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EFFECTS OF PRESSURISATION AND SMOKE MANAGEMENT SYSTEMS ON FIRE GROWTH AND SMOKE MOVEMENT IN A MULTI-STOREY BUILDING

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ABSTRACT

This paper describes experimental observations of the effects of stair pressurisation and smoke management systems on fire growth and smoke spread in a multi-storey building. Comparisons are made between the results of a set of fire experiments which involved a variety of ventilation conditions. Measurements were taken of mass loss in the burn room, flow velocity distributions at door vents, temperature and pressure in various enclosures of the building. It was found that the operation of the stair pressurisation and smoke management systems not only effectively prevented smoke spread to the corridor on the floor of fire origin and to upper levels, but also had strong effect on fire growth and flame spread in the burn room.

1. INTRODUCTION

Understanding of the performances of various components in fire safety systems is essential in the design process. Pressurisation and smoke management systems have been used in practice to protect against the spread of smoke in building fires. The effectiveness of these systems is often a major concern in risk assessment. Much of the research effort in the past has been directed towards the evaluation of the effectiveness of these systems [1]. Computerised models also exist in the literature for analysing smoke control systems [2]. Experimental and theoretical studies by Tamura [3] have yielded correlations for critical air velocities to prevent smoke backflow at a stair door opening on the fire floor. It has been demonstrated through various experiments and field model studies which cover a wide range of fire scenarios that pressurisation systems could provide smoke free exits for building occupants in the scenarios and the systems tested [4,5].

Smoke controls systems on one hand prevent smoke moving into protected areas in a building, and on the other, may force fresh air into the building areas where fires are burning. An investigation into the effect of smoke control systems on fire growth was described by Ziesler et al [6]. It was found that positive pressure ventilation system had reversed flame spread and reduced the potential for flashover by reducing the temperature of solid and gaseous fuel during live fire experiments. However, quantitative descriptions of these experiments are still scarce in the literature.

If stair pressurisation and smoke management systems are effective in preventing smoke spread to remote areas of a building, then it is plausible to introduce into the risk assessment model [7] the assumption that the egress routes in the protected areas are smoke free. This assumption will lead to a reduction in the computation burdens of the risk assessment mode. To use quantitatively analysed experimental results to support such an assumption is the prime motivation of the present study.

As part of the Fire Code Reform Centre Project [8], a series of realistic fire experiments were conducted in a full-scale multi-storey building to investigate fire growth and smoke spread under a variety of ventilation conditions. A stair pressurisation system and a smoke management system were used in some of these experiments. General descriptions of the experiments and the results have been documented by Alam and Beever [9]. Presented in this paper are the further analyses of the fire scenarios in which mechanical ventilation was involved. In order to identify and compare the effects of stair pressurisation and smoke management systems on fire growth and smoke spread, the results of a naturally ventilated fire were also included in the discussion.

