PERGAMON

International Journal of Heat and Mass Transfer 42 (1999) 3253–3265

International Journal of HEAT and MASS TRANSFER

Measurement of doorway flow field in multi-enclosure building fires

Yaping He [1]

Centre for Environmental Safety and Risk Engineering, Victoria University of Technology, PO Box 14428, MCMC, Melbourne, VIC 8001, Australia

Received 17 February 1998; received in revised form 19 November 1998

Abstract

This paper discusses fire induced smoke movement and associated species transport in a multi-enclosure compartment building. A set of steady state and transient state fires experiments have been conducted in a full-scale building. The distributions of various physical parameters such as temperature, velocity and species concentration, were measured. Particular attention is given to the flow fields at the doorway which connects the room of fire origin and a corridor. The experimental results indicated the effects of mixing between the hot upper layer smoke and the relatively cool lower layer air in the corridor. Some data processing techniques are also explained.

1. Introduction

Understanding of smoke movement in the built environment is a prerequisite for undertaking risk assessment of building fires. Fire induced flow in the built environment has been a major topic in fire research. There have in the literature been extensive theoretical analyses and experimental investigations of flow of air and gases in room fires. Unless intervened by mechanical ventilation systems the movement of smoke in a building subjected to a fire is always driven by buoyancy forces. The hot product gas, soot and air mixture tends to move upwards, creating the so-called layering, or stratification effect [1,2]. Pertaining to ventilation conditions, the lower layer of relatively cool air in an enclosure may provide the building occupant with crucial passage and time to evacuate. The formation of smoke layer and time-dependent physical conditions in various location of multi-enclosure buildings have been the major topics in fire related fluid dynamics research [3,4].

The buoyancy driven movement of smoke in a building is often through vent openings which connect various enclosures of the building. Therefore, flow velocity and temperature distributions at vent openings, as well as inside enclosures, have been the focus of much research. A detailed analysis of fire induced flows through openings using hydraulic theory and a bench scale apparatus was given by Prahl and Emmons [5]. McCaffrey and Quintiere [6] studied buoyancy driven countercurrent flows generated by a fire source of constant heat release rate in a full-scale corridor burn room facility. Their measured velocity profiles at the entrance and at a location downstream of the entrance, and the mass balance analysis based on these profiles indicated strong mixing and entrainment flows in the corridor connecting to the burn room. Fire induced flows under steady state burning conditions were also investigated experimentally by Steckler et al. [7]. In their study, the three-dimensional effect and the influence of the fire source position inside the burn room were considered.

[1] Present address: Scientific Services Laboratory, 177 Salmon Street, Port Melbourne 3207, Australia

0017-9310/99/$ - see front matter
PII: S0017-9310(98)00385-8

Nomenclature

C	calibration factor
H	height (m)
m	mass flow rate (kg/s)
N	number of measurement points
P	standard atmospheric pressure ($=1.013\times10^5$ Pa)
r	density or temperature ratio
R	gas constant of air ($=288$ J/kg K)
t	time (sec, min)
T	temperature (K, °C)
u	flow velocity (m/s)
W	door width (m)
x	dummy variable
y	coordinate variable, or height above floor (m)
Y	species concentration (mass fraction).

Greek symbol

ρ	density (kg/m^3).

Subscripts

av	average
c	calibration condition
d	door
e	exhaust stream
i	inlet stream
j	index
k	index
n	neutral plane.

The conditions of the counter-current flows at a doorway joining two adjacent enclosures are indicative of the conditions in the corresponding source regions. For example, the average exhaust flow conditions in Fig. 1 reflect the conditions in the upper layer of the burn room and the average conditions of the return air flow that in the lower layer of the adjacent room. Due to strong counter-current flows, mixing also occurs in the region near a vent opening. Although this phenomenon has been addressed in fire modelling and vent flow calculations [8], there has been a lack of experimental evidence to demonstrate the overall effect of such mixing on the transport of enthalpy and species across the opening.

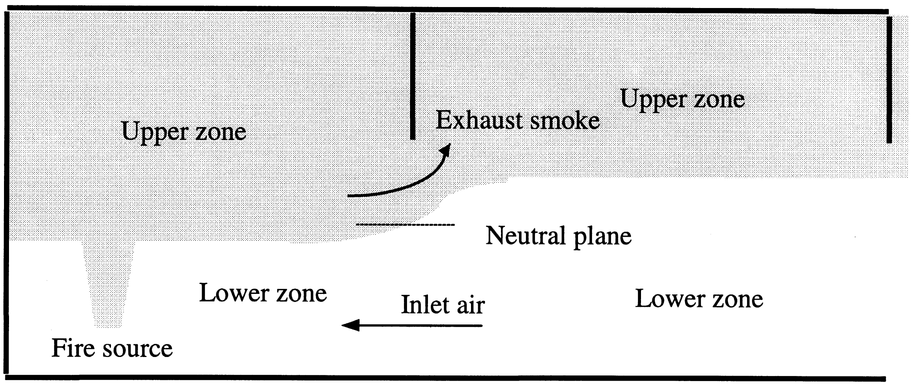

Fig. 1. A simplified sketch of fire induced flow in a multi-room scenario.

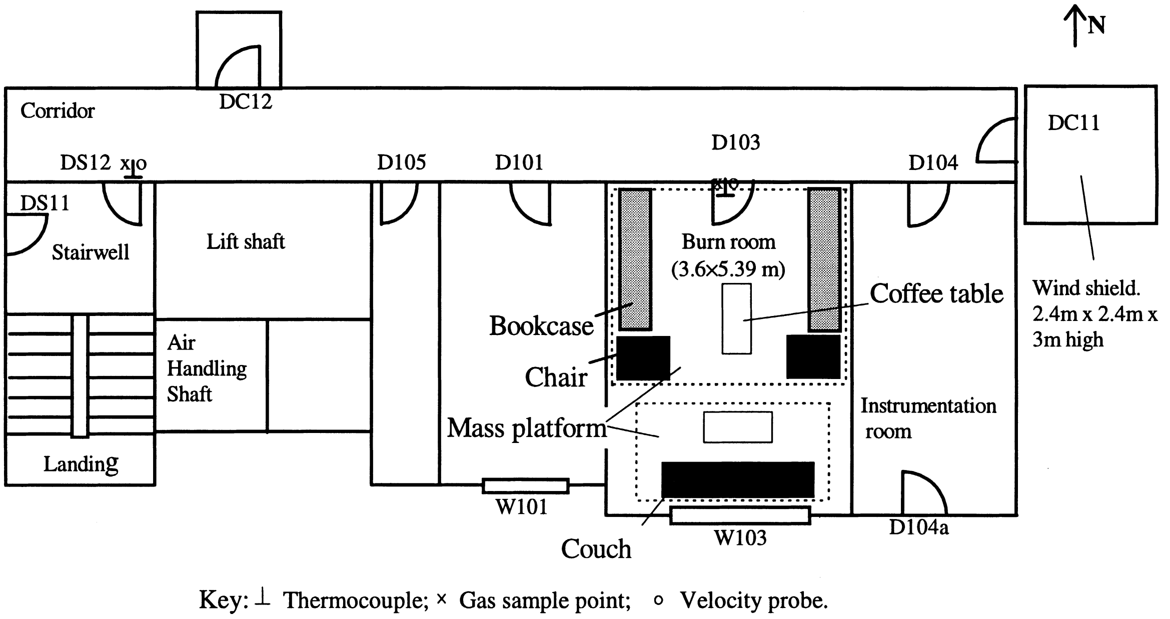

Fig. 2. Instrumentation and layout on Level 1 of the Experimental Building—Fire Facility.

