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AN ALTERNATIVE CONCEPT OF SMOKE MANAGEMENT

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ABSTRACT

Zone pressurisation systems have proved, both theoretically and experimentally, to be highly efficient in protecting the non-fire floors from smoke infiltration. Their reliability however may be doubtful as the design is fairly complex, and their efficacy depends on numerous factors; some of which are difficult to control and police, the system commissioning process could be tedious, and re-verification of the system performance could be difficult and costly. In addition, zone pressurisation systems are not intended to offer significant protection to the occupants on the fire floor and assume prompt evacuation on that floor will take place. An alternative concept of smoke management that satisfies the most significant parameters in performance-based designs, i.e. simple, effective, reliable and economical, is proposed. The philosophy and theory of such an alternative concept are provided in this paper, and comparisons are made with experimental results.

1. INTRODUCTION

Zone pressurisation systems in a high rise building work typically on the principle that the building is divided into smoke zones on a floor by floor basis. In the event of a fire occurring anywhere on a floor, the floor of fire origin will be kept at a pressure sufficiently and relatively lower than the other floors so that smoke spread from the fire floor to other floors is kept to a minimum. The general theoretical basis for zone pressurisation systems is discussed in [1]. Variations on the number of floors to be pressurised and on arrangements of the smoke zones can be found in [2].

Full scale testing carried out by using canister smoke in a 12-storey office building indicated that migration of smoke from the fire floor (nominated as the 1st floor in the test) to the upper floors could be prevented by a floor by floor zone pressurisation system [3]. It was considered that tests using non-fire-generated smoke were not conclusive because the resulting smoke is cold [4]. Full scale tests carried out by Klote confirmed that zoned pressurisation systems could be effective under real fire conditions [5].

Whilst the efficacy of zoned pressurisation systems has been both theoretically and experimentally proven, the reliability of such systems can be questionable since a large number of components, including fire detection devices on every floor, air supply and smoke exhaust fans, air control or smoke dampers on every floor, and a complex control system, are involved. A theoretical reliability analysis on new smoke management systems was carried out by Klote [6] and it was shown that for a complex system, for instance one that involves 5 HVAC system fans and 54 other components, the reliability of the new system before commissioning could be as low as 0.03 and the mean life of the system after commissioning could be as short as 3 months. In order to maintain a satisfactory level of performance, costly and disruptive maintenance and testing regimes need to be implemented.

In addition, zone pressurisation systems are not intended to offer significant protection to the occupants on the fire floor but assume prompt evacuation on that floor will take place. This assumption may not be valid in many cases, for instance, significant delays in the commencement of evacuation were reported in apartment buildings and offices [7-11].

In this paper, an alternative smoke management concept that is engineered to overcome the shortcomings above is proposed.

2. PHILOSOPHY OF THE ALTERNATIVE SMOKE MANAGEMENT CONCEPT

The alternative concept on smoke management is intended to apply to buildings which have a well defined common path of travel with a minimal fire load on each floor which leads to the escape stairs, such as that shown in Fig. 1. Typical apartments and some office buildings fall into this category.

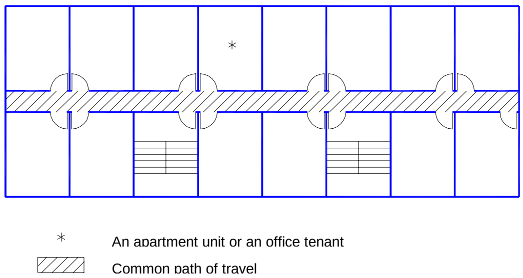

Fig. 1: Schematic floor layout with a common path of travel

It is obvious from Fig. 1 that to reach the escape stairs, the occupants on each floor must firstly commute in the common path of travel. In building codes, generally, the number and location of exits, the exit travel distances, the length of the dead ends, and the maximum lengths of the common path of travel are tightly controlled [12]. The intention is to assure that at least one egress route is available if the others happen to be blocked by the fire.

For smoke spread from the room of fire origin to the common path of travel to occur, leakage paths would have to be present. These paths include the HVAC system ductwork, clearances around the room entry door, the entry door opening at the room of fire origin when the door is significantly damaged by the fire or the door is left open, unprotected or improperly protected service penetrations through the building element separating the room of fire origin and the common path of travel, and leakage in the building construction. Secondary leakage paths could also be present, for instance, from the room of fire origin to the adjacent room(s) and then to the common path of travel. The estimate of the overall probability of smoke spread from the room of fire origin to the common path of travel would require a network analysis similar to that for fire spread [13].

