Numerical Studies on Different Stairwell Smoke Extraction Techniques in a High-rise Building

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ABSTRACT

Need for high-rise buildings has increased to meet the modern urbanization needs. With the increase in technology and computational power, engineers are shifting towards performance-based design instead of prescription design for ensuring a higher level of fire safety in high-rise buildings with increased flexibility. In the present study, various methods of stairwell smoke extraction, as available in the National Building Code of India 2016 (NBC), are analysed and comparison is drawn between them. Computational modelling technique using the large eddy simulation method in Fire Dynamics Simulator (FDS) is employed to study fire scenarios in a model high-rise building. It was found that natural ventilation and cross ventilation in the stairwell is not fully effective for smoke extraction. Furthermore, the pressurisation of stairwell at a minimum differential pressure of 25-30 Pa seems to be effective only when all windows in the stairwell are closed. It was noticed that the maximum differential pressure in the stairwell is not defined in NBC. Case studies were also performed to see the effectiveness of single and multiple stairwell pressurisation techniques. A new technique by installing long smoke extraction duct along with pressurisation is also proposed and investigated which works effectively even when windows are open in the stairwell. In the end, conclusions from this study can be used for further improving the stairwell smoke extraction methods in NBC. The study was performed by focusing on the Indian context but the findings may generalize elsewhere too.

KEYWORDS: High-rise building, FDS, positive pressure ventilation, smoke, exhaust fans, stairwell.

NOMENCLATURE

c_p	specific heat of air (J/kg.K)
D^*	characteristic diameter (m)
g	acceleration due to gravity (m/s^2)
Ma	Mach number (-)
Q	total heat release rate (W)
T	temperature (K)
t	time (s)

Greek

α	fire growth coefficient (kW/s^2)
ρ	density (kg/m^3)
Δx	grid size (m)

Subscripts

∞	ambient

Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulator
HRR	Heat release rate
LES	Large Eddy Simulation
NBC	National Building Code of India, 2016
PBD	Performance-based design
PPV	Positive pressure ventilation

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INTRODUCTION

With the advent of civilization and limited space availability, the need for high-rise buildings has increased to meet the modern urbanization needs. In recent years, record high-rise buildings have been created and many more are in the construction stage. This outburst has urged engineers and researchers worldwide to devise their safety measures [1]. Unfortunately, many fire accidents have already taken place in the past across the world with many more which were gone unnoticed and unreported [2-4]. In India also this number is increasing [5]. A huge amount of loss in terms of life and property is associated with these fire accidents.

Considering the severity of these accidents, there is an urgent need to carry out research to study the causes of accidents in high-rise buildings and formulating strategies for their safety. To achieve this, performance-based design (PBD) techniques [6] are being increasingly used these days. Smoke extraction is one of the key parameters in PBD as smoke reaches to the other floors of the building much earlier than the fire itself causing more casualty. About 3/4 of all fire deaths are caused by smoke inhalation only. Stairwells are the main route of smoke propagation, so keeping them smoke-free has always been a challenge for any fire engineer [7]. In literature, many techniques such as natural ventilation, compartmentation, airflow, stairwell pressurisation, mechanical exhaust, etc. are available for stairwell smoke extraction depending upon the building height and building code of the particular country [8, 9]. As per the National Building Code of India (NBC) [10], different methods for stairwell smoke control in high-rise buildings are compartmentation, natural ventilation, cross ventilation and pressurisation of staircases. This is the main objective of the present study to compare and see the effectiveness of these methods, as mentioned in NBC, for smoke extraction using a performance-based design (PBD) approach. Based on the results of this study, various recommendations have been given that can be incorporated in NBC for further enhancing stairwell smoke extraction methods. This study has been done by focusing on the Indian context, with particular reference to the National Building Code of India but the findings may generalize elsewhere too.