Measurement of gas composition in full-scale fire tests is one of the practical methods for toxic hazard assessment and, as pointed out by Purser [9], is the most valuable method since it reveals fire growth and product yield directly and offers first hand test results for combustion product-based approach to toxicity

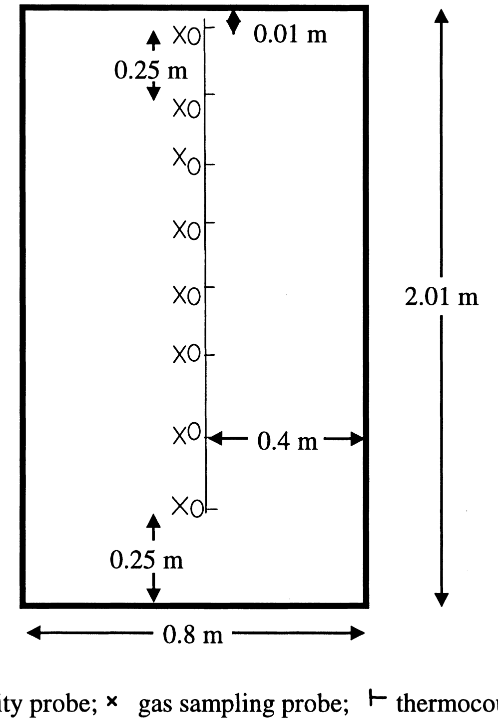

Fig. 3. Instrumentation at the burn room door.

assessment. Most of the previous investigations of fire induced flows were concerned with the transport of enthalpy and momentum. Emphasis was given to the measurement of temperature and velocity fields and the establishment of theoretical and empirical correlations for flow coefficient, volume and mass flow rates [10,11]. The measurement of the field of species concentration was dealt with insufficiently and very little is known about the transport of species in realistic transient burning fires.

In the present study, an attempt is made to reveal, through full-scale fire experiments, the flow field around the doorway in a multi-enclosure building. Of particular interest are the distributions of temperature, velocity and oxygen concentrations along the centre line of the doorway. The average schemes based on transport terms are applied to the measured parameter profiles to obtain the average temperature and species concentration in the counter flow streams at the door openings. The average quantities can be used to estimate the transport rates of mass, enthalpy and species.

2. Experimental arrangement

A series of fire experiments were conducted in a full-scale prototype building which has four storeys connected by a lift shaft, a stairwell and air handling shafts. Fig. 2 is a scheme of the first floor on which the fire source was located. The layout of the other levels, except for Level 4, are similar to Level 1. Level 4 consisted of a corridor only. Room 103 on the first floor was used as the burn room which has a size of $5.39 \times 3.69 \times 2.4$ m high. The burn room was connected to the first floor corridor ($15.6 \times 1.4 \times 2.57$ m high) through a door opening of standard size (0.8×2.01 m) located on the north face of the room. Opposite to this door was a 2.4×1.5 m high window in a standard three-pane configuration (two small sliding panels 3 mm thick and one fixed glass sheet 4 mm thick).

The burn room was equipped with two weighing platforms. Eight bidirectional velocity probes, eight gas sampling probes and eight thermocouples were placed vertically along the centre line of the burn room door as shown in Figs. 2 and 3. The top of the probe tree was 10 mm below the top edge of the door. The vertical distance between any two adjacent probe groups was 250 mm. All thermocouples used were of chromel–alumel ('K' type) and were 1.5 mm mineral insulated and metal sheathed (MIMS). Pressure differences across the velocity probes were measured with differential pressure transducers. The oxygen sensors in the gas analyser were galvanic cell type with a range of 0–25% by volume and a resolution better than 0.01%. For oxygen concentration measurement, the sample gas stream was cooled, dried and filtered before passing through the gas analyser. Data signals were sampled at a nominal frequency of 1 Hz. Raw data were smoothed over 15 points before further analysis to obtain the transport rate of various quantities.

The results of two experiments are reported in this paper. The first experiment involved steady state burning fire with a propane burner. The burner was placed in the centre of the burn room and its heat release rate was set at 200 kW. The second experiment was a transient fire using realistic furniture as fuel load. The fuel configuration in the burn room for this experiment is illustrated in Fig. 2. The fuel load included a three-seat couch, two single-seat sofas, two coffee tables, and two book shelves with phone books. The couch and one coffee table were located on the small platform, the others were on the large platform. The total fuel load is 542.1, corresponding to a fuel load density of 27.9 kg/m^2 of floor area. The ignition source was a 150 g wooden crib placed at the centre of the three-seat couch on the small platform (Fig. 2). In both experiments, the building was naturally ventilated internally and was functionally closed to the outside, that is, all the doors and windows to the outside were closed. However, small leakage areas existed in the doors and windows. Inside the building, the stair doors to the corridors of every floor and the burn room door (D103) were open and all other doors and windows were closed.

3 . Data reduction and error analysis

Experimental data analysis to generate appropriate and meaningful physical parameters for the purpose of computer model validation has been a challenging task. He [12] reviewed the traditional volume weighted average scheme and proposed a reciprocal or mass weighted average scheme for obtaining the average zone quantities. Another average scheme proposed by He [12] is based on transport terms, which requires the knowledge of velocity as well as the parameter distributions. Since velocity, temperature and oxygen concentration profiles were measured at the door openings in the present study, this scheme is readily applicable to the measured data.

