, a spherical model, three different cylindrical models and a planar model. The effectiveness of these models is tested for a variety of situations so as to provide recommendations about the suitability of different radiation models for use in the QRA tool.

In order to evaluate the performance of the thermal radiation models being investigated, the predictions made by these models are compared with experimental data. To obtain this data, a comprehensive experimental programme has been undertaken. In these experiments, measurements of radiant heat flux are taken at various positions surrounding a gas burner. Details of the experimental programme are provided later in this paper.

The context of the investigation is with respect to compartment fires. As such, the fire dimensions and heat release rates tested are restricted to those that are representative of typical single-item compartment fires. Physical constraints with the laboratory and burner limited the maximum heat release rate tested to 300 kW.

## LITERATURE REVIEW

With respect to fire radiation models, the majority of the work has gone into predicting the thermal radiation from hydrocarbon pool fires (Beyler, 2002) and this forms the basis for this research. Rew, Hulbert, and Deaves (1997) outline that two approaches are generally used to determine the thermal radiation surrounding a fire: field models (computational fluid dynamics) and semi-empirical models. This research deals exclusively with semi-empirical models due to their relative ease of use.

### Shokri and Beyler Correlation

Shokri and Beyler (1989) developed a simple correlation based on experimental data from large-scale pool fire experiments. This method calculates the radiant heat flux at ground level as a function of the radial position of a vertical target. The heat flux received by the target is given by Equation 1:

$$\dot{q}'' = 15.4 \left( \frac{L}{D} \right)^{-1.59} \quad (1)$$

The correlation assumes that the target is vertical and located at ground level.

### Point Source Model

The point source model (Modak, 1977) is the simplest configurational model of a radiant source. The essence of the model is that radiation is assumed to emanate isotropically from a single point source

located at the centre of the flame, as shown in Figure 1a. The relationship varies with the inverse square of the distance  $R$  from the source, as given by the following equation:

$$\dot{q}'' = \frac{\dot{Q}_r \cos \theta}{4\pi R^2} \quad (2)$$

The location of the theoretical point source of energy is at the centre of the fire at the mid-height of the flame (see Figure 1b). The mean flame height,  $H$ , can be calculated by the Heskestad correlation:

$$H = 0.23 \dot{Q}^{\frac{2}{5}} - 1.02D \quad (3)$$

The distance,  $R$ , from the point source location to the target location can be determined using the Pythagorean theorem, as given below for the given application:

$$R = \sqrt{L^2 + H_T^2} \quad (4)$$

For a target located on the ground  $H_T = H/2$ , whilst for a target at the mid-height of the flame,  $H_T = 0$ . The total radiative energy output of the fire can be calculated by multiplying the fire heat release rate by the radiative fraction.

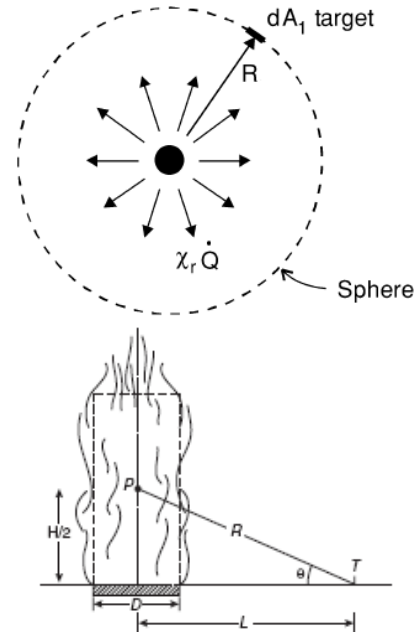


Figure 1: (a) Schematic of point source model (Karlsson & Quintiere, 2000), (b) Schematic and notation for point source model (Beyler, 2002)

The point source model is considered to perform poorly at heat fluxes at the target greater than 5 kW/m<sup>2</sup>, indicating that it is not a good choice when ignition of combustibles is to be considered (Beyler, 2002).

### Shokri and Beyler Detailed Method

To provide a simple yet realistic model of the flame the Shokri and Beyler (1989) model assumes the flame to be a cylindrical, black-body, homogeneous radiator with an average emissive power. It is assumed that thermal radiation is emitted from the surface of the cylinder and that radiation from non-visible gases is negligible (Iqbal & Salley, 2004).

Figure 2 provides a schematic and the nomenclature for the Shokri and Beyler detailed method for both vertical and horizontal targets. For targets above ground level, the cylinder must be broken down into two individual cylinders representing the flame below and above the height of the target, respectively.

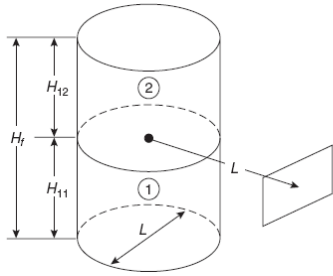


Figure 2: Two-cylinder representations of the configuration factor for target above ground level (Beyler, 2002)

The incident radiative flux to a target outside the flame is given by Equation 5.

$$\dot{q}'' = EF_{12} \quad (5)$$

The configuration factor is a function of the target location and the flame height and diameter.  $F_{12}$  always takes a value between zero and one, depending on these factors. The flame height can be determined using Equation 3.

Using the flame height and diameter, the configuration factors for horizontal ( $F_{12,H}$ ) and vertical ( $F_{12,V}$ ) targets can be calculated using Equations 6 and 7 (overleaf).

