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Numerical investigation on the effect of balcony open and solid upstand on smoke contamination in atrium balconies

Numerical investigation on the effect of balcony open and solid upstand on smoke contamination in atrium balconies

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Abstract. Atrium is a modern architectural design of buildings that has an open space at the middle and contains several floors. In atrium structure the smoke due to fire can easily flow through the open spaces and causes smoke contamination. CFD simulation using fire dynamic simulator (FDS) software is conducted in this work, to investigate the effect of balcony open upstand on smoke contamination in atrium's balconies and compare it with balconies with solid upstand. It was found that in case of open upstand, the smoke contamination occurrence decreased inside the balcony comparing with balconies with solid upstand.

1. Introduction

In a fire incident, significant amount of smoke is released which may cause hazards such as toxicity, visibility and thermal hazards. Past research shows that inhalation of the toxic gases released from the smoke is the main cause of death in a fire accident. In United states, it was reported that most fire victims died because of smoke inhalation rather than burns [1].

Atrium is a modern structural design of buildings that is used in airports, hospital and shopping malls. It has large open spaces in the middle and contains multiple floors. In a fire incident inside an atrium, the smoke can easily spread due to the open space which may endanger occupant's life. When fire occurs in an atrium compartment, It is expected that the smoke plume leaving the fire compartment rises vertically towards the atrium ceiling. However, past research found that sometimes smoke may curl into the atrium upper balconies instead of completely rising upward, resulting in smoke contamination. This phenomena may causes risk to the occupants.

Cox [2] investigated the reason of the smoke curling and found that the static pressure at the balcony is affected by the rising plume that cause it to drop in that region. This pressure drop inside the balcony creates a low-pressure region that cause the spill plume to curl inward the balcony and result in a smoke contamination in the particular balcony.

Previous researches [3-4] found that changing the atrium structure has a great effect on the occurrence of smoke contamination. Balcony breadth, fire compartment opening and down stand depth, and width effects on smoke contamination were well investigated. However, balconies upstand effect on smoke contamination occurrence was not investigated. Some balcony upstand (railing) design has openings, whilst other designs are solid with no opening. . These openings may affect the pressure distribution inside the balcony and hence the smoke contamination occurrence, past researches investigated only the effect of balcony upstand as a solid obstacle attached to the end of a balcony.

The objective of this paper is to compare the behavior of smoke and smoke contamination occurrence when open balcony and solid upstand are used.

2. Model development

A full scale three storey atrium was modelled using Fire Dynamic Simulator (FDS) as it is shown in Figure 1(a). FDS is a Computational Fluid Dynamic (CFD) software that models fluid flow driven by fire. It solves numerically a form of the Naiver-Stokes equations of a low speed fluid flow, thermally – driven flow with an emphasis on smoke and heat transport from fires [7].

FDS software is used to numerically study the effect of balcony open-upstand on smoke contamination in atrium's balconies. The modelled geometry has parameters that varies in every numerical simulation including balcony breadth, b, and fire compartment opening width, w. 1.6 MW, 3.2 MW and 4.7 MW heat release rates were selected for this study to be consistent with the recommended design fire range in an atrium [8] and corresponded to those used by [5-6]. The dimensions of the atrium used in this research are like the atrium dimensions used in Tan [9] experiment but for full scale Upstand structure modelled as shown in figure 1(c).