In order to maximise the available time and probability of the occupants to successfully reach the escape stairs, it is proposed to pressurise the common path of travel on all floors with outside air in the event of a fire alarm raised anywhere in the building. This may be complemented with a stair pressurisation system to provide some form of redundancy (or as required by the building regulations) to maintain a relatively smoke free environment in the escape stairs. No mechanical exhaust is to be provided and air relief is to rely on the leakages in the building.

The notion of common path pressurisation is that the occupants on the fire floor are also protected. The electrical and mechanical services control for such system is simple, and the reliability is higher than a zone pressurisation system because the exact location of the fire is not required to be known. A significant cost saving is expected, when compared with zone pressurisation systems, due to simpler control mechanism, no requirements for high temperature exhaust fans, and the possible use of non-fire-rated cabling since the components of the pressurisation system are not in the path of the hot combustion products.

3. THEORETICAL CONCEPTS

For the common path of travel pressurisation, if the door of the room of fire origin that opens into the common path of travel maintains its integrity, smoke spread into the common path of travel is expected to be minimised if the pressure at the edges of the door on the non-fire side is higher than the sum of the buoyancy and expansion pressures generated by the fire.

The buoyancy pressure of the hot gases generated by the fire is related to the temperature rise of the gases relative to the ambient and the location of the neutral plane [6]. For enclosures in apartment and office buildings with a typical ceiling height of 2.7 m, assuming a flashover fire with a temperature of the order of 1000°C to 1200°C and the neutral plane is approximately at mid-height of the enclosure, it can be shown that the buoyancy pressure would be of the order of 12 Pa. This is confirmed by experimental fires cited in [1] which indicates that 15 Pa could be considered a conservative estimate of expected pressure due to buoyancy force for ceiling heights up to 3.5 m.

The pressure generated by the expansion of the gases in a fire compartment is dependant on the rate of temperature rise of the gases, the size of the leakage paths in the fire compartment, as well as the volume of the fire compartment [6]. Experiments carried out in the 10-storey experimental fire tower, using propane gas burners and following the ASTM-E119 standard time-temperature curve to the maximum test temperatures and held constant thereafter, confirmed that when the fire temperature reaches a steady value, the gas is no longer expanding and the hot gas moves out of the compartment by buoyancy force alone [14]. In those experiments, the pressure difference due to thermal expansion increased to a peak of 31 Pa at ignition of the gas burner, but dropped sharply to 16 Pa and gradually decreased to 3 Pa when the temperature reached 500°C. For engineering design purposes, the pressure generated by gas expansion is transient and can be ignored provided that the enclosure concerned is not relatively airtight such as a bank vault or a ship compartment.

The protection of the common path of travel using the pressurisation method will only be effective when the door of the room of fire origin maintains its integrity. When the door is significantly damaged by the fire or is left open after evacuation, the static pressure difference across the door opening quickly dissipates into velocity pressure and a different approach has to be taken.

It is conjectured that if the door to the room of fire origin is fully open, the fire gases will tend to flow through the door opening into the common path of travel as it is the path of least resistance, if there are no other significant openings in the room of fire origin such as broken windows. However, if a sufficiently high counter air flow is applied across the door opening, spread of the fire gases into the common path of travel may be minimised. Such proposition is based on the findings of Thomas [15] that an airflow higher than a critical velocity can prevent smoke from flowing upstream of the fire in a corridor/tunnel type environment.

The door opening can be treated as a wall aperture extending from the floor to the underside of the door header. Using the work of Heskestad and Spaulding [16] as stated in [6], the minimum average air velocity required to prevent the smoke from moving through an open doorway can be approximately estimated by:

$$u_c = 0.64[gH(T - T_o)/T]^{1/2} \quad (1)$$

where

u_c = critical velocity to prevent escape of smoke from room of fire origin (ms^{-1})
g = gravitational acceleration (9.8 ms^{-2})
H = height of the door opening (m)
T = average fire gas temperature in the room of fire origin (K)
T_o = average gas temperature in quiescent cold space (K)

Assuming the average fire gas temperature to be 1000°C at flashover and the ambient temperature to be 20°C, the minimum average air velocity required to prevent smoke flowing through a door opening with a typical height of 2.0 m would be approximately 2.5 ms^{-1} from Eq. (1).