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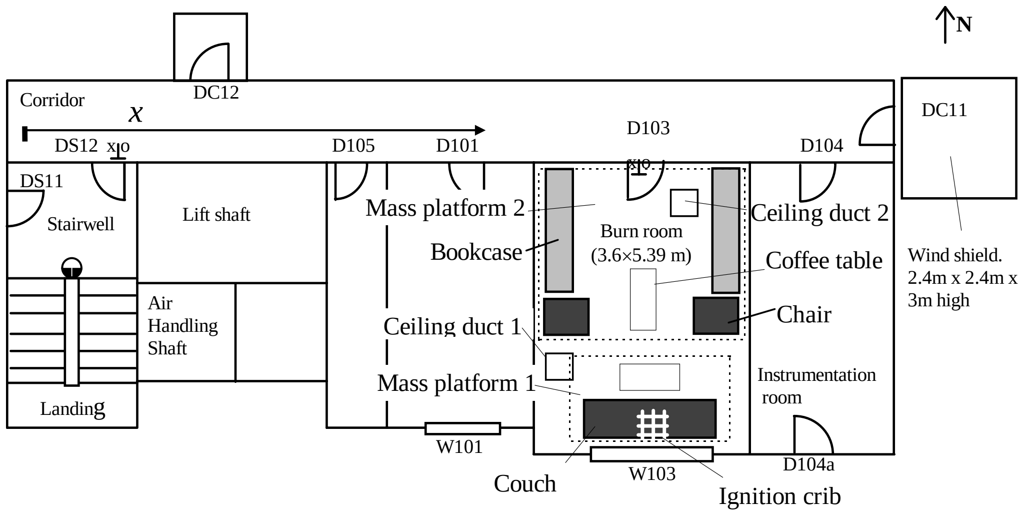
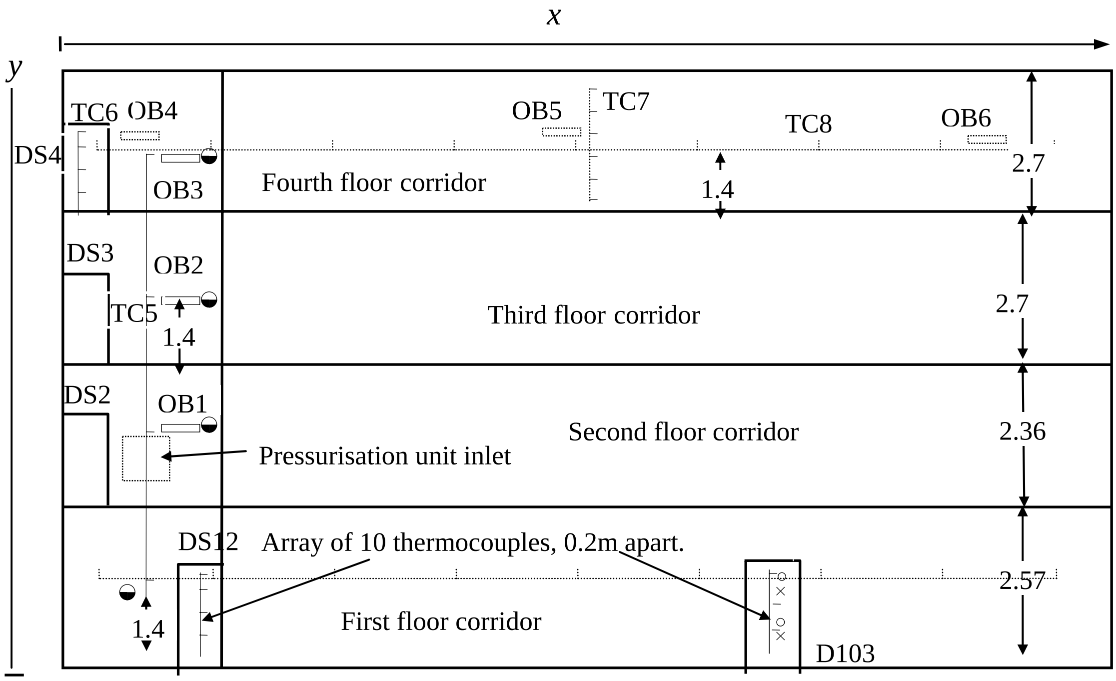
2. EXPERIMENTAL CONDITIONS

The fire experiments were conducted in the Experimental Building-Fire Facility (EBFF) of Victoria University of Technology. The facility has four stories connected by a lift shaft, a stairwell and air-handling shafts. Fig. 1 depicts the first floor layout, the fuel configuration and the instrumentation in the experiments. The layout of other floors was similar to that of the first floor. The air handling system in the EBFF can be run under two different modes: (1) normal air supply and return mode, (2) smoke management mode with smoke exhaust and stair pressurisation. In the normal air-handling mode (air supply and return), the system is run under a recycle condition with no fresh air. In the smoke management mode, the air-handling fans continue to operate but with 100% fresh air (no return air); the fresh air is supplied to all levels other than the level of fire origin. The exhaust system is applied only to the level of fire origin. In addition, the stairwell is pressurised using separate fans. The design accords with the Australian Standard (AS 1668) for the design of smoke management systems in multi-storey buildings.