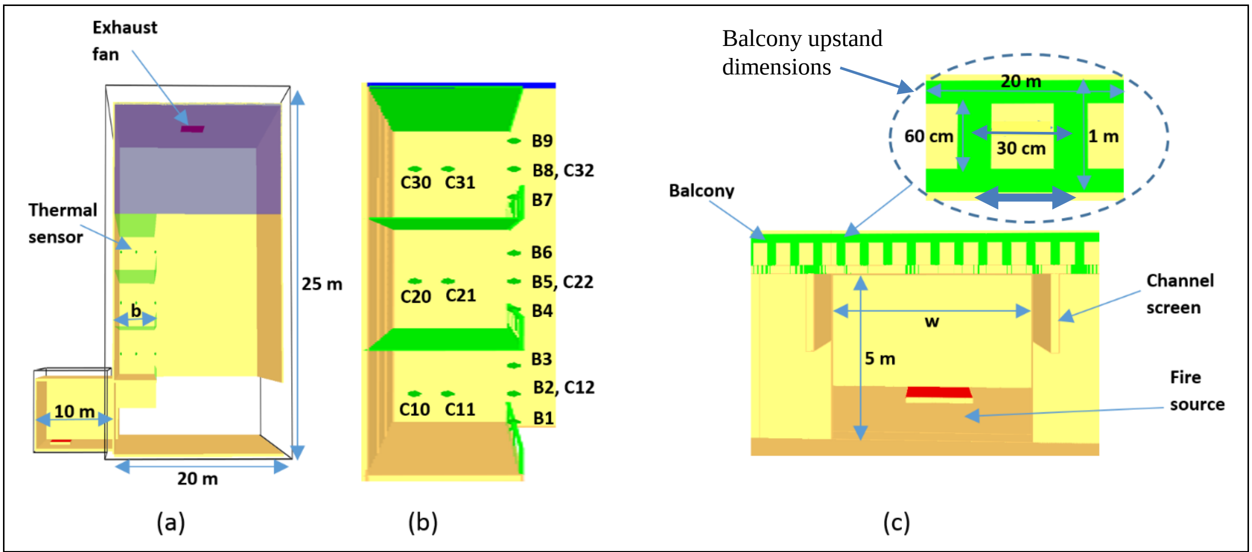

Figure 1. Schematic drawing of atrium and fire compartment (a) side view of atrium, (b) Location of temperature sensor, (c) Front view of fire compartment with the balcony upstand.

FDS utilized $\frac{D^*_{spill}}{\Delta x}$ ratio grid size determination in modelling [7]. The criterion that was utilized in this study for choosing an appropriate mesh size was set by Harrison [3]. The criterion for the size of grid cells is shown in equation (1) and (2).

$$n^*_{spill} = \frac{D^*_{spill}}{\Delta x} \geq 0.9 \quad (1)$$

$$D^*_{spill} = \left(\frac{Q_c/_w}{\rho C_p T\sqrt{g}}\right)^{\frac{2}{3}} \quad (2)$$

Where D^*_{spill} is characteristic length of plume for determining the grid size (m), n^*_{spill} is coefficient for determining the grid size, ΔX is grid dimension in x-axis, Qc is convective heat flow layer below spill edge, ρ is air density at ambient condition, Cp is a specific heat, T is absolute temperature and g is gravity acceleration. Hence, a grid size of 200 mm met the criteria mentioned above and it was selected for all simulations. The total number of mesh elements in the atrium space and fire compartment is 2332800 and 81000 respectively. Values adopted to the simulation like the balcony breadth (b), fire compartment opening width (w) and heat release rate (HRR) were varied for each case. However, down stand depth was kept constant as 1m for all cases. The maximum heat release rate used in this study is 4.8MW which is considered acceptable according to past studies performed for shopping mall fires with sprinklers fire protection system. The parameters used in the simulation are listed in Table 1.

Table 1. Values adopted to simulation.

Case	Balcony Breadth b (m)	Fire compartment opening width w (m)	Heat Release Rate (kW)
1	5	10	1581
2	3	8	1581
3	3	6	3160
4	2	6	3160
5	1.5	4	3160
6	1.5	2	4740

3. Results and discussion

Results presented in this section shows the comparison between the effect of balcony open and solid upstand on the smoke contamination in the balconies of an atrium. 6 cases were selected in this comparison and each case was simulated twice with open upstand and with solid upstand. Smoke temperature inside the balconies was recorded via FDS software sensors, which were located at specific places as it is illustrated in figure 1(b) and smoke contamination was assessed in both configurations.