The measured discrete flow velocity distributions along the vertical centre line of the doorway are linearly interpolated to obtain the neutral plane H_n at which velocity reading is zero. The smoke exhaust mass flow rate m_e is calculated from

$$m_e = W\int_{H_n}^{H_d} \rho u \, dy = W\frac{P}{R}\int_{H_n}^{H_d} \frac{u}{T} \, dy \qquad (1)$$

The three-dimensional effect may come into play when

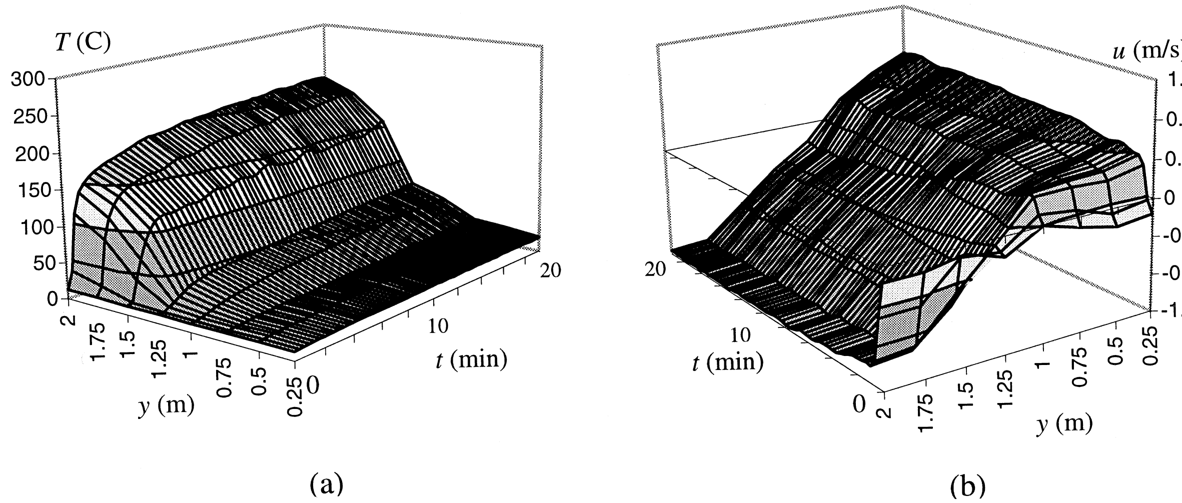

Fig. 4. Measured profiles along the centre line of the burn room door (steady state fire): (a) temperature; (b) velocity.

the opening width is considerably larger [13]. However, when the opening width is significantly smaller than the height, the assumption of two-dimensional flow field at the doorway can be justified [6].

For the exhaust stream, the average temperature and species concentrations based on transport terms are estimated according to

$$T_{\mathrm{ave}} = \frac{\int_{H_{\mathrm{n}}}^{H_{\mathrm{d}}} u\,\mathrm{d}y}{\int_{H_{\mathrm{n}}}^{H_{\mathrm{d}}} \frac{u}{T}\,\mathrm{d}y} \tag{2}$$

and

$$Y_{\mathrm{ave}} = \frac{\int_{H_{\mathrm{n}}}^{H_{\mathrm{d}}} \frac{uY}{T}\,\mathrm{d}y}{\int_{H_{\mathrm{n}}}^{H_{\mathrm{d}}} \frac{u}{T}\,\mathrm{d}y} \tag{3}$$

The expression for the inlet stream mass flow rate to the burn room through the door opening is the same as Eq. (1) except for a change in the integration limit

$$m_i = W\frac{P}{R}\int_0^{H_{\mathrm{n}}} \frac{u}{T}\,\mathrm{d}y \tag{4}$$

Similarly, with a change of integration region from $[H_{\mathrm{n}}, H_{\mathrm{d}}]$ to $[0, H_{\mathrm{n}}]$, the average quantities for the inlet stream can be obtained from Eqs (2) and (3). By definition, the product of average temperature, mass flow rate and specific heat of constant pressure gives an estimate of enthalpy transport rate; and the product of Y_{av} and m is the species transport rate [12].

Velocity, temperature, and species concentration profiles were measured at a finite number of discrete points along the centre line of the door opening. It is assumed that all the parameters are linearly distributed between any two adjacent measurement points. The parameter profiles are also linearly extrapolated down to the floor and up to the door frame. Under the aforementioned assumptions, numerical expressions can be worked out for various integral terms in Eqs (1)–(4). Readers are referred to the Appendix for details of these expressions. The method of obtaining heat release rate from the measured total fuel mass loss in the transient fire experiment was described in Ref. [14].

Errors in temperature measurement due to radiation effect are expected. In an earlier study conducted in the present experimental facility, the temperature measurement error was estimated to be less than 6% in terms of Kelvin [15]. However, the contribution of temperature measurement error to the mass transport term in Eq. (1) is reduced by half, or 3%, since the product of ρ and u is inversely proportional to the square root of the absolute temperature.

Let ΔP be the differential pressure reading across the velocity probe. The measured flow velocity u is related to ΔP and absolute temperature T by

$$u = C(T/T_{\mathrm{c}})^{0.5}\Delta P^{0.5} \tag{5}$$

where C is a calibration factor, T_{c} is the absolute temperature at the calibration condition. Therefore, the ratio of u/T can be written as

$$\frac{u}{T} = \frac{C_0}{T}\left(\frac{T\Delta P}{T_0}\right)^{0.5} = \frac{C_0}{(T_0)^{0.5}}\left(\frac{\Delta P}{T}\right)^{0.5} \tag{6}$$

It is seen from the above equation that a relative error in the measured temperature $\delta T/T$ would result in a relative error in the calculated mass transport by

$$\frac{\delta(u/T)}{u/T} \propto \frac{1}{2}\frac{\delta T}{T} \tag{7}$$

The oxygen mass flow rate across the doorway can be used to analyse the oxygen consumption rate inside the burn room and hence obtain an estimate of heat release rate based on the oxygen consumption principle. This topic has been discussed in Ref. [14]. In this paper, only the measured parameter distributions and the averaged quantities are presented.

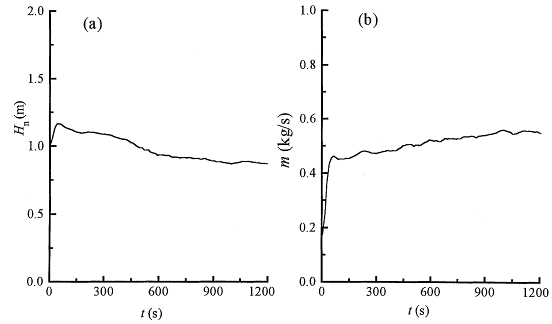

Fig. 5. Measured quantities at the burn room door (steady state fire): (a) neutral plane height; (b) vent flow rate from the burn room to the corridor.

