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# BUOYANCY DRIVEN FLOW IN BUILDING ENCLOSURES SUBJECTED TO FIRES

Yaping He and Paula Beever

Centre for Environmental Safety and Risk Engineering
Victoria University of Technology, Melbourne, Australia

## ABSTRACT

This paper discusses fire induced smoke movement and associated species transport in a multi-enclosure compartment building. A transient state fire experiment was conducted in a full-scale building. The distributions of temperature, velocity and species concentration were measured. Particular attention is given to the flow fields at the doorway between 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.

## INTRODUCTION

Buoyancy driven shear layer flow is of great interest in fire safety studies. Unless influenced 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 (Cooper *et al*, 1982) which leads to a combination of shear and buoyancy mixing layers (see Figure. 1). The buoyancy driven stratifying flow in building enclosures is generally stable (i.e. the density gradient is in the same direction as the gravitational force) and the lower layer of relatively cool air may provide the occupants with crucial passage and time to evacuate. The formation of a smoke layer and time-dependent physical conditions in various location of multi-enclosure buildings have been major topics in fire related fluid dynamics research.

Shear and buoyancy mixing layers of the unstable kind where density gradient is opposite to the gravitational force have been experimentally investigated by Snider and Andrews (1994). It was found that that buoyancy is the dominant drive for mixing once the mixing width reaches a self-similar state. However, in a stable stratifying shear layer, the influence of buoyancy in mixing may be weaker.

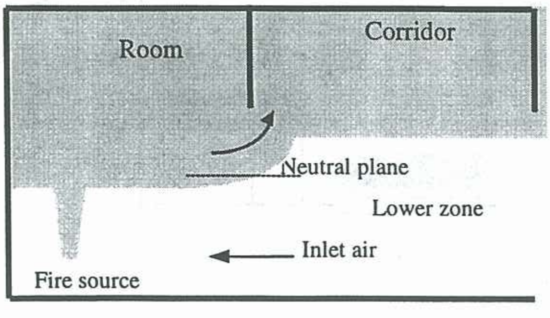

**Figure 1.** A simplified sketch of fire induced flow in a multi-room scenario.

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 the majority of research work. A detailed analysis of fire induced flows through openings using hydraulic theory and a bench scale apparatus was given by Prahl and Emmons (1975). In a fire situation, countercurrent flows arise in an enclosure with stratified two zones. They also arise at the opening of the enclosure where hot gases flow out and cool gases flow in (Figure 1). McCaffrey and Quintiere (1977) 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* (1982). In their study, the three dimensional effect and the influence of the fire source position inside the burn room were considered.

The conditions in the countercurrent flows at a doorway joining two adjacent enclosures are indicative of the conditions in the corresponding source regions. Due to strong countercurrent flows, mixing also occurs in the region near a vent opening such as a doorway. Although this phenomenon has been addressed in fire modelling and vent flow calculations, 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.

Most of the previous investigations of fire induced flows 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 (Nakaya *et al*, 1986). The measurement of the field of species concentration was dealt with insufficiently and very little is known about the transport of species in transient fire induced flows.

In the present study, an attempt is made to reveal the flow fields around doorways in a multi-enclosure building. Of particular interest are the distributions of temperature, velocity and oxygen concentrations along the centre line of the doorways. Averaging schemes based on transport terms are applied to the measured parameter profiles to obtain the average temperature and species concentration in the countercurrent flow streams at the door openings.

## EXPERIMENTAL ARRANGEMENT

The experiment was conducted in a full-scale prototype building which has four stories connected by a lift shaft, a stairwell and air handling shafts. Figure 2 is a schema of the first floor on which the fire source was located. The layout of the other levels, except for Level 4, is similar to Level 1. Level 4 consisted of a corridor only. Room 103 on the first floor was used as the burn room. The burn room was connected to the first floor corridor 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 (2 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 (denoted as D103 in Figures 2). 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. Detailed specification of the instruments, description of data acquisition procedures and error analysis can be found in He *et al* (1998).