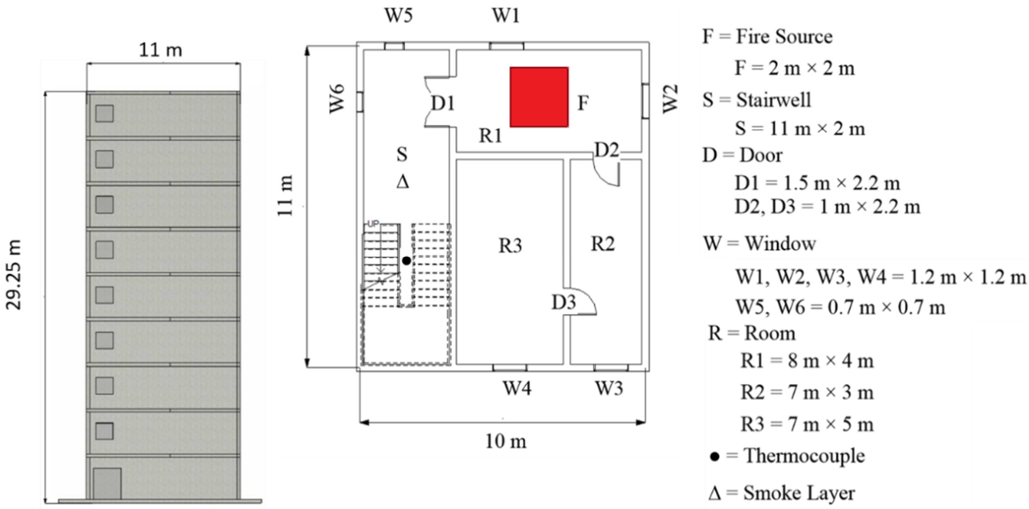
MODELLING

CFD model

Since the past few years, computational fluid dynamics (CFD) techniques are increasingly used for fire and smoke simulation. Modelling of fire and smoke accurately is very important to get reliable results. Fire Dynamics Simulator (FDS version 6.6.0) [11], an open source CFD code, was used for the current study. It has been very well validated in the past with experimental data and semi-empirical models for a variety of cases including smoke spread [12-14]. It is a finite difference, large eddy simulation (LES) model which solves numerically a form of the Navier-Stokes equations for low speed ($Ma < 0.3$), thermally-driven flow with an emphasis on smoke and heat transport from fires. The core algorithm in an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence model in FDS is based on LES where large eddies are directly resolved and for smaller eddies, modelling is done. Filtering of eddies is done by a sub-grid length scale based on mesh size. In order to determine the sub-grid scale turbulent viscosity, FDS provides various models with the "modified Deardorff" as the default model. For most applications, FDS uses a combustion model based on the mixing-limited, infinitely fast reaction of lumped species. Lumped species are reacting scalar quantities that represent a mixture of species. For radiation modelling, the radiative transfer equation is solved using the finite volume method. The governing equations and other details have been very well documented in the FDS technical reference guide [13]. For the present study, the default models and constants in FDS were used.

CAD model

A sample high-rise building as shown in Fig. 1 was created in PyroSim (version 2018.2.0730) [15]. The building is 29.25 m high with concrete walls and consists of 9 floors with dimensions of each floor including staircase of 11 m x 10 m x 3.25 m. Mattresses made of polyurethane foam with dimensions of 2 m x 2 m are taken as heat source placed inside the room on the second floor. Dimensions of all doors and windows are taken as per NBC guidelines [10] and are shown in Fig. 1. The fire source is placed in the room next to the stairwell so as to study the maximum filling of smoke in the stairwell. All rooms are connected via doors and windows. As the main objective of this work is to study smoke movement in the stairwell, so only the main door of the building at the first floor and the room doors on the second floor and seventh floor are assumed to be open and the rest of all doors are closed. The building is well ventilated with windows on all sides. Windows of rooms at every floor are open throughout while opening and closing of windows in the stairwell was varied depending upon the case being considered. Thermocouples and devices for measuring smoke layer height are also installed at the centre of the stairwell on every floor as shown in Fig 1 (b).