4. Result and discussion

4.1. The steady state fire experiment

Although the heat release rate of the propane burner was set at a constant level in the steady state fire, gas temperature in the burn room underwent a transient change from the ambient value to a quasi-steady state. Presented in Fig. 4 are the surface plots of measured temperature and velocity profiles as functions of time at the burn room door. The coordinate y is the distance from the floor. From the temperature traces [Fig. 4(a)] it is plausible to divide the experimental period into two stages: the growth period and the quasi-steady period. The growth period includes the first 3 mins when the temperature near the upper edge of the door increased by about 180°C. The average rate of temperature change in the upper layer was much higher in the growth period than that in the following quasi-steady period in which the hot layer temperature only increased by about 20° over a time span of 15 mins. There was a region in the lower part of the door where temperature remained almost uniform. On the other hand, the temperature in the upper region continuously increased with height y up to the top edge of the door frame, indicating that the temperature in the hot layer was not uniform. Constant temperature contour lines revealed a quick descending trend in respect to height in the transition period and was then maintained at almost constant heights in the quasi-steady period. The fire induced flow is driven by buoyancy forces which are determined by temperature fields. When the temperature distribution across the doorway reached a quasi-steady state, so would the velocity distribution as shown in Fig. 4(b). It should be noted that the top velocity probe at $y=2.0$ m was absent in this steady state experiment. However, the velocity profile was extrapolated to the top edge of the door in Fig. 4(b). The negative value in the velocity reading indicates smoke moving out of the burn room. The neutral plane position is defined at the location where flow velocity changes its sign. The result is shown in Fig. 5(a). The measured velocity and temperature profiles were integrated with Eq. (1) to obtain the vent flow rate as shown in Fig. 5(b).

Presented in Fig. 6 are the measured oxygen concentrations at a number of selected elevations along the centre line of the burn room door. Oxygen concentrations at other elevations were not recorded due to instrument malfunction. Therefore, the average oxygen concentrations in the outgoing and incoming streams could not be estimated. Nevertheless, Fig. 6 does indicate that the inlet stream, as well as the exhaust stream, were oxygen depleted.

4.2. The transient fire experiment

The distinctive characteristic of the transient fire is the gradual variation in heat release rate as shown in Fig. 7. After the ignition of fire at the centre of the three-seat couch, flame spread along the surfaces of the seat and back. As the burning surface area increased, so did the heat release rate and the gas temperature inside the burn room. The convective and radiant heat transfer to window glass created intensive thermal stress. The video record of the experiment revealed that the window glass cracked at 315 s and was completely dislodged at about 475 s after the ignition. The dislodgement of window glass created additional opening to the burn room and more fresh air was brought in by buoyancy. The result of this was the acceleration of fire growth to the flashover point where the gas temperature inside the burn room was so high such that flames spread to non-contiguous furniture items and the unburnt volatiles became involved in combustion [16]. With the consumption of fuel, the burning surface area was gradually reduced which was followed by a decay in heat release rate until the fuel was burnt out.

Fig. 8 contains surface plots of measured temperature and velocity profiles as a function of time at the

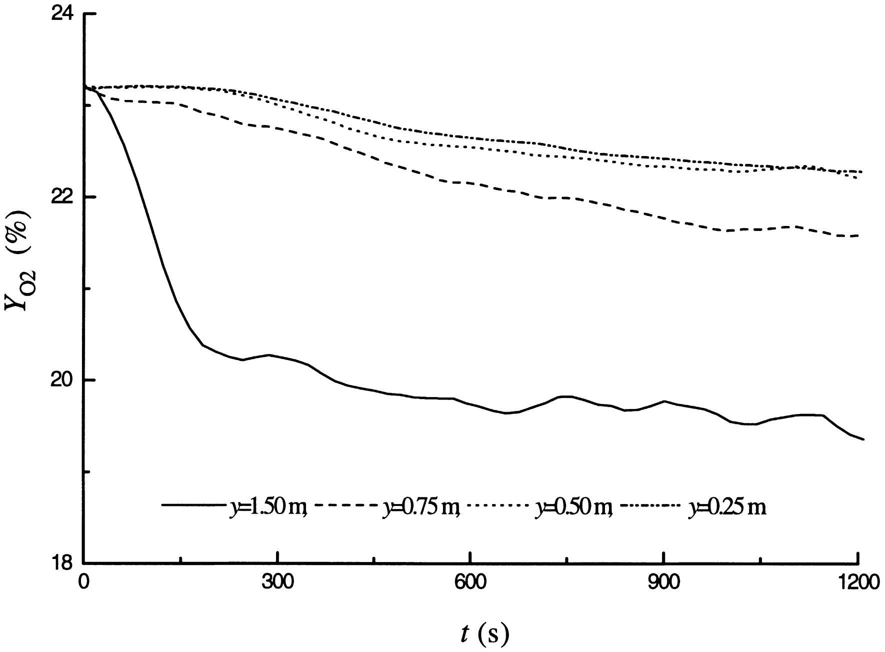

Fig. 6. Measured oxygen concentrations at the burn room door (steady state fire).

doorway of the burn room. In contrast to the propane fire, no quasi-steady state was discernible from the measured temperature profiles. The contour line at $u=0$ indicates the neutral plane position at the doorway and is replotted in Fig. 9(a). The initial low neutral plane position is a manifestation of an identified flow regime where thermal expansion forces the air out of the burn room [17]. For most part of the experimen-

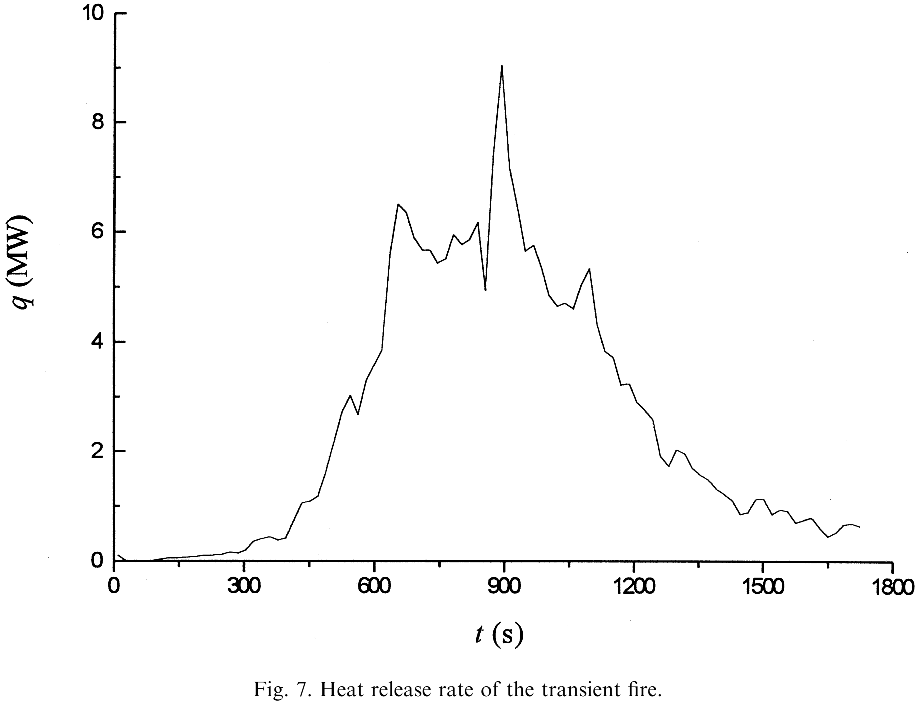

Fig. 7. Heat release rate of the transient fire.