The maximum configuration factor at a point,  $F_{12,max}$ , is given by the vector sum of the horizontal and vertical components:

$$F_{12,max} = \sqrt{F_{12,H}^2 + F_{12,V}^2} \quad (9)$$

For vertically oriented targets located above ground level, Equation 7 must be applied for both cylinders 1 and 2 (see Figure 2), yielding two configuration factors,  $F_{12,V1}$  and  $F_{12,V2}$ . The total configuration factor is given by the sum of the two individual configuration factors.

$$F_{12,V} = F_{12,V1} + F_{12,V2} \quad (10)$$

Horizontal targets, on the other hand, only require one equation as the target will only receive thermal radiation from one of the two cylinders.

Shokri and Beyler (1989) explain it is important to note that the 'effective' emissive power of the flame is defined only in terms of a homogeneous flame radiation model. Rather than being the local emissive power measured at a specific point in space, it is more of an averaged emissive power over the whole flame. As the model was developed for pool fire scenarios, an expression for the 'effective' emissive power was formed in terms of the effective pool diameter. It is:

$$E = 58(10^{-0.00823D}) \quad (11)$$

Shokri and Beyler (1989) observed that the major uncertainty with their model is in the definition of the emissive power and not in the view factor model. In fact, it was found that for pool fires the cylindrical approximation of the flame is highly accurate at predicting view factors over a wide range of conditions. Comparison with experimental data suggests that the performance of the method is better at heat fluxes greater than 5 kW/m<sup>2</sup> at the target (Beyler, 1999).

### Mudan Method

For this model the radiative heat flux to a target is given by:

$$\dot{q}'' = EF_{12}\tau \quad (12)$$

The atmospheric transmissivity is assumed to be equal to 1 for the purposes of this work as it would not be practical to determine it within the QRA tool.

As with various other radiation models, this method centres around the assumption that the flame is cylindrical in shape. Here, the correlation for mean visible height of turbulent diffusion flames, developed by Thomas (1963), is used:

$$\frac{H}{D} = 42 \left( \frac{\dot{m}''_{\infty}}{\rho_a \sqrt{gD}} \right)^{0.61} \quad (13)$$

The maximum view factor at a point is determined using Equations 6 – 9.

The effective emissive power,  $E$ , of the flame can be determined by the following correlation:

$$E = E_{max} e^{(-sD)} + E_s (1 - e^{(-sD)}) \quad (14)$$

Where  $E_{max}$  is the equivalent black body emissive power (140 kW/m<sup>2</sup>),  $s$  is the extinction coefficient (0.12 m<sup>-1</sup>) and  $E_s$  represents the emissive power of smoke (20 kW/m<sup>2</sup>), as given by Beyler (1999).

Comparison with existing experimental data shows that the Mudan method is inherently conservative for predicting radiant heat fluxes.

$$F_{12,H} = \frac{\left(B - \frac{1}{S}\right)}{\pi\sqrt{B^2 - 1}} \tan^{-1} \frac{\sqrt{(B+1)(S-1)}}{\sqrt{(B-1)(S+1)}} - \frac{\left(A - \frac{1}{S}\right)}{\pi\sqrt{A^2 - 1}} \tan^{-1} \frac{\sqrt{(A+1)(S-1)}}{\sqrt{(A-1)(S+1)}} \quad (6)$$

$$F_{12,V} = \frac{1}{\pi S} \tan^{-1} \left( \frac{h}{\sqrt{S^2 - 1}} \right) - \frac{h}{\pi S} \tan^{-1} \frac{\sqrt{(S-1)}}{\sqrt{(S+1)}} + \frac{Ah}{\pi S\sqrt{A^2 - 1}} \tan^{-1} \frac{\sqrt{(A+1)(S-1)}}{\sqrt{(A-1)(S+1)}} \quad (7)$$

where

$$A = \frac{h^2 + S^2 + 1}{2S}, \quad B = \frac{1 + S^2}{2S} \quad (8)$$

$$S = \frac{2L}{D}, \quad h = \frac{2H}{D}$$

### Dayan and Tien Method

The third cylindrical model tested was that of Dayan and Tien (1974). Their method calculates the incident radiant heat flux from the flame to a target element,  $dA$ , with a unit normal vector  $\bar{n} = u\bar{i} + v\bar{j} + w\bar{k}$ . Figure 3 depicts Dayan and Tien's model.

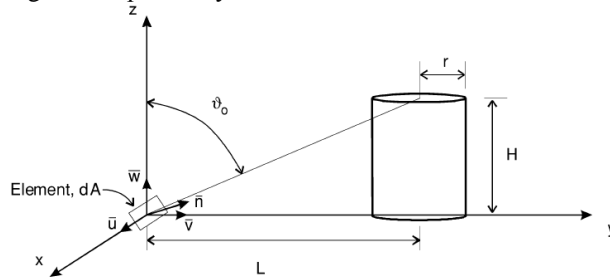


Figure 3: Schematic of radiation exchange between a target element,  $dA$ , and a homogeneous cylindrical flame (Karlsson & Quintiere, 2000)

The heat flux to the target is given by:

$$\dot{q}'' = \epsilon T_f^4 (F_1 + F_2 + F_3) \quad (15)$$

Where:  $\epsilon = 1 - e^{-0.7\mu}$ ,  $\mu = \frac{2r\kappa}{\sin \beta}$ ,  $\beta = \frac{\theta_0 + \frac{\pi}{2}}{2}$ ,

$$F_1 = \frac{u}{4\pi} \left( \frac{r}{L} \right)^2 (\pi - 2\theta_0 + \sin 2\theta_0),$$

$$F_2 = \frac{v}{2\pi} \left( \frac{r}{L} \right) (\pi - 2\theta_0 + \sin 2\theta_0)$$

$$F_3 = \frac{w}{\pi} \left( \frac{r}{L} \right) \cos^2 \theta_0. \quad (16)$$

Note  $u$ ,  $v$  and  $w$  are the components of  $\bar{n}$  in the  $i$ ,  $j$  and  $k$  directions, respectively (see Figure 3).