A set of realistic furniture was used as fuel load in the experiments to generate transient heat release rate. 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 chairs, two coffee tables, and two bookshelves with phone books. The couch and one coffee table were located on the small weighing platform, the others were on the large platform. The total fuel load was 542.1 kg, 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). During the experiment, the building was naturally ventilated internally and was functionally closed to the outside; that is, all the doors and window to the outside were closed. However, small leakage areas existed in the walls, 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.

## RESULTS AND DISCUSSION

The distinctive characteristic of the transient fire is the time-dependent variation in heat release rate. After the ignition of the fire at the centre of the three-seat couch, flame spread along the surfaces of couch 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 intense 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 as smoke and hot gases were vented through the top of the opening, fresh air was brought in below. 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 flame spread to non-contiguous furniture items and the unburned volatile became involved in combustion (Drysdale, 1990). With the consumption of fuel after a period of some 20 minutes sustained burning, the burning surface area gradually reduced which was followed by a decay in heat release rate until the fuel was burn out.

Figure 3 contains surface plots of measured temperature and velocity profiles as functions of time at the doorway of the burn room. The $y$ coordinate is the height from floor. The contour line at $u$=0 indicates the neutral plane position at the doorway and is re-plotted in Figure 4. 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 (Janssens and Tran, 1992). For

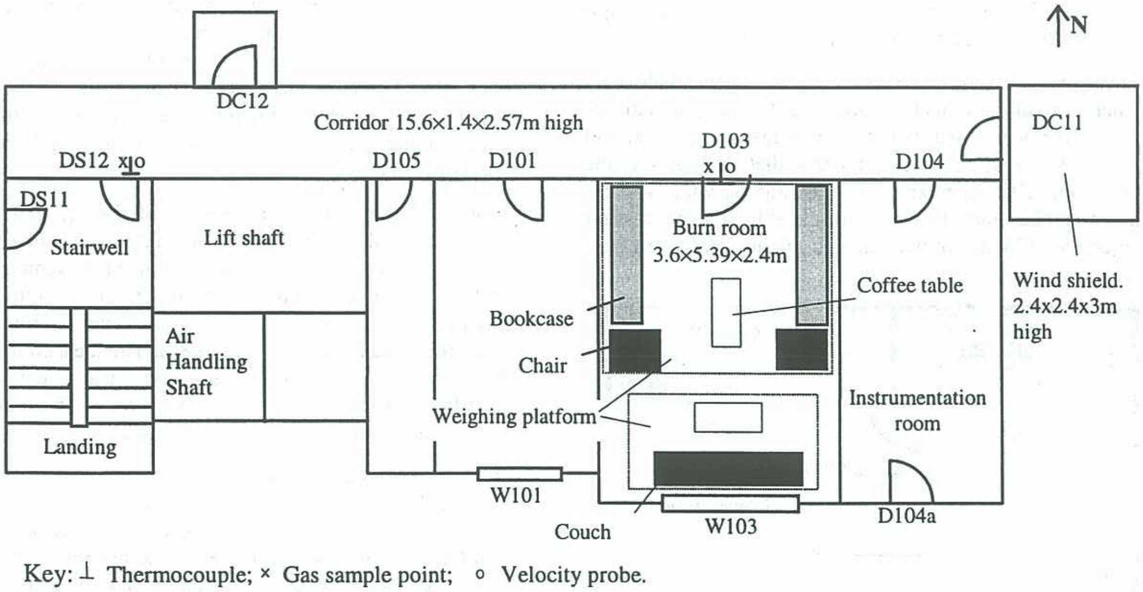

**Figure 2.** Layout of the first floor of the experimental building.

most of the experimental period, the neutral plane fluctuated around an elevation equal to half of the door height. The exhaust smoke flow rate $m$ is also plotted in Figure 4.