(a) (b)

Fig. 1. CAD model of the high-rise building showing (a) Front View (b) Top view of the second floor with fire source

Design fire and scenario

One of the most important steps in any PBD of a structure involves identifying various possible fire scenarios. The Life Safety Code and NFPA 5000 (2012b) has listed various scenarios based on the design fire, building and occupant characteristics. In the current study, Life Safety Code design fire scenario 2 was chosen. It is an ultra-fast developing fire scenario in the primary means of egress with interior doors open at the start of the fire. This scenario gives information about the maximum extent of smoke spread [16]. The design fire is predicted on the basis of the expected approximate fuel load based on the type of occupancy. In the present study, a residential building is assumed with the fire source placed inside the living room on the second floor for which approximate maximum loading is 642 kW/m^2 [17]. In addition, after studying the reconstruction of fire accidents in literature, the authors found that the design fire in the majority of accidents varied mostly between 1 MW and 10 MW, so the authors fixed the maximum HRR to be 5 MW with growth according to a t-squared fire curve [9, 18-21]:

$$Q = \alpha t^2 , \tag{1}$$

where Q is the maximum HRR (kW), α (kW/s^2) is fire growth coefficient and t (s) is the critical time in which fire reaches to maximum HRR. Considering the ultra-fast fire scenario with a critical time of 150 s, fire curve is shown in Fig. 2. It reaches a maximum at 150 s, stays maximum up to 250 s after which it starts decaying and reaches zero at 300 s.

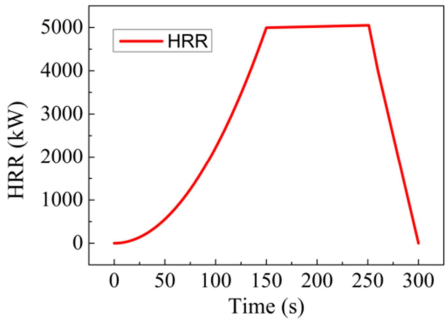


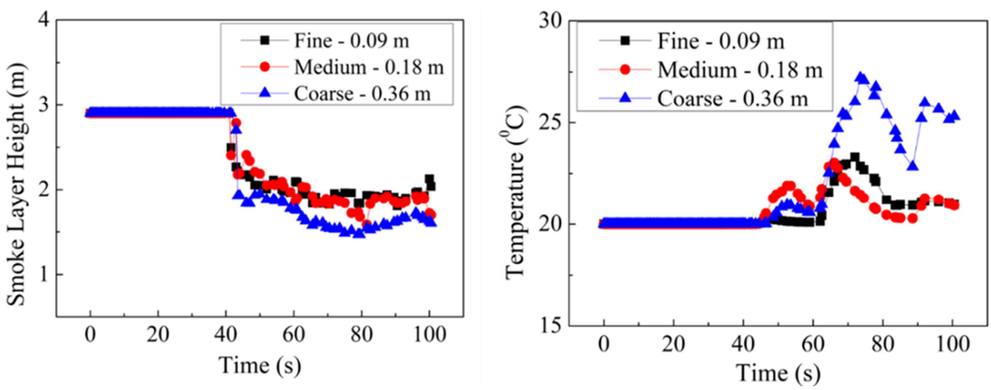
Fig. 2. Design fire curve.

Grid independence test

In FDS, the governing equations are solved on a rectilinear mesh. CFD results are always grid sensitive so a grid independence test needs to be performed. Uniform meshing is taken and the approximate idea of grid size (Δx) is obtained by calculating the characteristic fire diameter D* given by [11]:

$$D^* = \left(Q \big/ \rho_\infty C_p T_\infty \sqrt{g} \right)^{\frac{2}{5}}, \tag{2}$$

where Q is the maximum heat release rate (5000 kW), ρ_∞ is the density of air (1.2 kg/m^3), C_p is the specific heat at constant pressure (1.005 kJ/kg.K) and T_∞ is the ambient temperature (293 K). After putting the above values into Eq. (2), D^* comes out to be 1.85 m. For numerically stable results, McGrattan et al. suggested that the value of $\Delta x/D^*$ should be less than 0.1 [22]. In order to check the dependence of results on the grid size, simulations were performed by taking three different values of $\Delta x/D^*$ as 0.25, 0.1 and 0.0625. The corresponding grid sizes were 0.36 m for coarse, 0.18 m for medium and 0.09 m for fine mesh, respectively. Figure 3 shows the values of temperature and smoke layer height on the second floor with three different grid sizes.