This method can be employed for predicting the radiant heat flux to targets located both at ground

level and at elevated positions (Dayan & Tien, 1974). For targets above ground level, the cylinder which approximates the fire must be divided into two cylinders, in a similar fashion to the Shokri and Beyler detailed method. The approximations provided in Equation 16 are deemed to be applicable for  $L/r \geq 3$  (Dayan & Tien, 1974), where  $r$  is the fire radius (m). The advantage of Dayan and Tien's method over that of Shokri and Beyler is the relative simplicity in its mathematical expressions.

### Rectangular Planar Model

In addition to the existing models and methods available in the literature, an attempt was made to develop an original model. The objective for this new model was to move away from the common assumption of a cylindrical flame shape and try and emulate the typical shape of furniture items.

The basis for the determination of the shape factor for this model is that the flame can be approximated as two perpendicular intersecting planes (see Figure 4). The line of intersection between these two planes extends vertically from the centre of the fire.

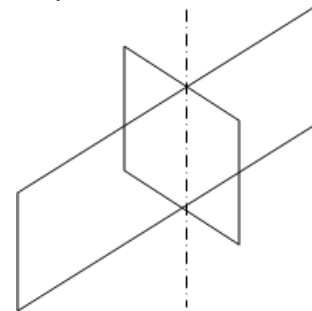


Figure 4: The rectangular planar model is made up of two perpendicular intersecting planes, which intersect at the centre of the fire

The rectangular flame shape assumption for this method is not an original concept. Drysdale (1999) describes that "the flame can be approximated by a simple geometric shape, such as a rectangle of height between 1.5 and 2 times the fuel bed diameter...". The radiant heat flux received by a differential target from planes  $\alpha$  and  $\beta$  is calculated using Equation 17 below.

$$\dot{q}'' = F_{12} \epsilon T_f^4 \quad (17)$$

Calculation of  $F_{12}$  uses an existing formula for the configuration factor between a finite rectangle and a differential element located at some distance from the rectangle (see Figure 5). Given by Howell (2008), the formula allows for the differential element to be oriented at any angle to the rectangle. The configuration factor from a finite rectangle to a differential element can be calculated using Equation 18 (overleaf).

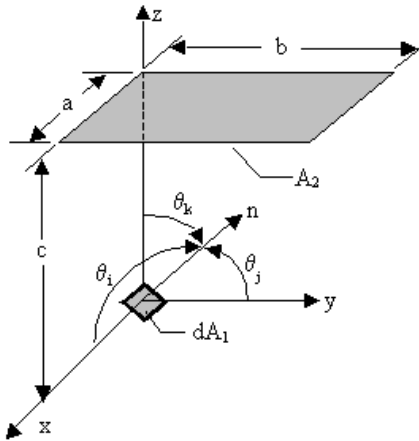


Figure 5: Pictorial representation and notation for the configuration factor from a finite rectangle to a differential element (Howell, 2008)

If the target does not align with the corner of the emitting plane, one must add or subtract configuration factors to achieve the overall configuration factor for the given scenario.

The flame emissivity is calculated using the following equation:

$$\varepsilon = 1 - e^{-\kappa D} \quad (20)$$

As this is a new model, there is currently no validatory data for the rectangular planar model.

## EXPERIMENTAL METHODOLOGY

### Scope of Experimental Work

The main purpose of the experimental work was to provide a comprehensive set of radiative heat flux data to be used for comparison with the thermal radiation models described previously. For the purposes of controllability and repeatability, a simple gas burner was used to model a burning object. This, however, represents a limitation in the experimental work.

### Fire Source

The fire was provided by one of three rectangular gas burners, each with a different length to width aspect ratio and a unit length of 300 mm. The aspect ratios tested were 1:1, 2:1 and 3:1; considered to represent

the shapes of a variety of common furniture items. The gas burner was able to be rotated to provide a different field of view to the heat flux gauges. Two different burner angles were tested,  $0^\circ$  and  $45^\circ$ , as shown in Figure 6.

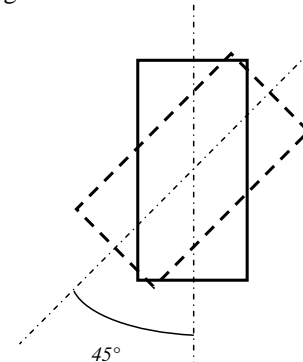


Figure 6: Relative angles of burner positions used in experiments. 2:1 burner aspect ratio depicted

### Laboratory

The gas burner was placed underneath a large extraction hood, so that the products of combustion could be collected and analysed using oxygen depletion calorimetry. Figure 7 shows a schematic of the layout of the laboratory.