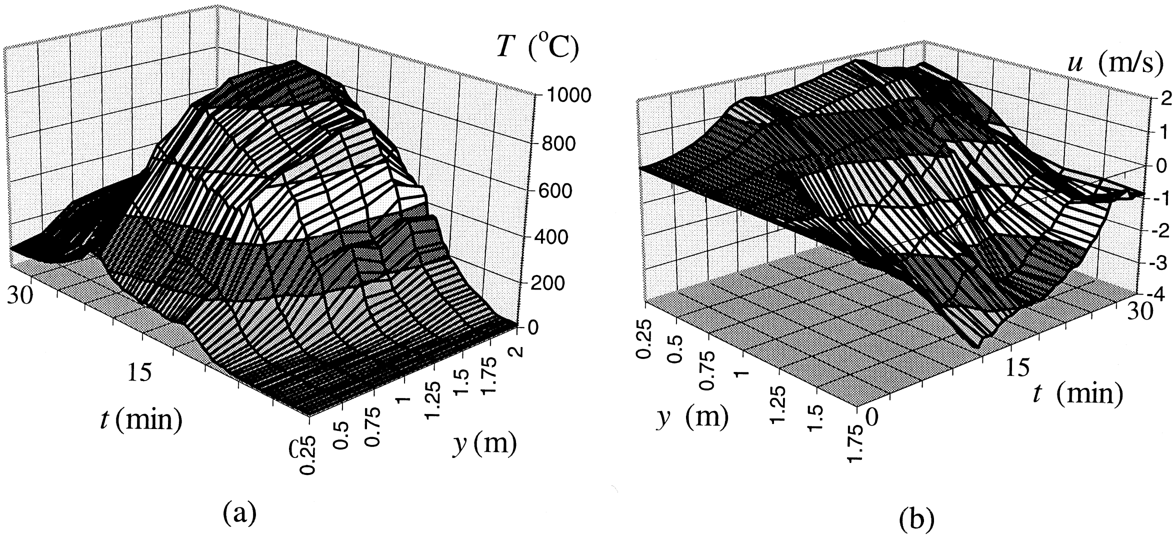

Fig. 8. Measured profiles along the centre line of the burn room door (transient fire): (a) temperature; (b) velocity.

tal period, the neutral plane fluctuated around an elevation equivalent to half of the door height. The exhaust smoke flow rate is plotted in Fig. 9(b). Compare Fig. 9(b) with Fig. 7, it is seen that the maximum mass exhaust rate through the door opening does not necessarily correspond to the maximum heat release rate in the burn room. This phenomenon is explained in the following.

The buoyancy driven flow across the door opening is related to the ratio of densities between inside and outside of the burn room. Let 1 denote the burn room and 2 the adjacent room. The density ratio is defined

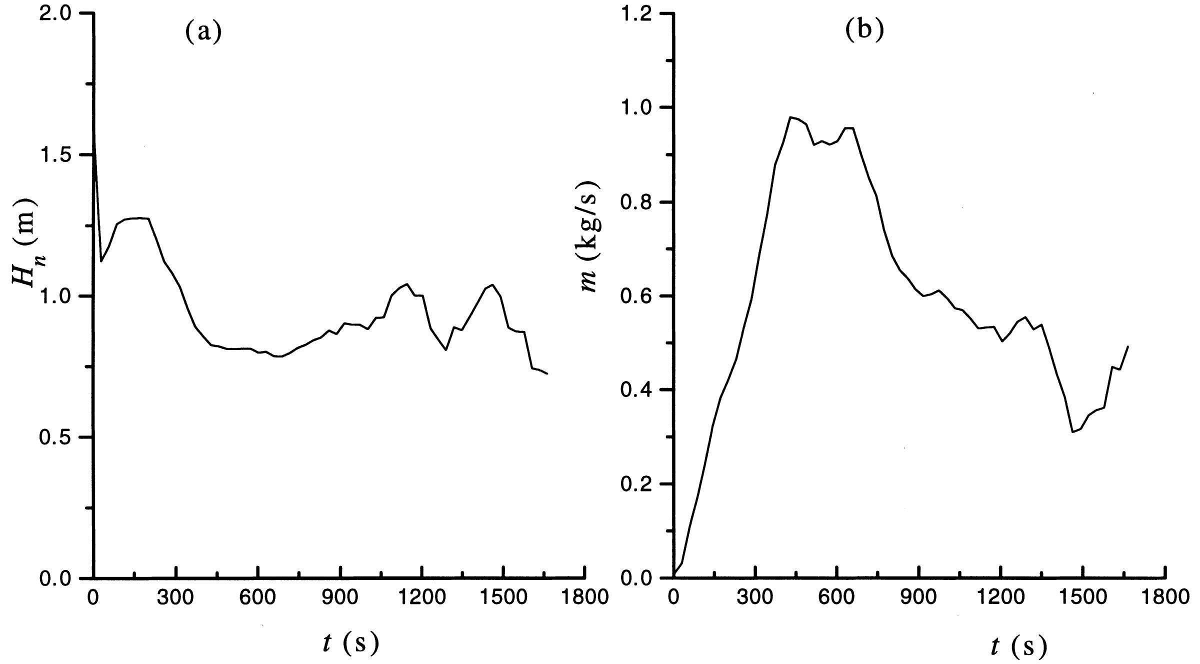

Fig. 9. Measured quantities at the burn room door: (a) neutral plane height; (b) vent flow rate from the burn room to the corridor.