3.1. Comparison of smoke temperature

Tan [3] found that temperature can be used as an indicator for smoke contamination. In his experiment, Tan recognized that when the smoke temperature was ≥ 10 °C above ambient temperature which is assumed to be $\mathbf{20}$ °C the smoke contamination appeared in the balcony. [5] and [6] used this criterion to determine the smoke contamination inside the atrium's balconies. In this study, 30 °C was highlighted in the temperature scale in smokeview and it appears as a black color in the temperature contours to determine the height as well as the location of the smoke layer within the balcony as it was very hard to determine them from FDS smoke contours directly.

Figure 2 clearly illustrates that the temperature along the balcony edges are higher for the balconies with solid upstand in comparison with the balconies with open upstand. This indicates that the smoke plume is closer to the atrium structure in the case of solid upstand than with open upstand. Figures 3 and 4 show the temperature inside the balconies for case 1. As seen in Figure 3 that the temperature at balconies 2 and 3 was higher than 30°C indicating that smoke contamination has occurred. However, when open upstand was modelled; Figure 4 shows that all temperatures were lower than 30°C which indicates that no smoke contamination occurred.

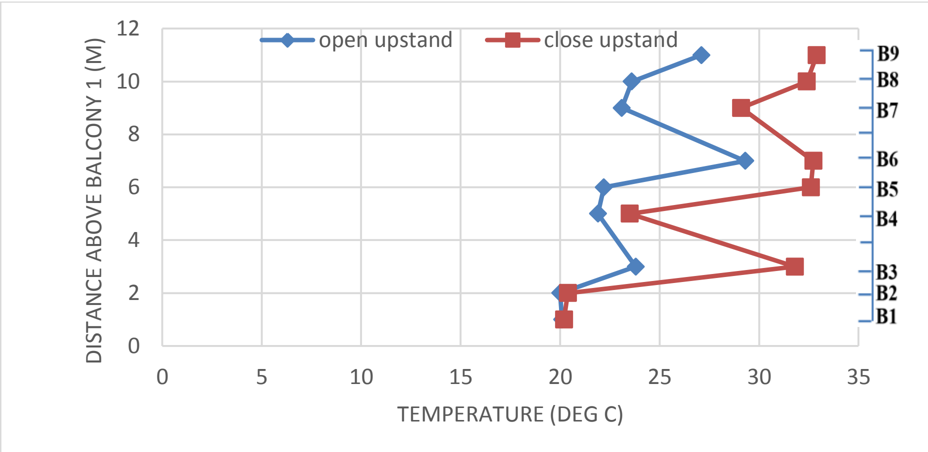

Figure 2. Temperature profile across balcony edge.

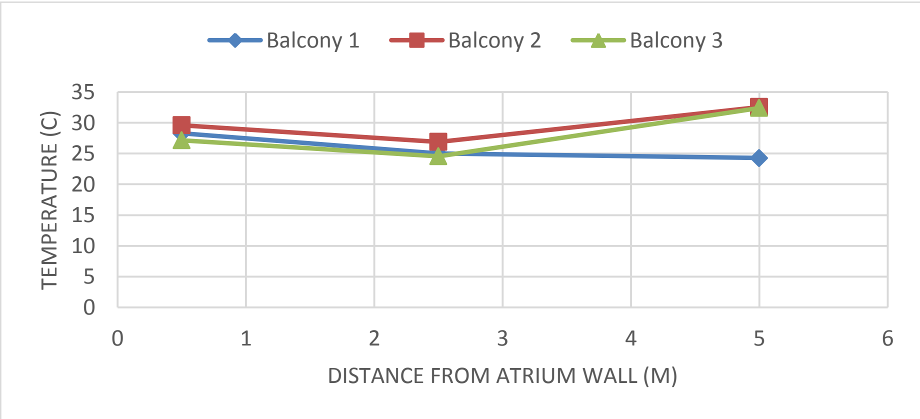

Figure 3. Temperature profiles along balcony breadth with solid upstand.