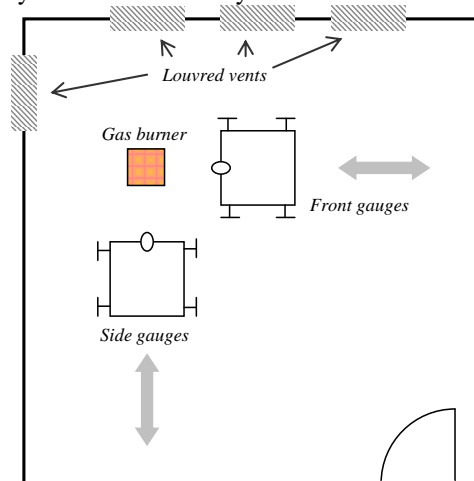


Figure 7: Schematic of laboratory layout (not to scale)

A total of eight Schmidt-Boelter heat flux gauges were used to measure the radiant heat flux from the fire during the experiments. Four gauges were mounted on each 'trolley', located at heights of 0.0, 0.5, 1.0 and 1.5 m above the base of the flame. Gauges were able to be oriented either vertically (facing the fire) or horizontally (facing upward). Furthermore, the gauges could be moved horizontally relative to the front face of the fire. The trolleys were also moved outward from the fire centre, to distances of 0.5, 0.75, 1.0, 1.5 and 2.0 m.

$$F_{12} = \frac{1}{2\pi} \left[ \tan^{-1} B \times \cos \theta_i + \tan^{-1} A \times \cos \theta_j + \frac{A \cos \theta_k - \cos \theta_i}{\sqrt{1+A^2}} \tan^{-1} \frac{B}{\sqrt{1+A^2}} \right. \\ \left. + \frac{B \cos \theta_k - \cos \theta_j}{\sqrt{1+B^2}} \tan^{-1} \frac{A}{\sqrt{1+B^2}} \right] \quad (18)$$

where

$$A = \frac{a}{c}; \quad B = \frac{b}{c} \quad (19)$$

All of the experimental work was filmed using a digital video camcorder so that the experimental flame height could be determined using computer analysis techniques.

The heat release rate of the fire was controlled via two mass flow controllers, arranged in parallel.

### Experimental Procedure

The total experimental programme consisted of 16 individual tests, where a test is defined as obtaining data at all distances for each heat release rate setting of a single burner geometry. Table 1 outlines the settings used for each of the 16 runs performed.

Table 1: Gauge and burner settings for each experimental test

Test #	Gauge Orientation	Gauge location	Aspect ratio	Burner angle
1	Vertical	Offset	2:1	0
2				45
3			3:1	0
4				45
5			1:1	0
6				45
7		Centre	1:1	0
8				45
9			3:1	0
10				45
11			2:1	0
12				45
13*	Horizontal	3:1	0	
14		3:1	0	
15		1:1	0	
16		2:1	0	

\* Repeat of Test 9 to check repeatability

### Flame Height Determination

The experimental flame height was determined using computer analysis of video images taken during the experiments. This was preferable to relying on visual observation, which tends to overestimate the actual

flame height (Beyler, 1986). In order to determine the mean flame height from the video footage of the experiments, an image processing computer software was employed. Developed at the University of Canterbury, *ImageStream* (Nokes, 2008) employs a systematic process for manipulating video images.

The video images recorded during the experiments were broken down into individual frames and then time averaged. This allowed an intensity plot to be created, with contours illustrating the probability of a flame existing at any particular location during that period (see Figure 6). From this the 0.5 probability, corresponding to 50 % flame intermittency, could be determined. The results were compared with a more crude manual method and found to be within 5 %; thus providing confidence to the *ImageStream* flame heights.

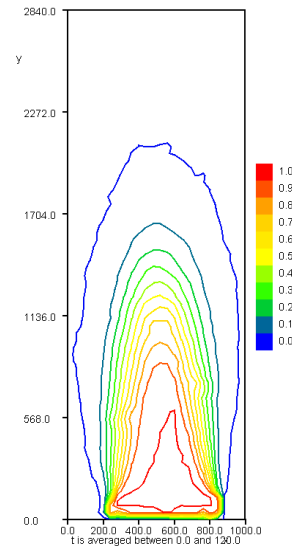


Figure 8: Time averaged contour plot for the 2:1 burner at 300 kW. Vertical axis gives flame height (in mm). Scale on right hand side gives probabilities of flames existing at different locations

The flame height values determined from the video image analysis were found to be considerably lower than predictions given by the Heskestad and Thomas correlations for the same scenario, as shown in Figure 9 for the 2:1 burner.



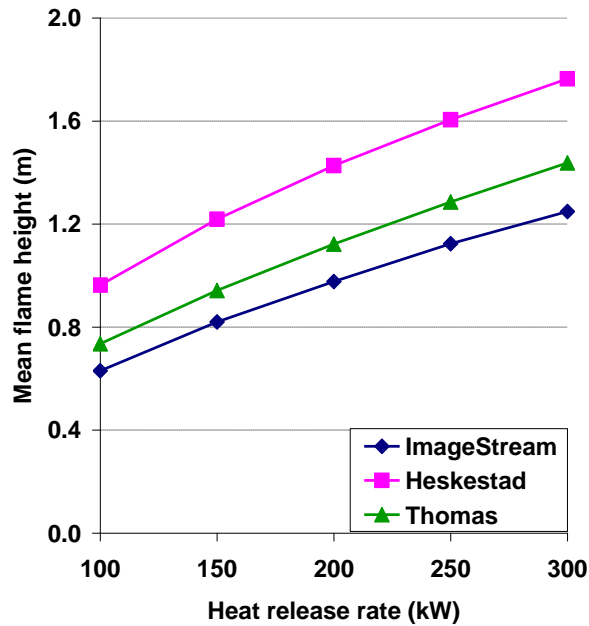


Figure 9: Mean flame height vs heat release rate for the 2:1 burner as determined using ImageStream, the Heskestad correlation and the Thomas correlation