(a) Instrumentation and layout of the first floor



(b) Elevation view of instrumentation layout

Key: ⊥ Thermocouple; × Gas sample point; ○ Velocity probe; Pressure transducer; Optical density meter

Fig. 1: Instrumentation and layout of the Experimental Building-Fire Facility

The experiments discussed below are designated FO4, FO5 and FO6. The fuel loads used in these three experiments were identical and only the ventilation conditions differed, as listed in Table 1. For those experiments conducted with the air-handling system turned on, the smoke management operation of the air-handling system was controlled by a smoke detector which was placed in a duct (see Fig. 1) at the ceiling level. The air-handling system was operating at the start of the fire experiments. Two air supply ducts (0.4m×0.4m) were located on the ceiling. The air flow rates through these two ducts were 46 and 50 *l*/s respectively. The system switched to smoke management mode automatically when the smoke detector activated; about 494 (or 1321) *l*/s of air (smoke) was then extracted out from the burn room if the burn room door and the stair door were closed (or open).

Table 1: Ventilation conditions in the three experiments

Test ID	Burn room door (D103)	Stairwell door (DS12)	Stair pressurisation and smoke management systems
FO4	Open	Open	Off
FO5	Open	Open	On
FO6	Closed	Closed	On

The facility was also equipped with thermocouples, pressure transducers, gas sampling probes, velocity probes and optical density meters during the experiments. The locations of some of the instruments are depicted in Fig. 1. Differential pressure transducers were placed in the stairwell at 1.4 m above each floor. Pressure difference between the stairwell and outside at each location. Temperature distributions in the first floor corridor and in the stairwell were also measured. A detailed description of the building structure, instrumentation and fuel load configuration and general observations of the experiments can be found in reference [9]. Detailed analyses of some of the experimental results, addressing the buoyancy driven flow field inside the building, have been published elsewhere [10].

3. EFFECTS ON FIRE GROWTH

The fuel load used in the three experiments was potentially sufficient to produce flashover fires. However, whether the flashover condition can be attained also depends on ventilation conditions [11]. Not all fires conducted in this series reached flashover. Listed in Table 2 are times of events in the three fire experiments. It should be noted that window glass breakage is a gradual process [12]. The presented window glass breaking time actually corresponds to the time of initial cracking of the glass. The criterion for flashover used here is the average room temperature of 550 ^{o}C.

Presented in Fig. 2 are measured heat release rate, temperature and species concentrations in the burn room for the three fire experiments. It may be seen from this figure that experiments FO4 and FO6 proceeded to fully developed fires, characterised by significant peaks in heat release rate and temperature rise. However, experiment FO5 failed to reach flashover condition, though the fuel load condition was identical to the other two experiments.

Table 2: Times of events in the three experiments (min:sec)

Events	FO4	FO5	FO6
Ignition	0:00	0:00	0:00
Smoke detector activation	0:55	0:55	0:55
Activation of smoke control systems	—	2:40	2:23
Sprinkler activation	3:00	5:00	4:10
Breaking of window glass	5:15	5:48	3:45*
Flashover	9:00	—	6:19

* Window glass did not dislodge itself during experiment FO6. The window was manually lowered at 4:55

in this experiment.