(a) Smoke layer height (b) Temperature

Fig. 3. Grid independence study with different cell sizes.

It can be seen from Fig. 3 (a) and (b) that the trend for smoke layer height and temperature is approximately similar for fine and medium mesh size. Further smoke layer height is becoming nearly constant after 60 s so averaging was done for 60-100 s and it was found that results of the grid independence test for the fine and medium mesh are approximately within 5 %, while for fine and coarse mesh, it is 13 %. Again from Fig. 3 (b), temperature starts increasing after 40 s and then decreases and becomes nearly constant after 80 s so, in this case, averaging was done for 80-100 s, and it was found that the results were deviating by 1.6 % for medium mesh and by 13 % for coarse mesh when compared with the fine mesh. Since the deviation in results for fine and medium size mesh was less than 5 %, considering time limitations, the medium size mesh (0.18 m) was chosen for further simulations. Furthermore, it was also satisfying the McGrattan criterion [22].

RESULTS AND DISCUSSION

Different methods of smoke extraction – natural ventilation, cross ventilation, stairwell pressurisation and smoke exhaust ducts – have been studied below as per NBC guidelines [10].

Natural ventilation

For natural ventilation in the stairwell, as per NBC, an opening of area 0.5 m^2 should be installed at each stairwell landing [10]. For this, windows (W5) of dimension 0.7 m x 0.7 m are provided and kept open on all floors while windows W6 are kept closed.

Cross ventilation

For cross ventilation, two openings of area 0.5 m^2 should be provided in a stairwell in opposite or adjacent walls which can be cross-ventilated through the corridor [10]. For this, windows W5 and W6 are kept open at every floor.

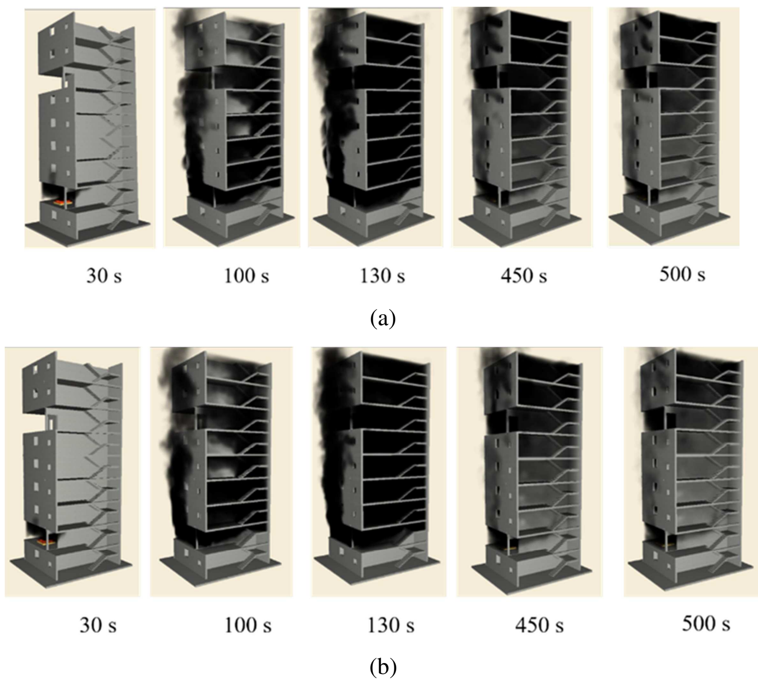


Fig. 4. Smoke at different time steps for (a) Natural ventilation (b) Cross ventilation