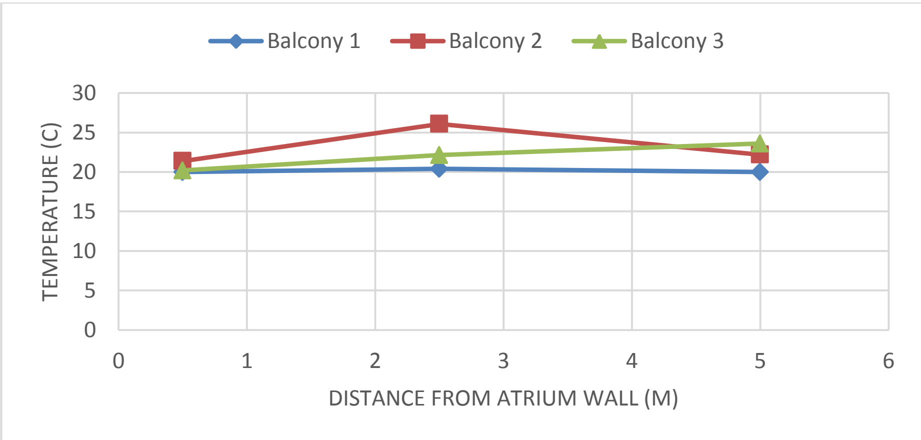

Figure 4. Temperature profiles along balcony breadth with open upstand.

3.2. Comparison of smoke contamination height

As mentioned in Table 1 that the atrium dimensioned varied for each case. Table 2 shows the simulation results including the height of smoke in the balcony (above balcony 1). As seen, that although in cases 3, 5 and 6, the smoke contamination occurred at the balconies when solid upstand was used and the height of smoke contamination is indicated in Table 2. However, when open upstand was used, no smoke contamination was observed for the mentioned cases.

Moreover, for cases 1,2, and 4, for both open and solid upstands, smoke contamination has occurred, however, the severity of the smoke contamination reduced (higher smoke height) as compared with solid upstand.

Table 2. A comparison of smoke contamination height in balconies with open and solid upstand.

Case	b(m)	w(m)	Open Upstand H(m)	Solid Upstand H(m)
1	5	10	7	2.7
2	3	8	8.7	1
3	3	6	No Smoke Contamination	12.4
4	2	6	13.9	8.3
5	1.5	4	No Smoke Contamination	7
6	1.5	2	No Smoke Contamination	13.4

Figure 5 (a) shows the effect of balcony open upstand on the pressure distribution. As the simulation progress to 158.5 seconds, the static pressure on both sides of the plume decreases below the ambient pressure but in the right side of the plume (away from the balcony) the pressure dropped to 0.78 Pa which is lower than the pressure on left side of the plume (near or inside the balcony) that is 0.52 Pa. Hence, the smoke was pushed outward the balcony and smoke contamination will not occur inside the balcony. Figure 5 (b) illustrates the pressure distribution of case 1 with balcony solid upstand at 158.5 second. The pressure inside the balcony dropped more than the side of the plume that is facing the open space of the atrium. The reason behind the static pressure drop in the region between the plume and the atrium structure is the continuous air entrainment and less air replacing the entrained air in that region. Hence, the smoke will curl inward and the smoke contamination will occur at that balcony.