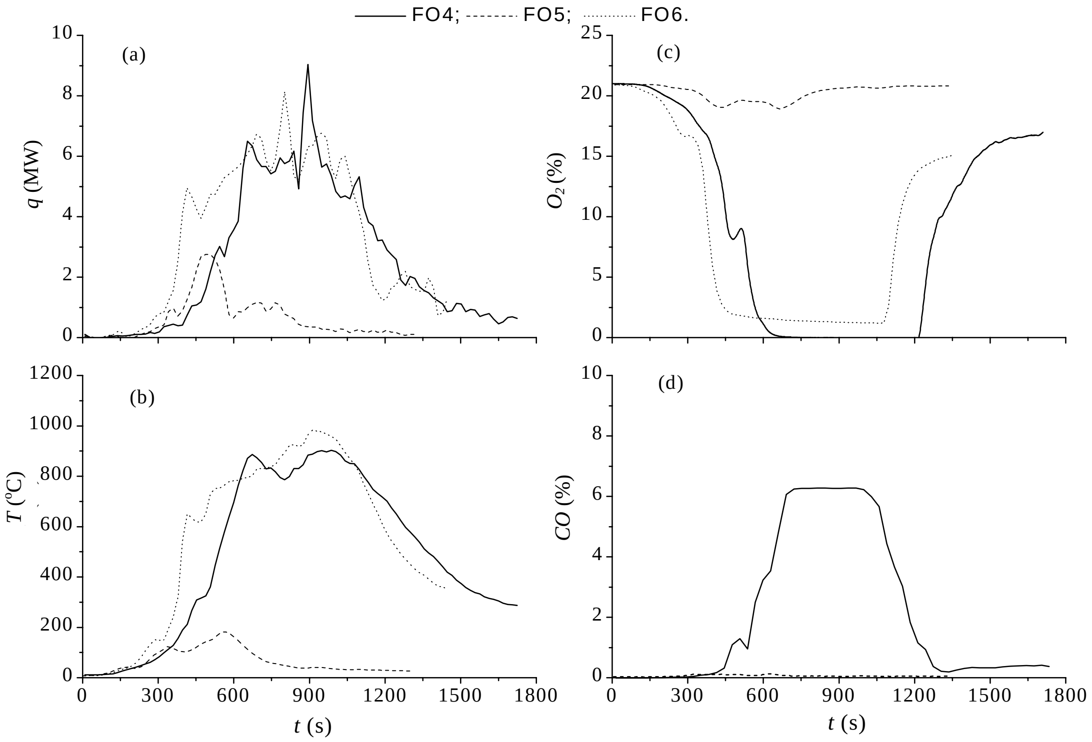


Fig. 2: Comparison of burn room conditions in experiments FO4, FO5 and FO6
(a) Heat release rate; (b) Average room temperature; (c) O_2 concentration; (d) CO concentration

Experiment FO4 involved a naturally ventilated fire. Vent openings of D103 and DS12 provided passage for smoke to spread to the stairwell and the higher levels of the building. Relatively fresh air also entered the burn room through this passage before the breaking of the window. The heat generated by the burning of the item of fire origin ignited other items after approximately 7.5 minutes. Ignition of those items occurred before the onset of flashover (Table 2). The fire in experiment FO5 underwent an initial growth pattern similar to that in FO4. However, soon after the activation of the smoke detector in the burn room, the stair pressurisation and smoke management systems were turned on. Smoke was pushed back to the burn room and extracted to the outside through the smoke management system. This change in ventilation condition curtailed the build-up of a hot layer, and hence the rise of temperature in the burn room. Even though the flame issuing from the item of fire origin was able to break the window, it failed to spread to other combustible items. In fact, the breaking of the window provided an additional vent opening for the burn room. As a consequence, the rate of air entering the burn room through the door was doubled (see the section below) and the additional airflow was directed to the outside through the broken window. The proximity of the item of fire origin to the window resulted in the immediate purging of heat and product gases to the outside. Very little variation in species concentration was detected in the burn room, especially after the window breakage (Fig. 2).

The change of vent opening status during experiment FO6 resembled a human intervention. The closure of the burn room door prevented sufficient fresh air entering into the room even after the activation of the stair pressurisation and smoke management systems. The window glass cracked at 3 minutes and 45 seconds after the ignition but failed to dislodge itself. The window was then lowered at about 5 minutes, creating a vent opening for the burn room. The fire growth history of this experiment was similar to that of FO4 (Fig. 2).

4. EFFECTS ON SMOKE SPREAD

To examine the effect of stair pressurisation and smoke management systems on smoke spread in the building, flow velocities across the burn room door, temperature, pressure and species concentration distributions in the corridors and stairwell are compared between experiments FO4 and FO5. Since both the burn room door and the first floor stair door were closed during the entire period of experiment FO6, smoke was not able to spread to any part of the building other than the room of fire origin. In experiment FO5 the stair pressurisation and smoke management systems were turned on at about 2 minutes and 40 seconds after the ignition (Table 2).

Plotted in Fig. 3 are velocity readings measured along the centre line of the burn room door in experiments FO4 (a) and FO5 (b). The positive values indicate that the flow is going into the burn room. In experiment FO4, gas flows throughout the building for the duration of this experiment were always buoyancy driven. The counter-current flow situation is usually expected [13] and there should be a neutral plane in the vicinity of the middle of the door height. The unusual fluctuation in the velocity reading near the top edge of the door was possibly caused by flow separation and a circulation bubble around the leading edge of the door jamb. Steady flows through burn room door and stairwell doors in experiment FO5 were established at about 3 minutes - soon after the activation of the stair pressurisation and smoke management systems. Flow velocities across these door openings were maintained slightly above 1 m/s (see Fig. 3). Then, around 5 and a half minutes window glass in the burn room was broken, creating a vent to the outside. As a result, air flow velocities, and hence mass flow rate across the first floor stair door and the burn room door, were increased by a factor of 2 as shown in Fig. 3 (b).