A section view of the stairwell filled with smoke is shown in Fig. 4 (a) and Fig. 4 (b). It shows that the smoke in both cases is entering the stairwell at 30 s, filling the rooms of the 7th floor at 100 s and completely filling the stairwell by 130 s. Even after the fire source goes off at 300 s, the stairwell is still having smoke up to 500 s. It can be deduced that both of these methods are not effective for keeping stairwell smoke free. In both cases, the stack effect is dominant by which fresh air enters from the windows into the stairwell and rises upwards due to buoyancy and in the process, smoke also starts moving upwards to higher floors. The stack effect is clearly visible in Fig. 4 where smoke is seen coming out of windows from higher floors only. As seen in Fig. 5, the neutral plane is one floor higher in cross ventilation (6th floor) as compared to natural ventilation (5th floor). This shows that the stack effect will increase with an increase in the number of windows in a high-rise building, and hence increasing smoke spread to other floors. This particular time step of 250 s was chosen in the whole study to show the comparison between different methods more in detail.

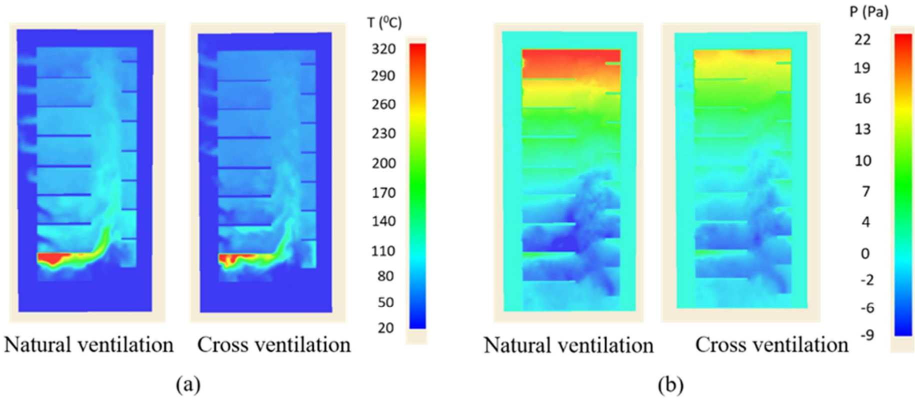


Fig. 5. Slice passing through the centre of the stairwell at 250 s showing (a) Temperature and (b) Pressure

Stairwell pressurization

For stairwell pressurization, a minimum pressure differential of 25-30 Pa is required [10]. In order to study the effect of opening and closing of windows in the stairwell, both cases were simulated. In general, there are two ways to achieve stairwell pressurisation – single injection and multiple injections. Single injection is achieved by installing a single supply vent either at the top or bottom of the building. But for buildings with a height greater than 15 m, it is difficult to maintain the required pressure differential. In such cases, a multiple injection system can be used by installing supply fans on different floors. In most cases, this is achieved by installing supply vents at alternate floors in the staircase.

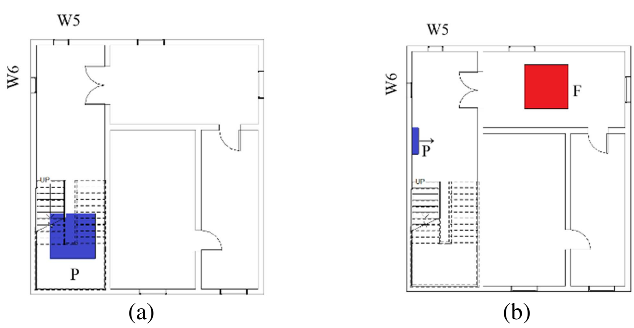


Fig. 6 CAD model showing top view of (a) the second floor (multiple injections) (b) Top floor (single injection) (P denotes PPV vents)

Without ventilation

In this case, all the windows in the stairwell (W5 and W6) were kept closed and PPV systems were installed depending upon multiple or single injection.