### THEORETICAL MODEL ANALYSIS

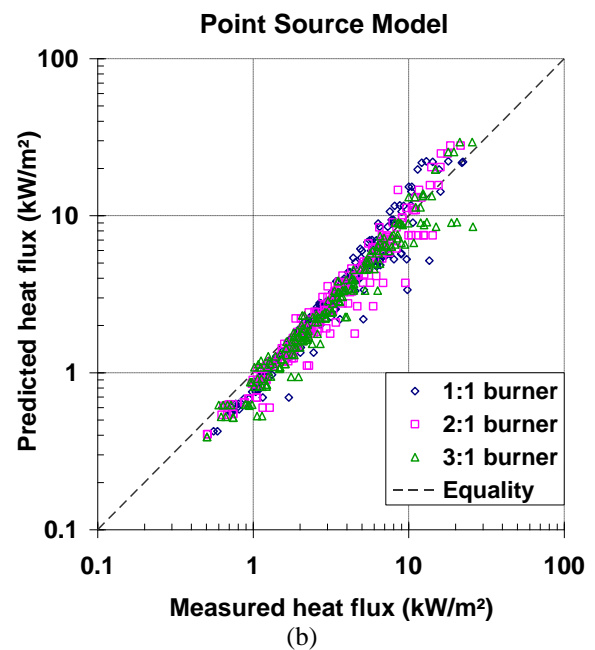
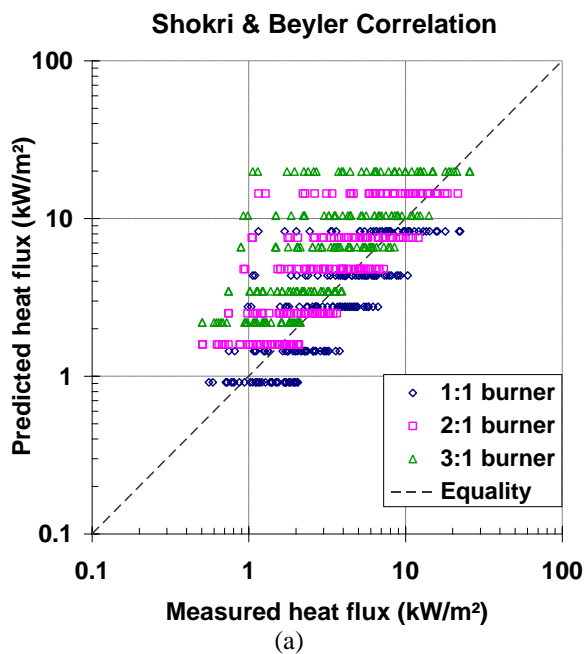
To evaluate the performance of the different radiation models, the experimental results were compared with predictions made by the models using the experimental parameters as inputs.

Figure 10(a)-(f) below compare the measured radiant heat flux with the predictions made by the theoretical models for the same conditions. The results are shown for three tests where the burner aspect ratio ranges from 1:1 to 3:1, the heat release rate is between 100 and 300 kW, the burner angle is  $0^\circ$ , the heat flux gauges are vertical and the gauges are located between 0.5 and 1.0 m from the burner centre and 0-1.5 m above the flame base.

Table 2 displays the average absolute percentage errors from the experimental results for each of the thermal radiation models across the 16 experiments. An absolute value is used so that positive and negative values do not have any 'cancelling out' effect. The table below shows that the accuracy of the different radiation models varies considerably.

Table 2: Summary of average absolute percentage errors from experimental results for all theoretical models

	Ave % error
Shokri & Beyler	103%
Point Source	29%
Shokri & Beyler Detailed	58%
Mudan	221%
Dayan & Tien	41%
Rectangular Planar	47%