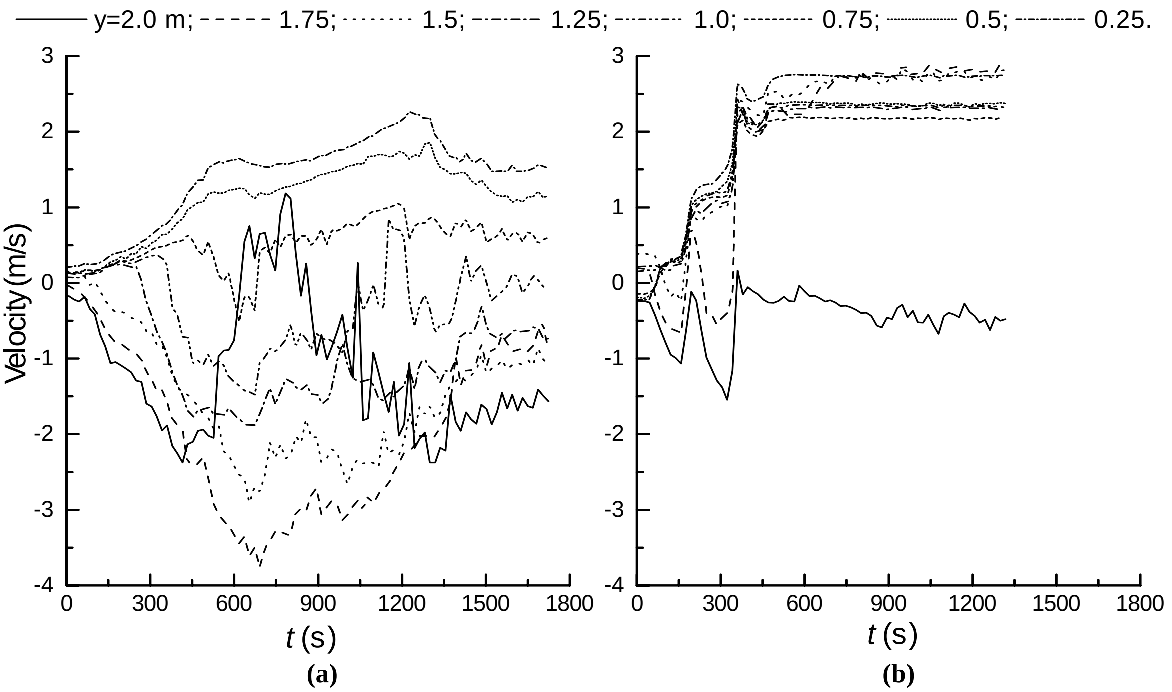
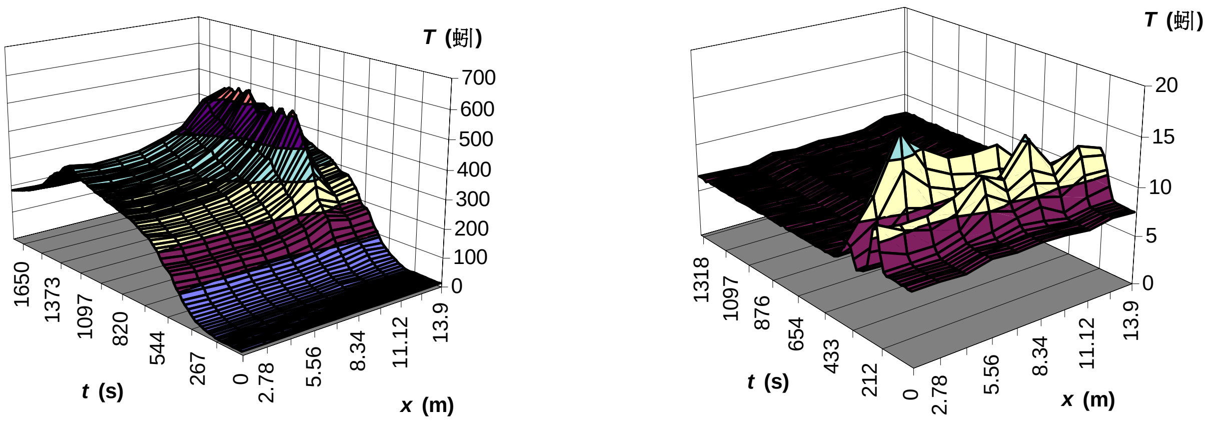