Multiple injections at alternate floors

Figure 6 (a) shows the top view of the second floor fitted with a positive pressure ventilation system (PPV). A similar installation was done on the 4th, 6th, and 8th floor. PPVs of different capacities - 1, 2, 5 and 10 m^3/s were tested to achieve a minimum pressure differential of 25 Pa. As can be seen from Fig. 7, in the first two cases smoke is entering into the stairwell and going to the top. This is due to a low-pressure differential between rooms and stairwell (less than 25 Pa) as clearly visible in Fig. 8. While for 5 and 10 m^3/s the stairwells remain smoke-free but a very high differential pressure is achieved with 10 m^3/s PPV as shown in Fig. 8. This high pressure can disrupt door opening during routine operation and evacuation. A maximum limit should be defined on this pressure so that it stays below the maximum door opening force.

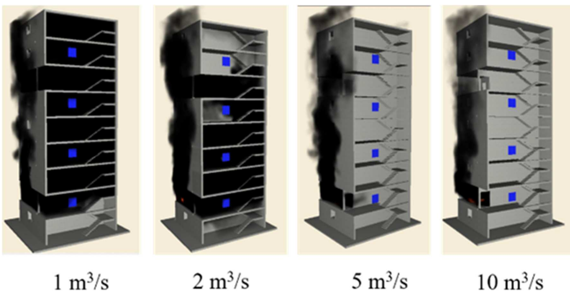


Fig. 7. Smoke at 250 s for different capacities of supply fans for multiple injections.

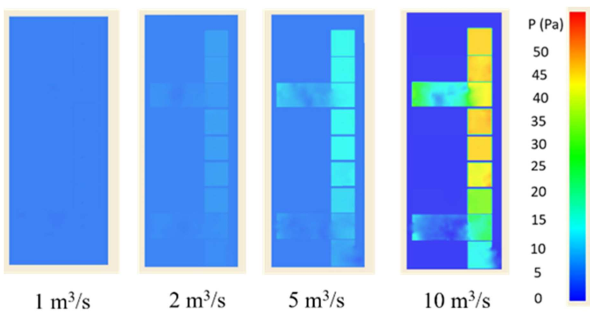


Fig. 8 Pressure slice passing through stairwell and Door D1 of all floors at 250 s for different capacities of supply fans in multiple injection systems.

Single Injection at the top floor

Again, windows (W5 and W6) were kept closed on all floors to simulate a case without ventilation. A single PPV system was installed at the top floor of the building above the stairwell as shown in Fig. 6 (b) and different capacities of 10, 20, 30 and 40 m^3/s were tested. It can be seen from Fig. 9 that the 10 m^3/s PPV, which was working well in multiple injection system, is not fully effective in this method, as a single fan is not able to create the required differential pressure of 25 Pa. Higher PPV systems prevent the smoke from entering into the stairwell, but a very high pressure differential is created at higher floors (Fig. 10). Also, the opening of doors in upper parts of the building can significantly reduce the pressure difference at lower floors making PPV ineffective.

This result can be included in NBC to indicate that, for high-rise buildings, only multiple injection systems should be used while for smaller buildings up to 15 m, both single and multiple injection methods can be used after doing a PBD analysis of those PPV systems.

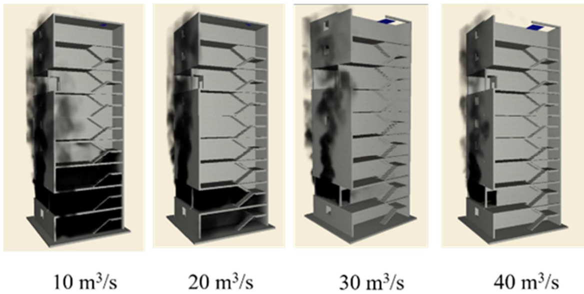


Fig. 9. Smoke at 250 s for different capacities of supply fans for a single injection.

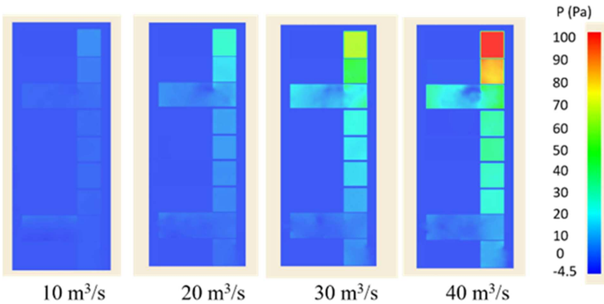


Fig. 10. Pressure slice passing through stairwell and door D1 of all floors at 250 s for different capacities of supply fans in the single injection system.