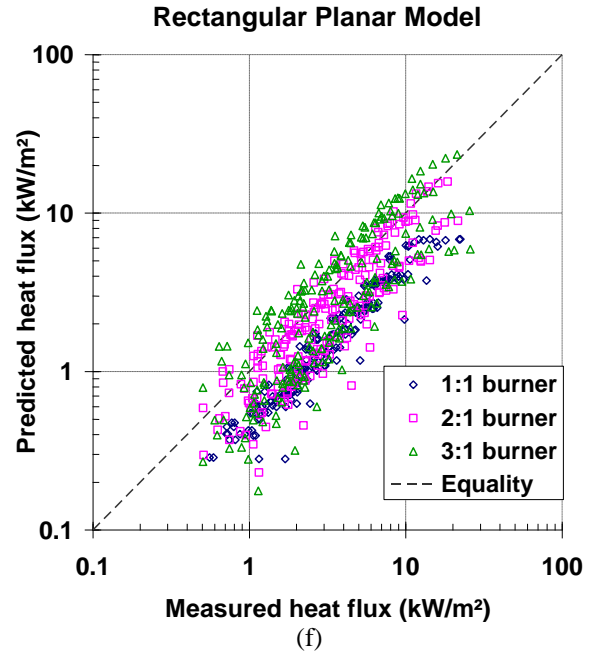
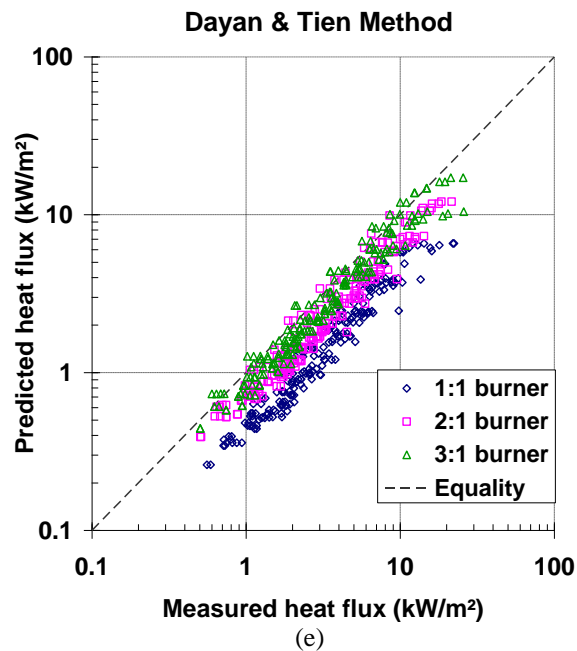
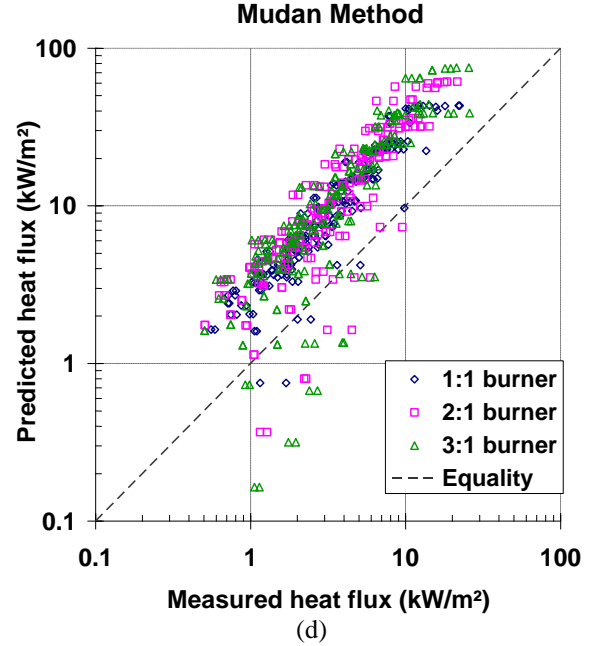
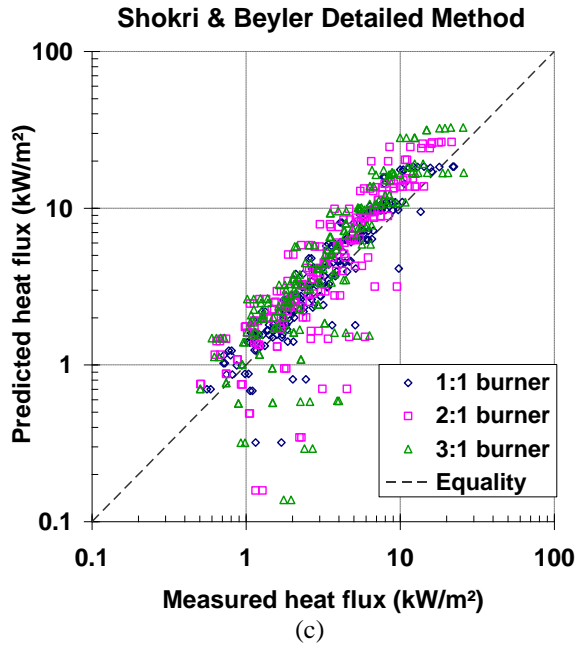


Figure 10: Comparison of measured and predicted radiative heat flux using the six models. Data taken from Tests 7, 9 and 11.

From Figure 10 and Table 2, it can be seen that the predictions made by the point source model are on average closer to the experimental data than any other model tested in this research. The fact that most data points are clustered around the equality line of Figure 10b, at both the high and low ends of the measured heat flux spectrum is rather surprising especially given the relative crudeness of the point source model compared with the more complex cylindrical methods. The next best performing model overall was the Dayan and Tien method.

To get a better understanding of which models perform best under different conditions, it is useful to further investigate the results presented in Table 2. In the following series of tables, the percentage errors of the models from the experimental results are broken down into different categories to be compared. The best performing model within each category is highlighted.

Table 3 provides the average percentage errors from the experimental results for each model in terms of



the target orientation. The point source model is confirmed as the best performing method for vertically oriented targets, whereas the Dayan and Tien method performed the best for horizontal targets. With the exception of the Shokri and Beyler correlation, which cannot predict the radiation heat flux to horizontal targets, and the Mudan method, all other models were considerably more accurate for vertically oriented targets compared to horizontally oriented targets.

Table 3: Average percentage error from experimental results for different target orientations

	Vertical	Horizontal
Shokri & Beyler	99%	N/A
Point Source	18%	76%
Shokri & Beyler Detailed	50%	89%
Mudan	224%	205%
Dayan & Tien	35%	71%
Rectangular Planar	40%	76%

A comparison of average percentage errors with varying burner aspect ratio is given in Table 4. Not only is the point source model the most accurate for all three burner aspect ratios tested, the model is also essentially equally accurate for each of the geometries. Other models, such as the Shokri and Beyler correlation and the Dayan and Tien method, exhibit significant change in the percentage errors for the different burner aspect ratios.