Fig. 3: Flow velocity distribution at the centre line of the burn room door in experiments (a) FO4 and (b) FO5

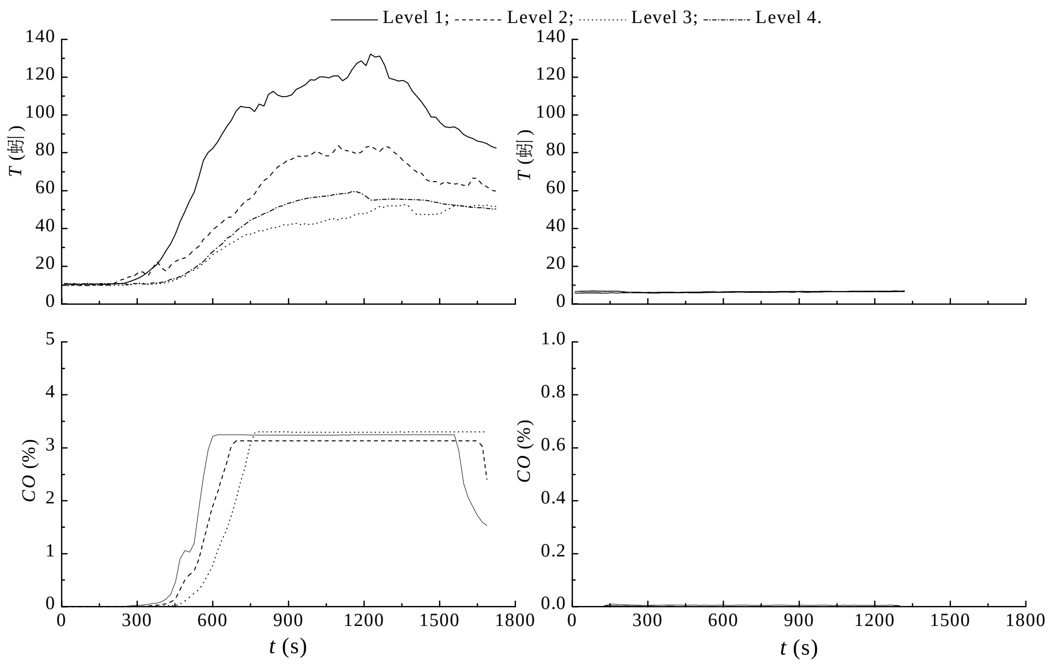
After smoke entered the first floor corridor, it split in two directions: one towards the eastern part of the corridor, the other along the western part of the corridor. Presented in Fig. 4 is the temperature horizontal distribution along the first floor corridor at an elevation of 1.7 m above the floor. The burn room door was situated between x=9.73 m and x=12.51 m in the corridor (Fig.1) and, therefore, thermocouples in this region in experiment FO4 gave the highest temperature readings when there was hot smoke discharging from the burn room. As smoke propagated along the corridor, heat was lost to the walls and to the air flow in the bottom layer and temperature distribution showed a decreasing trend along the distance away from the burn room door. The operation of the stair pressurisation and smoke management systems in experiment FO5 prevented smoke further entering the first floor corridor from the burn room. Temperature distributions in the corridor [Fig. 4 (b)] indicted that only small amount of smoke infiltrated the corridor before the mechanical ventilation systems were activated.



(a) (b)

Fig. 4: Temperature horizontal distribution in the first floor corridor (a) Experiment FO4; (b) Experiment FO5

Carbon monoxide concentration and temperature distribution in the stairwell are presented in Fig. 5. The plateau in the carbon monoxide concentration curves for levels 1, 2 and 3 are the results of instrument saturation. The rises in CO concentrations were nevertheless recorded and it can be discerned that there was a delay in the time of CO concentration rise in areas remote from the room of fire origin and this delay increases with the distance from the room of fire origin. This is also true for temperature rises in remote areas. Temperature and carbon monoxide concentration rises in the stairwell were insignificant during experiment FO5.