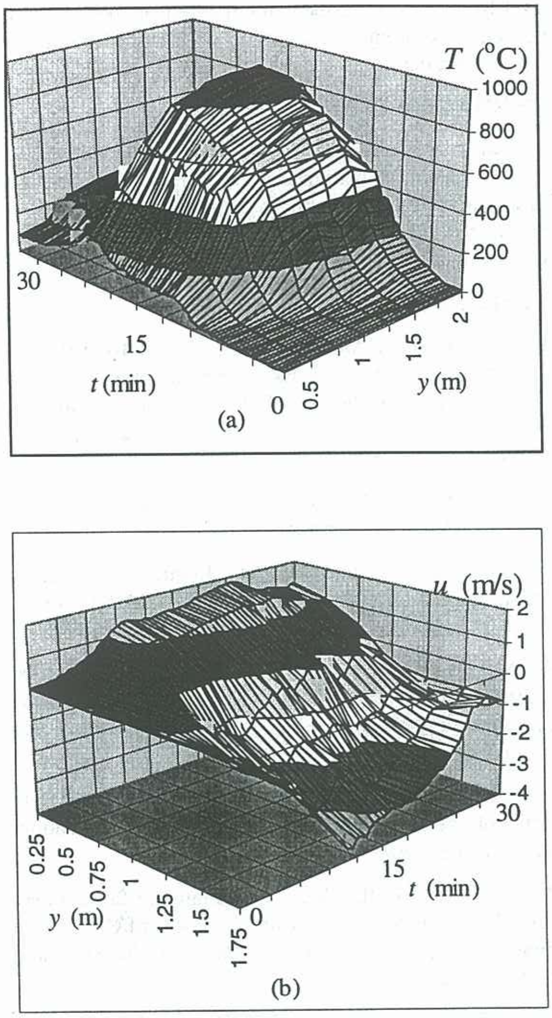

**Figure 3** (a) Temperature and (b) velocity distributions along the centre line of the burn room door.

The heat release rate in the burn room is estimated to have peaked in the region of 10 MW and, therefore, 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. Experience suggests that these gases will be toxic. Meanwhile, the oxygen concentration in the inlet stream was reduced. The measured oxygen concentrations along the centre line of the burn room door is presented in Figure 5. The gas sampling probes below the neutral plane height ($H_n \approx 1$ m) 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 along the $y$ direction. The lowest probe (y=0.25 m) registered a minimum reading as low as 10.7%.

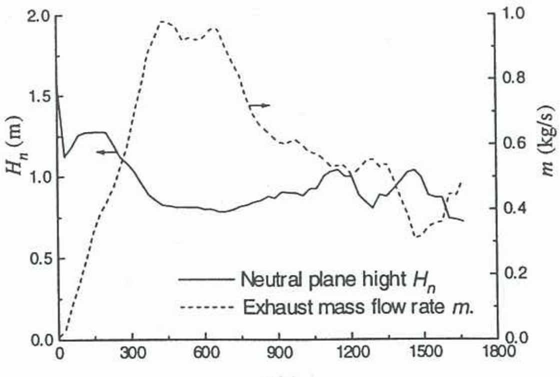

**Figure 4** Neutral plane height and vent flow rate from the burn room to the corridor.

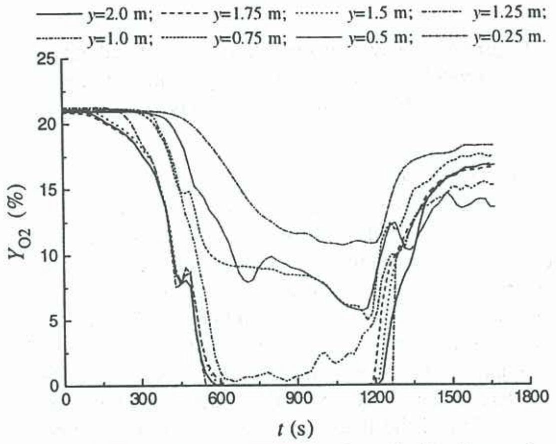

**Figure 5** Oxygen concentration distribution at the burn room door.

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. Figure 6 demonstrates the average temperatures and oxygen concentrations of the inlet and exhaust streams through the burn room door.