Table 4: Average percentage error from experimental results for different burner aspect ratios

	1:1	2:1	3:1
Shokri & Beyler	46%	90%	159%
Point Source	19%	18%	19%
Shokri & Beyler Detailed	34%	53%	62%
Mudan	199%	232%	240%
Dayan & Tien	54%	31%	20%
Rectangular Planar	45%	29%	45%

As shown by Table 5, the point source model was found to be the most accurate model when the measured radiant heat flux was less than 10 kW/m<sup>2</sup>. Above 10 kW/m<sup>2</sup>, the Shokri and Beyler correlation was marginally better and was the best performing model for higher heat fluxes. The Dayan and Tien method and rectangular planar model were the most consistent across a wide range of heat fluxes, although not the most accurate.

Table 5: Average percentage error from experimental results for different radiant heat flux ranges. From Tests 9, 11 and 13

	<5 kW/m <sup>2</sup>	5-10 kW/m <sup>2</sup>	>10 kW/m <sup>2</sup>
Shokri & Beyler	126%	48%	29%
Point Source	17%	17%	31%
Shokri & Beyler Detailed	46%	54%	49%
Mudan	205%	240%	238%
Dayan & Tien	36%	35%	36%
Rectangular Planar	44%	40%	41%

Table 6 summarises the average percentage errors for when targets are located centrally and offset in relation to the centreline of the burner. In general, all models seemed to be reasonably unaffected by the lateral change in target position, as can be seen by the fact that the percentage errors are very similar for the central and offset positions. This is somewhat expected, as the different lateral positions can easily be dealt with by the models by way of distances and angles, without any new assumptions required. As with many of the other results, the point source model was found to be the best performing model under different lateral target positions.

Table 6: Average percentage error from experimental results for different target positions

	Central	Offset
Shokri & Beyler	101%	97%
Point Source	19%	17%
Shokri & Beyler Detailed	48%	52%
Mudan	215%	234%
Dayan & Tien	36%	33%
Rectangular Planar	45%	34%

Similarly, all of the models seemed very capable at dealing with different burner angles, as shown in Table 7. It follows, therefore, that the point source model was the most accurate for both burner angles.

Table 7: Average percentage error from experimental results for different burner angles

	0°	45°
Shokri & Beyler	98%	100%
Point Source	18%	19%
Shokri & Beyler Detailed	48%	51%
Mudan	221%	227%
Dayan & Tien	35%	35%
Rectangular Planar	38%	41%

## **DISCUSSION**

Under the conditions tested in this work, the Shokri and Beyler correlation struggled to accurately predict the radiant heat flux to targets located at many different positions. Due to its simplistic nature, the model is unable to predict changes in radiant heat flux with varying heat release rate or height above the burner surface. Furthermore, it cannot be used when the target is horizontally oriented. The Shokri and Beyler correlation was best suited to low burner aspect ratios and high heat fluxes. The shortcomings of this correlation arise from the fact that the correlation was formed based on heat flux measurements conducted around large, circular, liquid pool fires. Also, only two inputs are required for the model; none of which relate to the fire's energy release rate or emissive power. All of this resulted in an average percentage error of around 100 % from the experimental results.

The point source model was seen to perform surprisingly well for predicting the radiant heat flux around a propane burner. In fact, it was the best performing method overall out of the six different models investigated. Taking into account all of the experimental data, the point source model resulted in an average percentage error of 29 %, as shown in Table 2. However, this was reduced to 18 % when the predictions to horizontal targets were excluded. The point source model proved to be the most capable model at dealing with varying fire source geometries, with essentially no difference in percentage errors for the three burner aspect ratios tested. The rather common advice of restricting the use of the point source model to applications where the radiant heat flux is 5 kW/m<sup>2</sup> or less was found to be irrelevant in this application.

The Shokri and Beyler detailed method was found to be the fourth most accurate model, with an average percentage error of 58 %. The model was largely let down by its performance in dealing with horizontal targets and high burner aspect ratios. The performance of this model was made considerably worse when the flame height was determined using Heskestad's correlation, rather than *ImageStream*. This suggests that the model is too reliant on the mean flame height value, which can be a significant issue if the correlation is unable to accurately predict the flame height. Furthermore, it is considered that the experimental conditions tested in this work are likely outside the realistic bounds of Equation 8 for determining the effective emissive power of the flame. It was, however, outside the scope of this research to attempt to modify the expression for the effective emissive power or determine a more suitable value for the propane burners used.

The Mudan method proved to be the least accurate model out of the six tested in this work. The effective emissive power calculation appeared to be inappropriate for the propane gas burner used in the experiments, resulting in an average over-prediction of 221 %. Other researches have found the Mudan method performs much better than what was found in this work, when significantly larger fire diameters are used.

The Dayan and Tien method was the second most accurate model, having an average percentage error of 41 % from the measured data. This was the best performing cylindrical model and the most accurate method for predicting the radiant heat flux to horizontal targets. The percentage errors of this model were only slightly affected by the use of the flame height correlation rather than the *ImageStream* flame height and the model was able to deal with a wide range of heat fluxes with no consequence to its accuracy. The Dayan and Tien method was found to be rather sensitive to two inputs; namely the effective absorption coefficient and the flame temperature.

Finally, the rectangular planar model was found to be the third most accurate; however, was not as robust as some of the other models at coping with changing conditions. This model strangely performed best for the 2:1 burner aspect ratio and the offset targets rather than the central ones. The predictions were quite sensitive to the effective absorption coefficient and the flame temperature; however, a sensitivity study showed that the representative values used in the calculations were very near the optimal values for minimising the percentage error from the experimental data. This model had more flexibility than the others in terms of modelling different fire source geometries. However, the drawback of added flexibility is more complex computer programming.