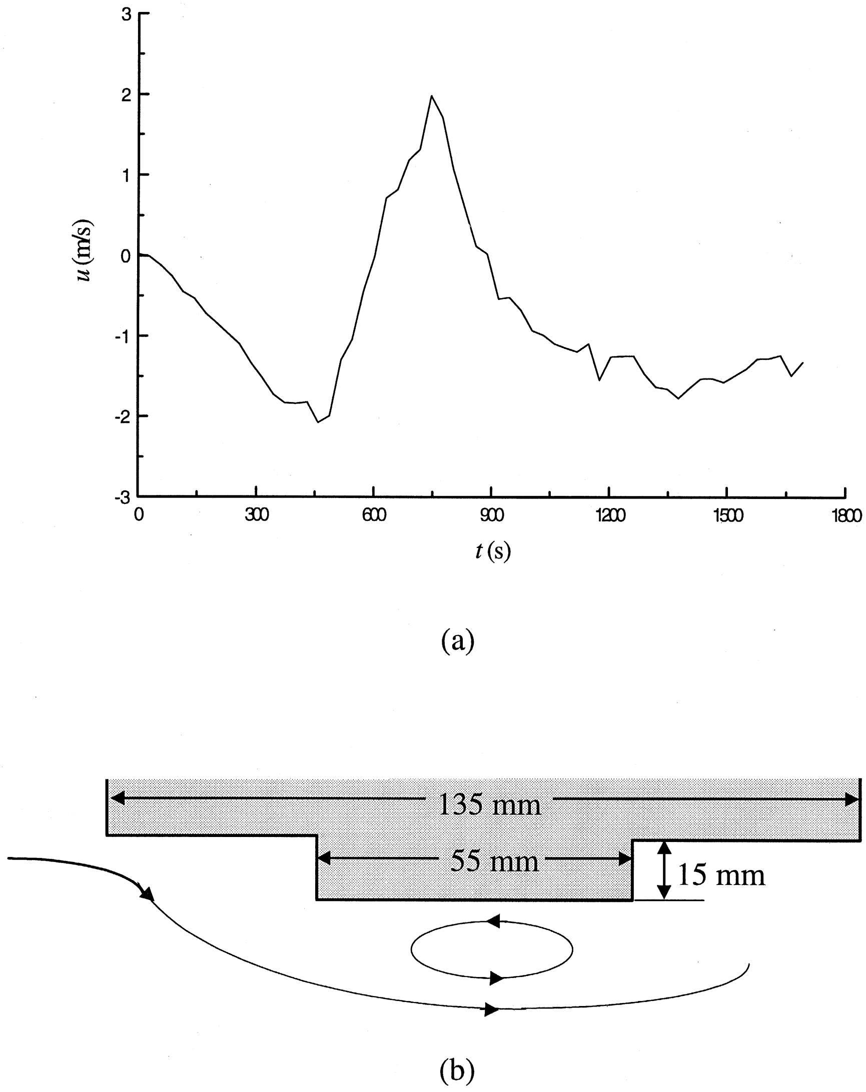

Fig. 10. Flow field near the top edge of the burn room door: (a) velocity reading at $y=2.0$ m, or 0.01 m from top surface; (b) door jamb geometry.

as

$$r=\frac{\rho_1}{\rho_2}=\frac{T_2}{T_1} \tag{8}$$

According to the analysis by Prahl and Emmons [5] for an idealised situation

$$m_e \propto \sqrt{r(1-r)}=\sqrt{\frac{T_2}{T_1}\left(1-\frac{T_2}{T_1}\right)} \tag{9}$$

The mass flow rate reaches the maximum only when the function $r(1-r)$ attains the maximum. As the fire grows in the burn room, more and more hot smoke is discharged to the adjacent room and the temperature difference between T_1 and T_2 may be reduced, resulting in a value of r close to unity. Hence, the mass flow rate may attain a less than maximum value even when the heat release rate of the fire is increasing or at the maximum.

Velocity readings of the very top probe was not included in Fig. 8(b). It actually registered a very peculiar trace as shown in Fig. 10(a). The change in flow direction indicated formation of flow separation and a recirculation region around the leading corner of the door jamb. This phenomenon has been observed by Lyn and Rodi [18] in their investigation of the turbulent shear layer and the associated recirculation

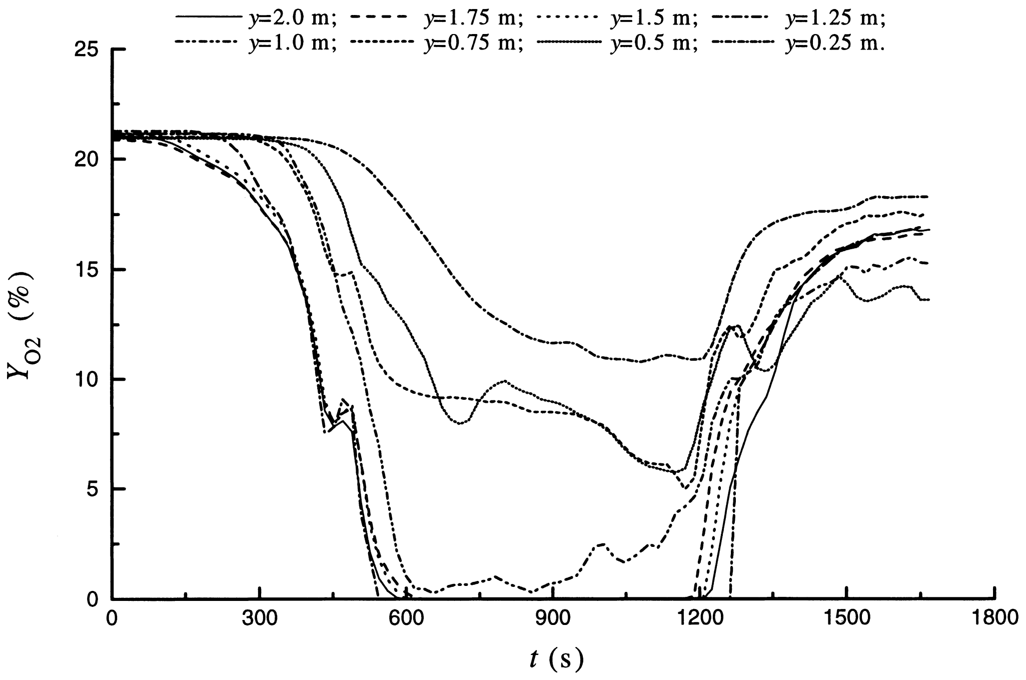

Fig. 11. Measured oxygen concentrations at the burn room door (transient fire).