The average quantities of flow rate, temperature and species concentration based on measurement of temperature, velocity and species transport terms (He, 1997) were estimated according to the following equations, assuming uniform horizontal distribution for all the parameters

$$m = W\int_{H_n}^{H_d} \rho u dy = W\frac{P}{R}\int_{H_n}^{H_d} \frac{u}{T} dy \tag{1}$$

$$T_{\text{ave}} = \int_{H_n}^{H_d} u dy \left( \int_{H_n}^{H_d} \frac{u}{T} dy \right)^{-1} \tag{2}$$

$$Y_{\text{ave}} = \int_{H_n}^{H_d} \frac{uY}{T} dy \left( \int_{H_n}^{H_d} \frac{u}{T} dy \right)^{-1} \tag{3}$$

where $H_d$ and $H_n$ are respectively the door height and the neutral plane height, $u$ is flow velocity, $Y$ is species concentration, $T$ is temperature, $P$ is pressure, $W$ door width and $R$ the gas constant for air.

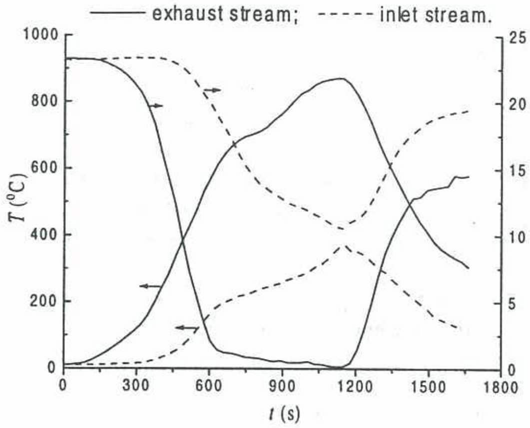

**Figure 6** The average conditions of inlet and exhaust streams through the burn room door. (a) temperatures and (b) oxygen concentrations

Flow separation and recirculation behind the corner of a doorjamb was observed in the experiment. The velocity probe near the top edge of the doorframe ($y$=2.0 m) gave strong fluctuating readings (not included in Figure 3) and sometimes even with opposite sign. It was believed that the probe was inside of a separation bubble. The flow field around the doorjamb was similar to that around one-half of a square cylinder investigated by Lyn and Rodi (1994). The detected reverse flow near the doorjamb in the present study confirmed the findings of Lyn and Rodi. Although the boundary layer formation and separation at the doorjamb may not significantly alter the result of mass flow rate through the door opening, its effect on heat transfer to the doorjamb may influence the endurance of the structure in a fire environment, and hence deserves proper investigation.

## CONCLUSION

A stable shear and buoyancy driven stratifying flow was established in a corridor which was connected to a fire room and a stairwell in a full-scale experimental building facility. Turbulent mixing is believed to be significant. Its effects were observed at the doorway connecting the corridor to the fire room. The flow measurements revealed that the oxygen concentration in the inlet stream from the corridor to the fire room was reduced due to the contamination by combustion product gases during the experiment, indicating that the lower layer air in the corridor was not free of toxic species. As a result of the shear layer mixing and radiation heat transfer, the inlet flow also had a significantly high average temperature (greater than 100 °C) soon (about 9 minutes) after the start of the fire. The oxygen concentration dropped below 16% at about the same time. Both of these parameters indicated an unsafe passage for building occupants. For most part of the experimental period, the neutral plane, where flow velocity remains zero, fluctuated around an elevation equivalent to half of the door height. It is also observed that the maximum exhaust flow velocity in the upper region of the vent opening was almost twice as the maximum inlet flow velocity in the bottom region.

The oxygen concentration is somewhat an indirect indication of tenability for occupants 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. Demand is also posed by hazard assessment for theoretical modelling of turbulent mixing and recirculation of fire products in the built environment.

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