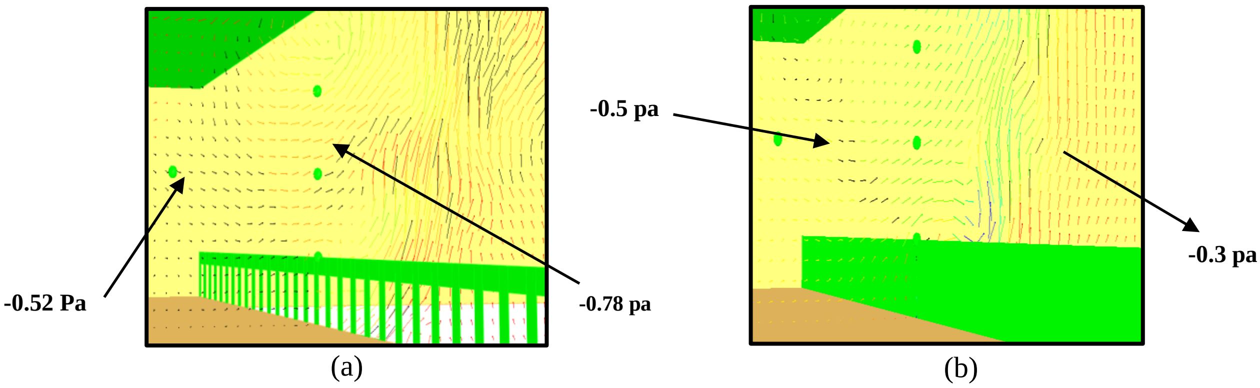

Figure 5. Pressure distribution of case number 1 at simulation time = 158.5 sec
(a) Open balcony upstand (b) Solid balcony upstand.

Cases 1 and 5 were selected to present the effect of upstand type on smoke contamination. For case 1, at time 158.5 sec and 198.5 sec and for case 5 at time 162.5 sec and 246.5 sec. The smoke contamination is highlighted in a red dotted circle, in the contours. As seen in figure 6 that for both cases with solid upstand, the temperatures at the balconies were higher than 30°C indicating smoke contamination has occurred. However, when open upstand is modelled, the temperature inside the balcony were lower than 30°C indicating no smoke contamination occurrence. As seen in Figure 6 (a) he smoke contamination decreased in the case of open upstand. (b) The smoke contamination was deep in balcony 1 and 2 and it becomes shallow in the presence of open upstand. Similarly, in figure 6 (c) and (d) balconies with open upstand are clear after it had been contaminated in the case of solid upstand. That reflects the effect of balcony open upstand in reducing the smoke contamination occurrence inside the balcony.

