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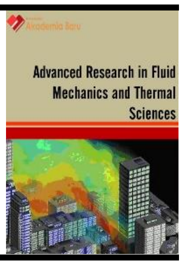


# Numerical Simulation of Alternative Smoke Control Approach in a High-Rise Building

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**ABSTRACT**

Smoke inhalation is a major cause of death in fire accident. Three quarters of building fire casualties were the result of excessive smoke inhalation, even with the presence of a control system. One of the main reasons to a high percentage of fatality is poor circulation and exhaustion of smoke. A proposed system, including an integrated ACMV exhaust with additional louver, will be simulated and compared with the current conventional approach, the fixed pressurization system. The purpose of this study is to determine the effectiveness of the newly proposed approach to smoke exhaustion. Results showed that the path of obscuration for the conventional system in the room displayed a lowered value of 8.77 %, as compared to 9.71% for the integrated ACMV system, due to the greater propagation of smoke out of the room. The results are in agreement as there is a noticeably faster subsiding of hot air temperature at the corridor for the integrated ACMV system than that of the conventional system, after the peak temperature spread of 115 seconds. The current study concluded that the proposed integrated ACMV system with additional louver is more effective for smoke control than the conventional design.

## 1. Introduction

The United States Fire Administration estimated in 2016 that there were 364,300 residential building fire cases, causing 2,775 deaths, 11,025 injuries, and a total loss of $US5,726,300,000 in the United States. Out of the aforementioned cases, 375 deaths were due to smoke inhalation [1]. While advance research in the green building is paramount [2-5]; the safely egress for occupants during fire event is equally important. The purpose of a smoke control system is to trigger an emergency whereby toxic smoke or fire occurs inside an enclosed room; such a system reduces the chances of

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fire and smoke propagation away from the outbreak location and more often than not, will attempt to extinguish the fire. In a brief context, the system, be it mechanical or natural, will localize the smoke production and fire outbreak to the specific room, allowing occupants more time to evacuate. Lay [6] highlighted that conventional localized pressurization of the fire outbreak zone is ineffective to impede smoke and fire propagation, which may be unsafe for victims and firefighters also. Such a system is often subjected to the operational dynamics at the point of a fire event, and it would affect some of the design parameters, such as air flow rate and room pressure. Although the desirable pressure can be found in the available standards NFPA 92 A and NFPA 92 B, a huge challenge for designers is to ensure that such standards can be maintained. Any leakages, even those through the seams of door and windows, would affect the required pressure and air flow. Moreover, for high-rise buildings (essentially more than 30 storeys), height represents another obstacle for which to account in the design phase. An effective system may require serious adjustments to compensate for any changes to any of the design parameters during a fire event. In view of the weakness in the conventional system, alternative approaches involving positive pressure ventilation have been proposed.

This study aims to improve the existing building system's smoke control approach by integrating the air-conditioning and mechanical ventilation (ACMV) system in a non-dedicated approach. Modification to the existing ACMV system is done by adding an automatic louver in accordance to NFPA 92 A [7]. The study intends to evaluate the effect of the modification on the smoke propagation and the overall smoke temperature in the fire zone. The aforementioned parameters are important to ensure safe evacuation of the affected building occupants by ensuring a clear escape route and prolonging the window for evacuation. A comparison between the conventional and the proposed modified smoke control approach is made to evaluate their smoke control effectiveness.

The following sub-sections will provide a brief account on the fundamental aspects considered in this study, including the fixed smoke management system, stairwell pressurization, formation of fire, fire modelling and contingencies in high-rise building, as well as the role of louver and pressure utilization.

### *1.1 Fixed Smoke Management System*

It is common to come across smoke management control that have more than one system; typically, high-rise buildings will utilize a combination of dedicated and non-dedicated systems to effectively deal with smoke containment. In the event of fire, fixed smoke management system will exhaust the smoke from the floor of the fire outbreak through an exhaust shaft, which will prevent positive pressure build-up from the fire [8]. Toxic fumes will travel along the corridor or room towards one of the exhaust shafts before exiting the building. For its part, the ACMV system is programmed to cease operation during a fire outbreak to minimize disruption of the smoke exhaust process and to prevent any potential damages to the system's vents and filters. In addition, it ensures that the entire floor is brought to negative pressure. Residual atmospheric pressure from other levels will indirectly provide a positive pressure, creating a "pressure sandwich". Although studies have proven that a pressure difference will introduce more fuel (oxygen) to the fire outbreak floor, the system prioritizes the safety of the building occupants by providing an escape route. It's worth noting that a fixed smoke management system does not solely rely on the smoke exhaust; it is often coupled with pressurization of the stairwell, thus, preventing smoke from entering the evacuation route.