4. EXPERIMENTAL ARRANGEMENT

Full-scale flaming non-flashover and flashover fire tests were carried out at the CESARE Experimental Building-Fire Facility (EBFF) at Fiskville. The basic structure consists of a 21×15×12 m high steel frame and concrete slabs. Part of the facility has been fitted out to simulate a portion of a multi-storey apartment building. Level 1 was used in this series of test and its layout is illustrated in Fig. 2. The area in the vicinity of the burn room window was shielded so that the effect of wind was minimised.

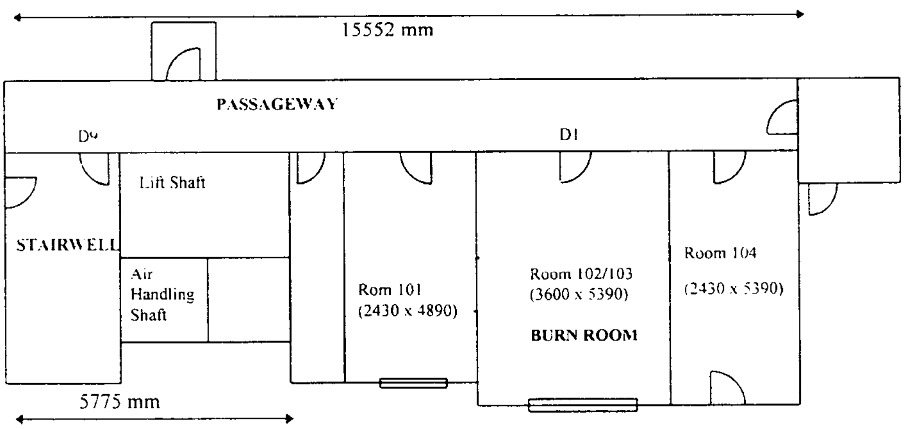

Fig. 2: Level 1 layout of the experimental building-fire facility

Room 102/103 was designated as the burn room. Room 104 was used as the instrumentation room, which was isolated from the rest of the building during the experiment. Room 101 was used as the ambient reference point for measuring the gauge pressure in the burn room and the corridor. Other rooms were isolated from the rest of the building during the experiment. The corridors on all levels led to the stairwell and resembled a common path of travel for the occupants on the respective level.

Timber cribs and polyurethane foam slabs were used as fuel in this study. The quantity of fuel used, of the order of 35 kg of foam and 415 kg of timber crib, resembled the total fire load in a typical apartment lounge room in a previous research study [17].

The EBFF was equipped with instruments to measure temperature in the burn room, the corridors on all levels, and in the stairwell on all levels; smoke optical density in the burn room and room 101, the level 1 corridor, and the stairwell on level 1 and level 1 mezzanine; gas compositions (CO, CO_2, O_2) in the burn room, the level 1 corridor, and the stairwell on level 1 and level 1 mezzanine; differential pressure in the burn room and the level 1 corridor; air velocity through the burn room door opening; and radiation from the burn room door opening. The measured data were collected using a PC-based data acquisition system.

In all tests, the door to the burn room was left open, simulating the scenario where the occupants forgot to close their apartment door after evacuation. The dimension of this door was 0.8 × 2.0 m. This scenario was considered to be the worst scenario for the common path of travel pressurisation system because no assistance could be obtained from the barrier system (the door) to minimise smoke spread and sole reliance would be placed on the pressurisation system. Other doors in the rest of the building were fully closed during the experiment.

The window opening to the burn room was sealed with a fire rated plasterboard mounted on a steel frame and incorporated with an open/closed mechanism. The selection of plasterboard instead of normal float glass to seal the window opening permitted a higher degree of control of the window 'breakage' time and was also used to provide additional oxygen in the event that the fire growth did not proceed as planned.

Four axial fans each with a duty point of 1.1 m^3s^{-1} at 50 Pa were fitted on the ceiling in the corridor outside the burn room and evenly spaced. Control of these fans was provided by a manual start/stop switch outside the EBFF. Air supply to these fans were obtained from the corridor on level 1 mezzanine which had the door at the end of the corridor fully opened to outside. With all four fans running, a velocity of approximately 2.5 ms^{-1} across the burn room door was recorded in a no fire situation with the burn room window fully opened and a gauge pressure of 50 Pa was recorded in the corridor with the burn room window closed.