With ventilation

To study the effect of opening and closing of windows in a PPV system, two previous effective case studies of multiple injection systems with 5 and 10 m^3/s were repeated with windows open in the stairwell. As can be seen from Fig. 11, both PPV systems are not as effective in controlling smoke spread as they were in the previous case when all the windows were closed. This is due to the drastic fall in pressure in the stairwell due to the opening of windows (Fig. 11). Hence, for effective smoke control using PPV, all windows should either be closed in the stairwell or higher PPVs must be installed to compensate for the decrease in pressure.

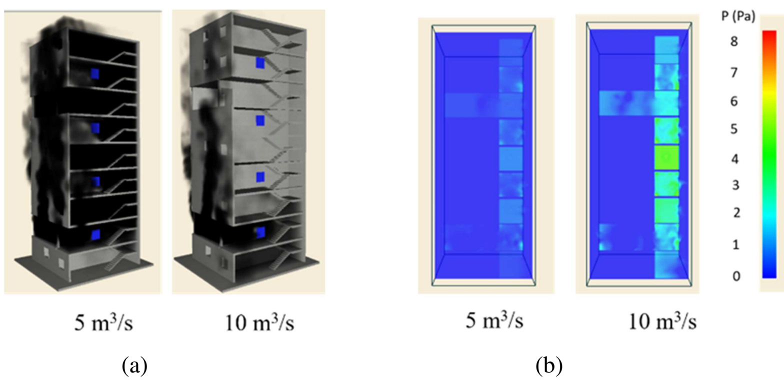


Fig. 11. With ventilation: (a) Smoke spread at 250 s (b) Pressure slice passing through the stairwell and door D1 for multiple injections with open windows in the stairwell

Stairwell pressurization with exhaust duct

Results from the previous section suggested that, for effective smoke control using positive pressure ventilation (PPV), all windows should either be closed in the stairwell or higher PPVs must be installed to compensate for the decrease in pressure due to the opening of windows. But higher PPVs can also increase the door opening force making evacuation difficult. Also, it is not always possible to keep all windows closed in the stairwell. These problems can be overcome by installing a long exhaust duct at the back side of the building as shown in Fig. 12. In this case, PPV of capacity 2 m^3/s was tested with windows (W5 and W6) open at all floors.

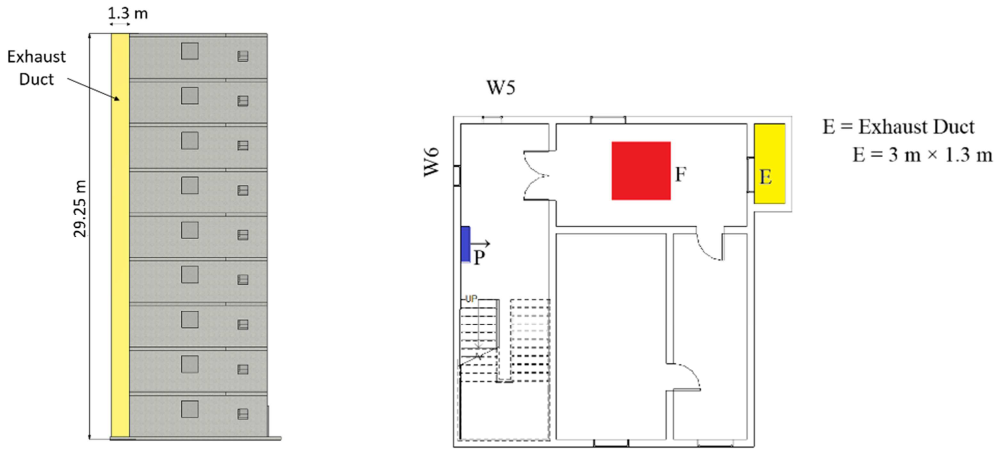


Fig. 12. CAD model showing exhaust duct- Side view of building (left) and top view of the second floor (right)