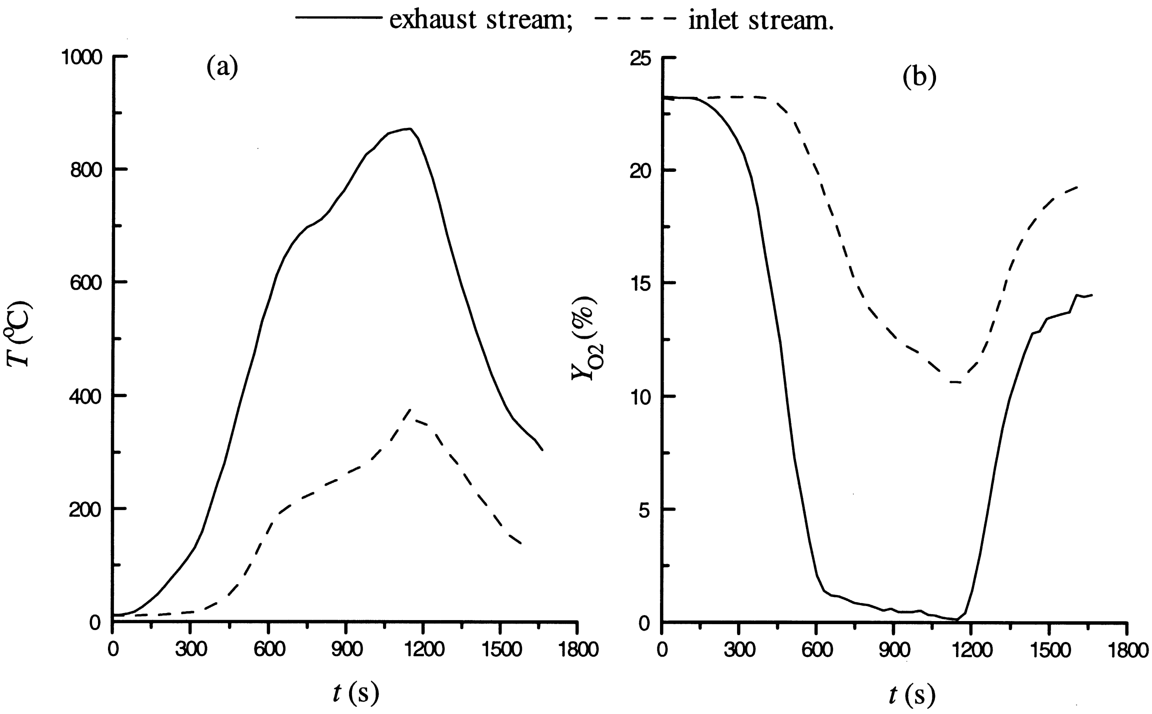

Fig. 12. The average conditions of inlet and exhaust streams through the burn room door (transient fire): (a) temperatures; (b) oxygen concentrations.

region on the sidewall formed in flow separation from the forward corner of a square cylinder. Their results revealed that at a distance half way from the forward corner, reverse flow or recirculation occurred for $y/D < 0.15$. In this case, y is the vertical distance from the sidewall surface and D the diameter of the square cylinder. Although the door jamb geometry [Fig. 10(b)] in the present work is different from the square cylinder of Lyn and Rodi, the separation and recirculation were still expected. Due to heat transfer to relatively cold jamb wall, temperature in the recirculation bubble was lower than that in the free stream. At any given time, the temperature reading at this location was lower than that at $y=1.75$ m [Fig. 9(a)]. The velocity reading at $y=2.0$ m was excluded from the integration to obtain smoke exhaust flow rate, average flow temperature and oxygen concentration (see Fig. 12 below). The error due to this exclusion was believed to be small since thickness of the corner flow region was negligible in comparison to the door height. It is also observed in (b) that the maximum exhaust flow velocity in the upper region of the vent opening was almost twice the maximum inlet flow velocity in the bottom region.

The intensive heat release rate in the burn room is believed to have created strong buoyancy forces and turbulent mixing in the corridor. As a result, the return air flow, or the inlet stream, from the lower layer in the corridor to the burn room was severely contaminated with product gases. In Fig. 11, the gas sampling probes below the neutral plane height ($H_n \approx 1$ m), in the inlet stream, registered oxygen concentrations lower than that of standard atmospheric value for a good part of the experimental period. At any given time, there was usually a negative oxygen concentration gradient, i.e. $(dY_{02}/dy) < 0$. The lowest probe ($y=0.25$ m) registered a minimum reading as low as 10.7%.

Associated with the mixing is also heat transfer. In addition, the lower layer air in the corridor received thermal radiation from the upper layer hot smoke and its temperature was, therefore, increased. Fig. 12 demonstrates the average temperatures and oxygen concentrations of the inlet and exhaust streams through the burn room door.

5. Conclusion

Temperature, velocity and species concentration profiles at a vent opening can be used to estimate the transport rates of smoke in building fires. Significant contamination by combustion products is expected in the lower region of the stratified buoyancy driven counter current flow in building enclosures. In the full-scale fire experiments described herein, the effects of strong mixing between smoke and air layers in a corridor were observed at the doorway connecting to a fire room. The experimental result revealed that the oxygen concentration in the inlet stream from the corridor to the burn room was reduced due to the contamination by combustion product gases during intensive building fires, indicating that the lower layer air in the corridor was not free of toxic species. The inlet flow in the transient fire experiment also had significantly high average temperature (greater than 100°C) soon (about 9 min) after the start of the fire. The oxygen concentration dropped below 16% at about the same time. Both of these parameters articulated an unsafe passage for building occupants.

Flow field around a door jamb can be quite complicated. Flow separation and recirculation behind the forward corner of a door jamb was detected in the transient fire experiment. Although this phenomenon may not significantly alter the result of mass flow rate through the door opening, its effect on heat transfer to the door jamb may influence the endurance of the structure in a fire environment, hence it deserves proper investigation.

The oxygen concentration is somewhat an indirect indication of tenability in building fires. Experiments with the measurement of toxic species would be desirable to obtain direct information on their yield and transport behaviour for toxicity analysis.

Acknowledgements

This research work was partially supported by an Australian Research Council Collaborative Research Grant in association with Fire Code Reform Centre Ltd. The author is indebted to Ms T. Alam, Prof. V. Beck, Mr S. Stewart and Mr M. Coles for their assistance in managing the experiments and in data processing.

Appendix

Let N be the number of measurement points, j be the index of position ($1 \le j \le N$). The vertical distance y_j ($j=1,\ldots,N$) from the floor is the height of measurement point j. u_j, T_j and Y_j are velocity, temperature and oxygen concentration measured at y_j. The parameter profiles are linearly extrapolated down to the floor and up to the door frame. The total number of data points is $N+2$ after extrapolation with index j ranging from 0 to $N+1$. Let k denote the index of the location which is right below the neutral plane. We have $y_j < y_{j+1}$ for $j=0,\ldots,N$ and $y_k < H_n < y_{k+1}$. Note that $y_0=0$ and $y_{N+1}=H_d$.