### **Limitations to Results**

Although this work has attempted to simulate a range of conditions and scenarios, there are still many limitations to the results. The main scenario of interest was item-to-item fire spread within compartments. Accordingly, the experimental programme was set up to emulate likely single-object fires within a compartment. The findings therefore may only be applicable to fires of this scale and not to other fire scenarios, such as large, open fires.

Ideally, when investigating single-item fires it would be most useful to burn real objects, such as items of furniture, and measure their radiative properties. However, it was not economically or practically viable to do this for the amount of data that was desired. The propane gas burner provided a very

controlled, repeatable fire from which extensive radiative heat flux measurements could be taken. Although it was intended to represent a compartment fire, the propane fuel would have different radiative properties than the solids that are the likely fuel source in compartment fires.

Other limitations were naturally imposed by the equipment and the laboratory in which the experiments were carried out. The delivery of propane gas and the flame height observed meant that heat release rates greater than 300 kW were not viable in this research. Also, the effective diameter of the fires investigated were limited by physical constraints and were significantly smaller than experimental work carried out by other researchers – some which were at least 10 m in diameter.

Overall, it cannot be said with certainty that the findings of this work extend to any application outside the conditions of the experimental programme. One can, however, make reasonable assumptions to extend the results to fires of a similar fuel and order of magnitude as those tested in this work.

## CONCLUSIONS

When recommending one of the models for use in the radiation sub-model within the QRA tool, one must consider two main factors. Firstly, the accuracy of the model must be considered. Obviously, as the function of the model will be to predict the radiant heat flux from a fire at given locations around the room, one wishes the predictions to be as close an approximation of the real scenario as possible. It has been determined that the point source model was, on average, the most accurate model under the conditions tested. In addition, when selecting a model for BRANZFIRE, it is important that the model is accurate over a wide range of conditions. The point source model satisfies this, as it was found to be not only the most accurate model, but also the most robust.

The second consideration of importance when selecting the most appropriate model is the ease of implementation into BRANZFIRE. Coupled with this is the ease of application by the end-user. A model that is very complex, such as the rectangular planar model, would be somewhat difficult to program into the software so that it could be applied in a user-friendly manner by the operator. Often zone models such as BRANZFIRE are used for design purposes, where the exact locations and orientations of objects within rooms are unknown. This introduces the need for a great number of assumptions to be made by the operator and less experienced users may run into

trouble. A simpler model, like the point source model, is not orientation-specific and therefore always assumes the maximum heat flux at a given location. This is of great importance in design purposes and necessarily takes some responsibility away from the user.

The point source model satisfies both of the important considerations discussed above: it was found to be the most accurate model and apart from the Shokri and Beyler correlation, would be the simplest model to program into the BRANZFIRE software. It follows, therefore, that the recommended thermal radiation model for use in a radiation sub-model within BRANZFIRE is the point source model.

For a more detailed review of the models discussed in this paper, the reader is referred to the thesis by Fleury (2010).

## NOMENCLATURE

$A_2$	Finite rectangle area (rectangular planar model)	(m <sup>2</sup> )
$dA_1$	Differential target element	(-)
$D$	Fire/pool diameter	(m)
$E$	(Effective) emissive power of flame	(kW/m <sup>2</sup> )
$E_{max}$	Equivalent black body emissive power	(kW/m <sup>2</sup> )
$E_s$	Emissive power of smoke	(kW/m <sup>2</sup> )
$F_{12}$	Configuration/shape/view factor from fire to target	(-)
$F_{12,max}$	Maximum configuration factor at a point	(-)
$g$	Gravitational acceleration	(9.8m/s <sup>2</sup> )
$H$	Flame height	(m)
$H_T$	Height of target relative to height of equivalent point source at H/2	(m)
$L$	Distance of target from centre of fire/pool	(m)
$\dot{m}''_{\infty}$	Mass burning rate per unit area	(kg/m <sup>2</sup> s)
$\bar{n}$	Unit normal vector to differential target element	(-)
$\dot{Q}$	Heat release rate of fire	(kW)
$\dot{Q}_r$	Radiative energy output of fire	(kW)
$\dot{q}''$	Radiant heat flux	(kW/m <sup>2</sup> )
$R$	Distance from point source to target	(m)
$r$	Fire/pool radius	(m)
$s$	Extinction coefficient	(m <sup>-1</sup> )
$t$	Time	(s)
$T_f$	Flame temperature	(K)
$u$	Component of $\bar{n}$ in i direction	(-)

$v$	Component of $\bar{n}$ in j direction	(-)
$w$	Component of $\bar{n}$ in k direction	(-)
$x$	Position of target relative to origin in i direction	(m)
$y$	Position of target relative to origin in j direction	(m)
$z$	Position of target relative to origin in k direction	(m)

### Greek Symbols

$\beta$	Mean value of $\theta$ in Dayan & Tien method	(radians)
$\varepsilon$	Emissivity	(-)
$\theta$	Angle between normal to target and line of sight from target to point source location	(radians)
$\theta_0$	Angle between $z$ axis and line of sight from target to centre-top of cylinder, Dayan & Tien method	(radians)
$\kappa$	Effective flame absorption coefficient	( $m^{-1}$ )
$\rho_a$	Ambient air density	( $kg/m^3$ )
$\sigma$	Stefan-Boltzmann constant	( $5.7 \times 10^{-8} W/m^2K^4$ )
$\tau$	Atmospheric transmissivity	(-)
$\chi_r$	Radiative fraction	(-)

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