5. EXPERIMENTAL RESULTS

It is considered that the temperature, visibility and the toxicity level are the most critical parameters in determining the tenability in the common path of travel (corridors in the EBFF) as they directly affect the capability of the occupants to escape [18]. These parameters were measured in the EBFF level 1 corridor during the full scale tests and their values at critical times are summarised in Tables 1 to 4.

Table 1: Corridor temperature ★

Test No.	Time of fan start (s)	T_{av} at fan start (°C)	T_{av} at 120s after fan start (°C)	Time of window broken (s)	T_{av} just before window broken (°C)	T_{av} at 60s after window broken (°C)
012A (NF)	69	10.0	19.3	145 *	74.3	15.3
012B (NF)	155	189.3	138.2	430 *	98.7	32.5
Test No.	Time of fan start (s)	T_{av} at fan start (°C)	T_{av} at 120s after fan start (°C)	Time of flashover ** (s)	T_{av} at flashover (°C)	T_{av} at 60s after flashover (°C)
012D (FO) †	1370	293.2	85.2	1340 (1320) #	285.7	164.0
012G (FO) †	195	239.0	28.4	150 (170) #	218.4	177.9
012H (FO)	244	214.4	59.9	210 (545) #	189.7	144.8 (28.2) §

Table 2: Corridor optical density ★

Test No.	Time of fan start (s)	OD_{av} at fan start (m^{-1})	OD_{av} at 120s after fan start (m^{-1})	Time of window broken (s)	OD_{av} just before window broken (m^{-1})	OD_{av} at 60s after window broken (m^{-1})
012A (NF)	69	0.0	0.1	145 *	0.5	0.1
012B (NF)	155	0.1	3.8	430 *	4.0	3.0 ‡
Test No.	Time of fan start (s)	OD_{av} at fan start (m^{-1})	OD_{av} at 120s after fan start (m^{-1})	Time of flashover ** (s)	OD_{av} at flashover (m^{-1})	OD_{av} at 60s after flashover (m^{-1})
012D (FO) †	1370	3.1	3.7	1340 (1320) #	3.1	3.9
012G (FO) †	195	3.3	1.6	150 (170) #	3.5	3.2
012H (FO)	244	4.3	4.4	210 (545) #	2.9	4.0 (2.1) §

Table 3: Corridor carbon monoxide concentration ★

Test No.	Time of fan start (s)	Co_{av} at fan start (% by vol)	CO_{av} at 120s after fan start (% by vol)	Time of window broken (s)	CO_{av} just before window broken (% by vol)	CO_{av} at 60s after window broken (% by vol)
012A (NF)	69	0.000	0.013	145 *	0.005	0.009
012B (NF)	155	0.000	0.16	430 *	0.085	0.042
Test No.	Time of fan start (s)	CO_{av} at fan start (% by vol)	CO_{av} at 120s after fan start (% by vol)	Time of flashover ** (s)	CO_{av} at flashover (% by vol)	CO_{av} at 60s after flashover (% by vol)
012D (FO) †	1370	2.43	0.205	1340 (1320) #	0.046	2.55
012G (FO) †	195	0.71	0.046	150 (170) #	0.18	0.75
012H (FO)	244	0.12	0.46	210 (545) #	0.003	0.89 (0.29) §

Table 4: Corridor carbon dioxide concentration ★

Test No.	Time of fan start (s)	CO_{2av} at fan start (% by vol)	CO_{2av} at 120s after fan start (% by vol)	Time of window broken (s)	CO_{2av} just before window broken (% by vol)	CO_{2av} at 60s after window broken (% by vol)
012A (NF)	69	1.34	1.53	145 *	1.33	1.52
012B (NF)	155	0.88	5.53	430 *	5.03	3.49
Test No.	Time of fan start (s)	CO_{2av} at fan start (% by vol)	CO_{2av} at 120s after fan start (% by vol)	Time of flashover ** (s)	CO_{2av} at flashover (% by vol)	CO_{2av} at 60s after flashover (% by vol)
012D (FO) †	1370	14.9	3.19	1340 (1320) #	4.67	15.0
012G (FO) †	195	14.2	2.13	150 (170) #	8.62	15.0
012H (FO)	244	3.80	3.72	210 (545) #	0.53	7.27 (1.33) §

Notes:

★ Properties were that along the longitudinal axis of the corridor with the temperatures measured at 2000 mm above the floor whilst other parameters were measured at 1700 mm above the floor.