Under the assumption of linear parameter distribution between any two adjacent measurement points, the velocity integration term in Eq. (2) is straightforward

$$\int_{H_\mathrm{n}}^{H_\mathrm{d}} u\,\mathrm{d}y = \frac{1}{2}\left(\sum_{j=k+1}^{N}(u_{j+1}+u_j)(y_{j+1}-y_j) \quad + u_{k+1}(y_{k+1}-H_\mathrm{n})\right) \tag{A1}$$

The numerical expression for the integral term in Eq. (1) and the denominator in Eqs (2) and (3) reads

$$\int_{H_\mathrm{n}}^{H_\mathrm{d}} \frac{u}{T}\,\mathrm{d}y = S_2(0,u_{k+1},T_\mathrm{ref},T_{k+1},H_\mathrm{n},y_{k+1}) + \sum_{j=k+1}^{N} S_2(u_j,u_{j+1},T_j,T_{j+1},y_j,y_{j+1}) \tag{A2}$$

where T_ref is the interpolated temperature at the neutral plane position and

$$S_2(x_1,x_2,x_3,x_4,x_k,x_6) = \frac{(x_2-x_1)(x_4-x_3)-[(x_2-x_1)x_3-(x_4-x_3)x_1]\ln\left(\frac{x_4}{x_3}\right)}{(x_4-x_3)^2}(x_6-x_5) \tag{A3}$$

The numerical expression for the numerator in Eq. (3) reads

$$\int_{H_\mathrm{n}}^{H_\mathrm{d}} uY\,\mathrm{d}y = S_3(0,u_{k+1},Y_\mathrm{ref},Y_{k+1},H_\mathrm{n},y_{k+1}) + \sum_{j=k+1}^{N} S_3(u_j,u_{j+1},Y_j,Y_{j+1},y_j,y_{j+1}) \tag{A4}$$

where Y_ref is the interpolated species concentration at the neutral plane position and

$$S_3(x_1,x_2,x_3,x_4,x_5,x_6) = \left(x_1x_3 + \frac{x_1(x_4-x_3)+x_3(x_2-x_1)}{2} + \frac{(x_4-x_3)(x_2-x_1)}{3}\right)(x_6-x_5) \tag{A5}$$

The expression for the integral term on the right-hand side of Eq. (2) is more complicated

$$\int_{H_\mathrm{n}}^{H_\mathrm{d}} \frac{Yu}{T}\,\mathrm{d}y = S_4(0,u_{k+1},Y_\mathrm{ref},Y_{k+1},T_\mathrm{ref},T_{k+1},H_\mathrm{n},y_{k+1}) + \sum_{j=k+1}^{N} S_4(u_j,u_{j+1},Y_j,Y_{j+1},T_j,T_{j+1},y'_j,y_{j+1}) \tag{A6}$$

where

$$S_4(x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8) = \left\{\frac{(x_4-x_3)(x_2-x_1)[0.5x_6^2+(r-0.5)x_5^2-2x_5(x_6-x_5)]}{(x_6-x_5)^3} + \frac{[x_3(x_2-x_1)+x_1(x_4-x_3)](x_6-x_5-x_5r)}{(x_6-x_5)^2} + \frac{x_1x_3r}{x_6-x_5}\right\}(x_8-x_7) \tag{A7}$$

and

$$r = \ln\left(\frac{x_6}{x_5}\right) \tag{A8}$$

References

[1] G. Mulholland, T. Handa, O. Sugawa, H. Yamamoto, Smoke filling in an enclosure. 20th National Heat Transfer Conference, Paper no. 81-HT-8, Milwaukee, 1981.

[2] L.Y. Cooper, M. Harkleroad, J. Quintiere, W. Rinkinen, An experimental study of upper hot layer stratification in full-scale multiroom fire scenarios, Journal of Heat Transfer 104 (1982) 741–749.

[3] K. Kapoor, Y. Jaluria, Penetrative convection of a plane turbulent wall jet in a two-layer thermally stable environment: a problem in enclosure fires, International Journal of Heat and Mass Transfer 36 (1) (1993) 155–167.

[4] W.G. Bos, V.D. Elsen, C.J. Hoogendoorn, F.L. Test,

Numerical study of stratification of a smoke layer in a corridor, Combustion Science and Technology 38 (5/6) (1984) 227–243.

[5] J. Prahl, H.W. Emmons, Fire induced flow through an opening, Combustion and Flame 25 (1975) 369–385.

[6] B.J. McCaffrey, J.G. Quintiere, Buoyant-driven counter-current flows generated by a fire source, in: D.B. Spalding, N. Afgan (Eds.), Heat Transfer and Turbulent Buoyant Convection, vol II, Hemisphere, 1977, pp. 457–472.

[7] K.D. Steckler, J.G. Quintiere, W.J. Rinkinen, Flow induced by fire in a compartment. Nineteenth Symposium (International) on Combustion, The Combustion Institute, 1982, pp. 913–920.

[8] R.D. Peacock, G.P. Forney, P. Reneke, R. Portier, W.W. Jones, CFAST, the Consolidated Model of Fire Growth and Smoke Transport, NIST Technical Note 1299, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899-0001, USA, 1993, pp. 25–27.

[9] D.A. Purser, Assessment of combustion product, in: P.J. DiNenno (Ed.), The SFPE Handbook of Fire Protection Engineering, 2nd ed., The National Fire Protection Association, Boston, 1995, pp. 2.85–2.146.

[10] K.D. Steckler, H.R. Baum, J.G. Quintiere, Fire induced flows through room openings—flow coefficients. Twentieth Symposium (International) on Combustion, The Combustion Institute, 1984, pp. 1591–1600.

[11] I. Nakaya, T. Tanaka, M. Yoshida, K. Steckler, Doorway flow induced by a propane fire, Fire Safety Journal 10 (1986) 185–195.

[12] Y. He, On experimental data reduction for zone model validation, Journal of Fire Sciences 15 (2) (1997) 144–161.

[13] V. Babrauskas, Upholstered furniture room fires—measurements, comparison with furniture calorimeter data, and flashover predictions, Journal of Fire Sciences 2 (1984) 5–19 January/February 1984.

[14] Y. He, I. Moore, M. Luo, V. Beck, Doorway calorimetry for heat release rate measurement in building fires, Combustion Science and Technology 132 (1998) 365–389.

[15] M. Luo, Y. He, V. Beck, Application of field model and two-zone model to flashover fires in a full-scale multi-room single level building, Fire Safety Journal 29 (1) (1997) 1–25.

[16] D.D. Drysdale, in: An Introduction to Fire Dynamics, Wiley, Chichester, 1990, p. 280.

[17] M.L. Janssens, H.C. Tran, Data reduction of room tests for zone model validation, Journal of Fire Sciences 10 (1992) 528–555.

[18] D.A. Lyn, W. Rodi, The flapping shear layer formed by flow separation from the forward corner of a square cylinder, Journal of Fluid Mechanics 267 (1994) 353–376.