(a) (b)

Fig. 5: Temperature and carbon monoxide concentration distributions in the stairwell (a) Experiment FO4; (b) Experiment FO5

The phenomenon of stack effect was detected via differential pressure measurement in experiment FO4. Measured differential pressures between inside of the stairwell and the outside as functions of time and elevation are shown in Fig. 6. From Fig. 6 (a) it can be asserted that the neutral plane was located somewhere between the first and the second levels, or between 1.7m and 3.2m above the ground in experiment FO4. In experiment FO5, gas temperature inside the stairwell was almost the same as ambient, there was no stack effect in the well and the pressure variations were dominated by mechanical systems. Soon after the activation of mechanical systems, the pressure difference between the inside and outside reached approximately 110 Pa. This high pressure difference was maintained until the window in the burn room broke. It then reduced to 70 Pa. The pressure transducer on level 1 of the stairwell was saturated after the activation of the pressurisation system.

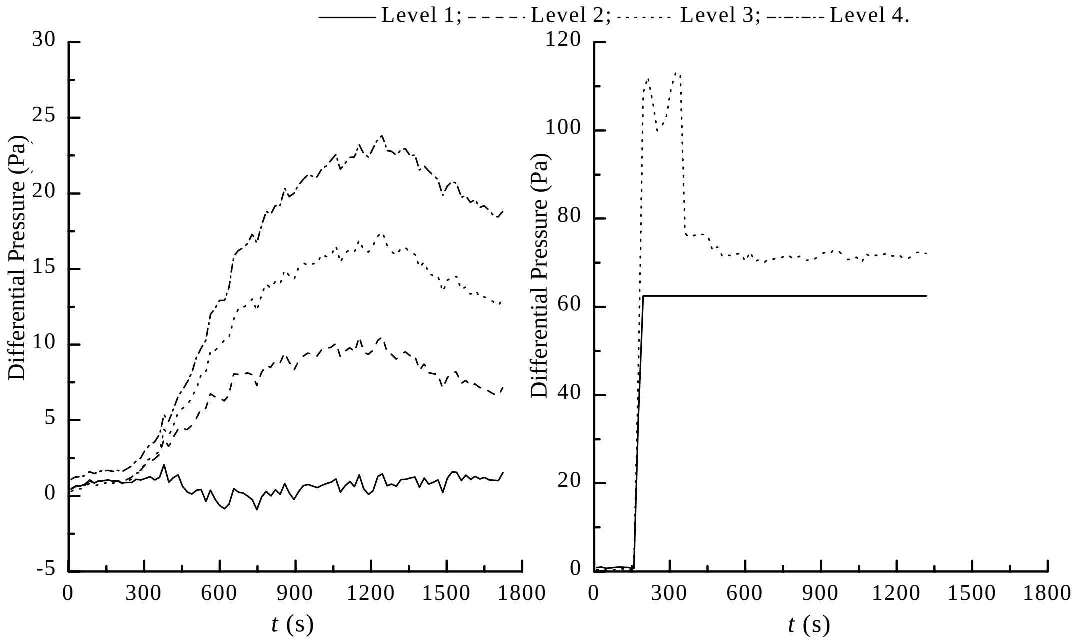


Fig. 6: Differential pressure distributions in the stairwell during experiments (a) FO4 and (b) FO5

5. CONCLUSION

Analysis and comparison of the results of the experiments conducted in the full-scale Experimental Building-Fire Facility demonstrated that the stair pressurisation and smoke management systems could provide smoke free egress routes in the fire scenarios tested. The operation of these systems not only effectively prevented smoke spread to the corridor on the floor of fire origin and to upper levels, but also had strong effect on fire growth and flame spread in the burn room. The cooling and unfavourable air movement could hinder the spread of flame to non-contiguous items in the burn room and hence prevent the occurrence of flashover. It was also demonstrated that the creation of vent openings to the burn room by human intervention could result in the attainment of flashover which otherwise might not have occurred. Fire control, as well as smoke control, can be achieved with the proper use of the systems.

Modelling of the effects of stair pressurisation and smoke management systems on both smoke spread and fire growth remains a challenging issue. The location of the initial burning object and the overall configuration of fuel load are crucial factors in determining whether the fire will be aided or controlled by forced air movement.

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