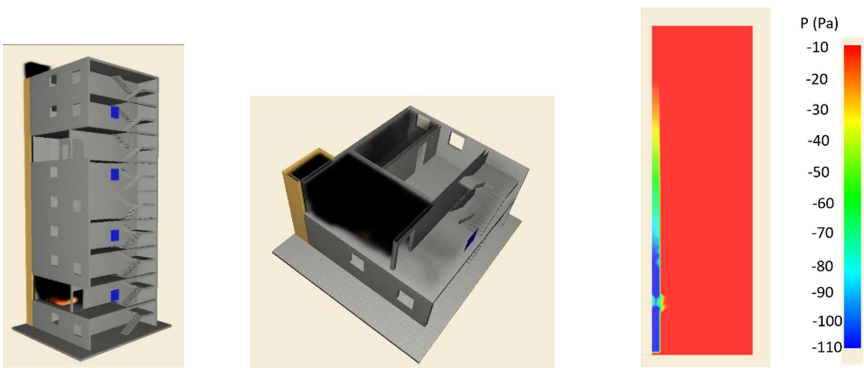


Fig. 13. (a) Smoke spread (b) Section view of the second floor
(c) Pressure slice passing through the exhaust duct at 250 s

It can be seen from Fig. 13 that with the exhaust duct, a PPV of 2 m^3/s is able to keep the stairwell smoke free. Furthermore, in all previous cases, the fire was spreading to all rooms of the second floor but in this case, less smoke has spread to other rooms. This is due to the formation of the stack effect inside the duct which removes the smoke rapidly from the fire room without allowing it to spread to other parts of the building and stairwell. Hence, this method proves very effective in keeping the stairwell smoke free even if windows are open in the stairwell with the advantage that it requires lesser PPV. Such exhaust ducts will also prove beneficial in those places where natural ventilation is not possible. Further studies on using smoke exhaust fans in these ducts can be performed.

CONCLUSIONS

A common scenario of a fire in a high-rise building is investigated using validated numerical techniques. Various smoke evacuation strategies mentioned in the National Building Code of India, 2016 are evaluated. Based on the results of the present study, the following conclusions are suggested to be included in NBC for making smoke extraction methods more effective and easy to use:

1. It was found that for high-rise buildings, natural or cross ventilation systems are not effective. They enhance the stack effect and hence promote smoke spread to higher floors via the stairwell.
2. For the pressurised method, the minimum specified differential pressure of 25-30 Pa in NBC works very well and is able to prevent smoke spread. Maximum pressure in the stairwell should be defined. As high pressure in the stairwell can hinder the opening of doors obstructing the evacuation, an upper limit should be fixed based upon the maximum door opening force.
3. From the present study it was observed that, for stairwell pressurisation, multiple injection systems are more effective than single injection for high-rise buildings. With multiple doors opened at various floors, the single injection system fails to maintain the required pressure differential in the stairwell.
4. The effect of opening or closing of windows in the stairwell should be taken into consideration while designing the PPV system. It was found that, if stairwell windows are open, then the effectiveness of the stairwell pressurisation method is considerably reduced. So, it is suggested that for effective stairwell pressurisation windows in the stairwell should either be closed or higher PPV systems should be installed. To serve the purpose of lighting and ventilation in the stairwell, the PPV system can be made to run at lower air volume at normal operation and at higher air volume in case of fire accidents.
5. It was also observed that, if along with the pressurised system the exhaust duct is fixed near windows, then the PPV method works even at a lower capacity of supply vents. This method also proves effective when windows are open in the stairwell due to the creation of a higher stack effect in the exhaust duct.

Hence, CFD models can help to design the layout and evaluate the performance of various smoke extraction systems in a high-rise building. Further studies for optimizing the location and capacity of the pressurised ventilation system, exhaust fan, duct size, etc. can be done. Since it is not possible to perform experiments, such modelling techniques can be useful for formulating pre- and post-building fire mitigation strategies.

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