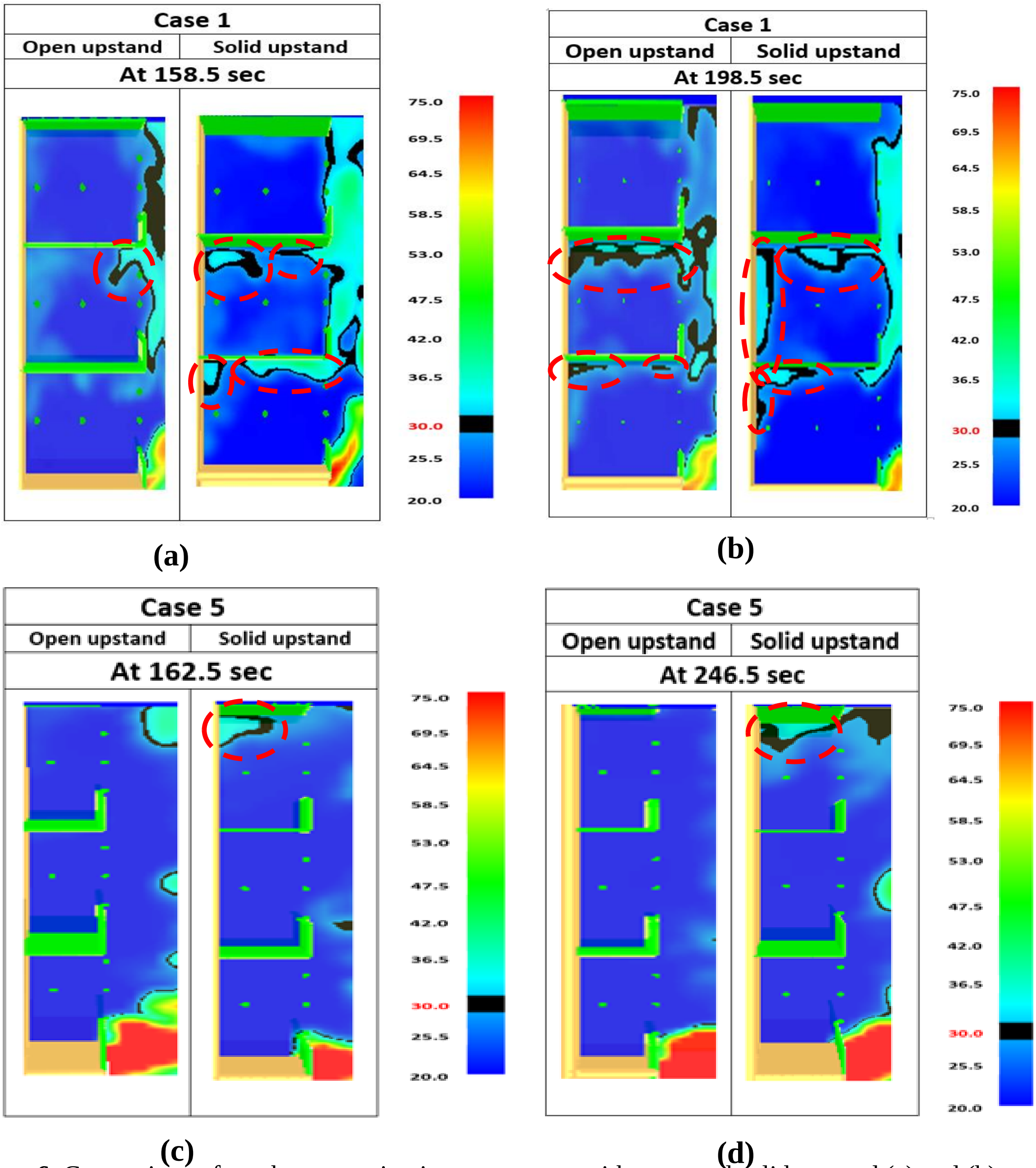

Figure 6. Comparison of smoke contamination occurrence with open and solid upstand (a) and (b).

Case 1 at 158.5 sec and 198.5 sec, (c) and (d) Case 5 at 162.5 sec and 246.5 sec

It can be concluded that in case of fire, using open upstand provide safer occupant environment than solid upstand.

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4. Conclusions
CFD simulation using fire dynamic simulator is carried out by varying structural parameters of an atrium such as balcony breadth, fire compartment width and the heat release rate. The effect of balcony open upstand on smoke contamination in atrium's balconies is investigated in this study and compared to the effect of balconies with solid upstand. It was found that in case of open upstand, the smoke contamination is decreased inside the balcony comparing with balconies with solid upstand.

5. References
[1] Association N.F.P. 1991 Smoke management systems in malls, atria and large areas 92B.
[2] Cox G 1995 Compartment fire modelling *J. Combust. fund. of fire* 329-404
[3] Harrison R 2009 Entrainment of air into thermal spill plumes
[4] Hasnain SA, Nasif MS, Pao W and Al-Waked R 2017 Numerical investigation of smoke contamination in atrium upper balconies at different down stand depths *J. Building Simulation*
[5] Hasnain SA, Nasif MS, Pao W and Al-Waked R 2014 Effect of Down Stand Depth Variation on Atriums Upper Balconies Smoke Contamination *J. MATEC Web of Conferences*
[6] Ho CL, Li KY and Spearpoint MJ 2013 Numerical simulation of scale-model smoke contamination of upper atrium levels by a channelled balcony spill plume *J. Fire and Materials* **37(8)** 581-96
[7] McGrattan K, Hostikka S, Floyd J, Baum H, Rehm R, Mell W and McDermott R 2010 Fire dynamics simulator (version 5), user's guide **1019(5)** 1-186.
[8] Morgan HP, Ghosh BK, Garrad G, Pamlitschka R, De Smedt JC and Schoonbaert LR 1999 Design Methodologies for Smoke and Heat Exhaust Ventilation. Construction Research Communication Ltd, Londres, R, U.
[9] Tan F, Harrison R and Spearpoint MJ 2010 Physical scale modeling of smoke contamination in upper balconies by a channeled balcony spill plume in an atrium *J. of Fire Sciences* **1;28(4)** 313-36.