* The window of the burn room was manually opened when the burn room hot layer temperature reached 350°C for the non-flashover fire tests.

** Flashover was deemed to occur when the mobile thermocouple in the middle of the burn room at the ceiling level reached at least 500°C and maintained the temperature for at least 30s.

‡ The OD in the corridor outside the burn room remained almost constant at 3.8 m^{-1} for the next 4 minutes after the window was broken, but the OD in the corridor next to the stair door remote from the burn room reduced from 4.09 to 0.15 m^{-1} at 4 minutes after the window was broken.

† Only two fans in the corridor were used in the test.

\# The window of the burn room was manually opened at approximately 1320s in test 012D, 170s in test 012G, and 545s in test 012H.

§ The value in the bracket is the parameter at 60s after the window was manually opened.

In tests 012A and 012B, the fans were started at times that would be expected in real installations, i.e. a short time delay after the smoke detector has detected the fire (a standalone smoke alarm was present in the room of fire origin in the tests) and when the fire has not yet reached the fully developed stage. The test results indicated that when the window of the burn room was ‘broken’, the positive pressure differential generated by the corridor pressurisation system caused an air flow from the corridor through the open burn room door and then to outside via the ‘broken’ window, and as a result the temperatures in the corridor quickly approached ambient.

Adopting the proposed limiting conditions for tenability [18,19], i.e. 100°C for exposure to convective heat, 0.6% (6000 ppm) of carbon monoxide and > 7% of carbon dioxide for incapacitation during five minutes exposure, and a minimum visibility of 2 m (OD of 1.25 m^{-1} for back illumination) in small rooms and 10 m (OD of 0.25 m^{-1} for back illumination) in other rooms, the results of tests 012A and 012B indicated that the corridor quickly restored to tenable conditions within a relatively short period of time. Based on visual observations during the tests and the video records, the fires did not proceed to the flashover stage despite the additional oxygen provided after the pressurisation system was activated.

In tests 012D and 012G, only two fans were used so as to determine if there was any spare capacity in the four fan system and there was a deliberate delay in starting the fans from 30s to 45s after flashover had occurred. The time delay was to simulate the situations where there was a failure in the automatic fan start mechanism and the pressurisation system has to be manually started at a later time. In test 012D, the window was opened prior to flashover whereas in test 012G, the window was opened after the flashover had occurred.

The results of tests 012D and 012G indicated that the conditions in the corridor had a significant improvement in terms of temperature and toxic gas species generally two minutes after the fans were started, except in test 012D the temperature in the corridor did not reach tenable conditions until manual fire suppression commenced at about 1660s. The visibility in the corridor however did not have significant improvement for the rest of the tests after flashover.

In test 012H, all four fans were used however the window of the burn room was deliberately kept closed for over five minutes after flashover was deemed to have occurred. This was to determine if the pressurisation system would be effective if there was not a relief path for the pressurised air through the burn room. The test results indicated that the temperatures in the corridor dropped significantly to within the tenability limit after the fans had started for 60s, the carbon monoxide and carbon dioxide concentrations in the corridor also dropped to within the tenability limit after the fans had started for 120s despite the window was still closed at that time, however the visibility in the corridor did not have significant improvement until some time after the window was opened.

6. CONCLUSION

The results of this initial study have indicated that the pressurisation of the common path of travel is a feasible alternative to floor-by-floor zone pressurisation systems. It has the advantages over zone pressurisation systems of being simpler, having a higher reliability and less expensive to build and maintain. It is most effective when actuated at the early stages of the fire and if the window in the room of fire origin is in the open position or is broken prior to flashover, offering a relief path for the pressurised air, even with the door to the room of fire origin being fully open. In the event that there is a delay in the start up of the pressurisation system or the window in the room of fire origin is not open, the pressurisation system could provide a tenable environment to the common path of travel in terms of exposure to convective heat and toxic gases, although the visibility in the common path of travel may not improve to the point that enables the occupants to evacuate. This is however a far improved situation when compared with unprotected common path of travel as permitted in many building codes and regulations. Further studies are however required to determine the efficacy of the system for other circumstances, to define and justify general design parameters, and to evaluate the adverse effects from wind on the design parameters.

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