### *1.2 Stairwell Pressurization*

As mentioned briefly in previous subsection, the stairwell pressurization system is paired to function with other dedicated or non-dedicated systems to inhibit smoke propagation. Such an approach is known as the positive-pressure ventilation as axial fans operate to provide a positive pressure zone for the stairwell (Figure 1) [9]. Outside air is introduced into the stairwell through a dedicated duct, which will complete the pressure sandwich. A successful implementation to the coupled system will enable the occupants to evacuate the building efficiently; moreover, it will advance the ventilation process to expel smoke [10]. NFPA 92 and ASHRAE Standard 62 [11] stated that the difference in pressure zones should not exceed 50 Pa.

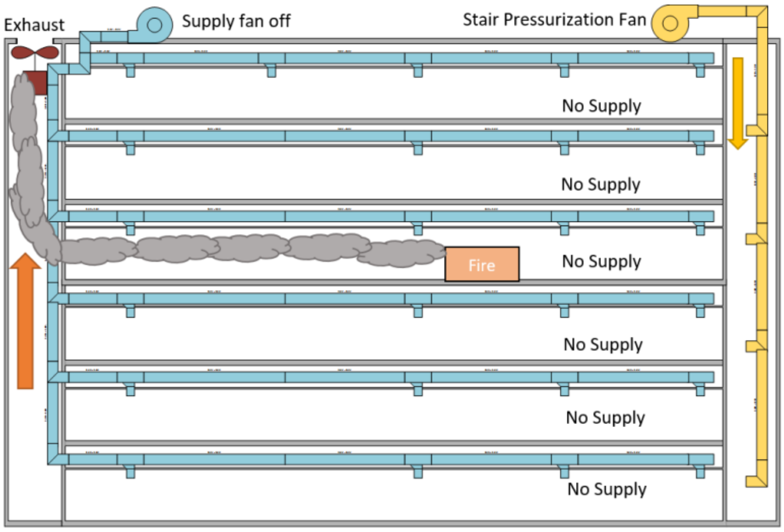

**Fig. 1.** Fixed pressurization system

### *1.3 Formation of Fire*

Whenever an object is undergoing exothermic reaction, it releases heat while it loses energy. Normally, these reactions require an activation energy or temperature to carry out an exothermic response successfully, along with the presence of oxygen. More often than not, the release of energy through an ignition temperature is likely to cause combustion, or fire. Every object will have varying thermal conductivity due to its elements and its structure of lattices [12]. When left unsupervised, the fire will spread rapidly to its surroundings when other object's ignition temperature is reached. Other than releasing immense heat, combustions taking place in non-ideal situations will cause incomplete combustion, thus, creating a by-product known as soot. Soot production is very unpredictable in many cases, as combustion in high-rise buildings comprises of many objects with different thermal conductivity and ignition temperature. Although many computational simulations are trying to replicate a complex fire, there are, however, notable differences in the soot production and the fire capacity when two or more fuels are mixed. The results from the studies prepared by The United States Fire Administration [1] showed that three quarters of the fatalities are caused by inefficient smoke control and excessive smoke inhalation, rather than the fire source; therefore, the emphasis is on the significance to create a more effective method to prevent the spread of smoke.

### *1.4 Fire Modelling and Contingencies in High-Rise Buildings*

The three most common types of fire models are the algebraic models, the zone models, and the computational fluid dynamics (CFD) models. Each model comes with its own applications, with respective advantages and limitations. Moreover, the Fire Dynamics Simulator (FDS) is an open source simulation software developed by National Institute of Standards and Technology (NIST) by CFD modelling. Being flexible, the FDS can simulate complex fires with sophisticated vent conditions. Furthermore, the software allows flexibility in designing desired rate of fire heat release, growth, maturity, and decay [12]. One main disadvantage to using this software is the inefficient workflow to design a case study as well as the requirement of a longer simulation time.

Nonetheless, the FDS has been proven to be a reliable tool for fire modelling in various studies. Yu, Chu and Liang [13] did a similar study on smoke control systems in a high-rise building with the FDS, especially focusing on the effects of smoke exhaust. Tilley, Rauwoens and Merci [14] verified the accuracy of the FDS with physical experimental data for a small-scale tunnel and atrium fire configuration. Ji *et al.,* [15] conducted physical and numerical study of fire in two stories building with ensemble Kalman filter algorithm, in which the FDS was integrated to display the smoke movement. Zhang *et al.,* [16] employed the FDS for multi-room compartment fire analysis with large eddy simulation fire modelling. Mammoser III and Battaglia [17] conducted numerical study with the FDS on the adaption of balconies to minimize flame spread in high-rise building. However, it should be noted that one of the contingencies in fire simulation is the unpredictability of pressure build-up in closed rooms. Exothermic reaction will cause a release of large amounts of energy that excites nearby air particles, thereby, increasing the overall room pressure, which may require depressurization of the room on fire in the event of increasing soot production.

### *1.5 The Role of Louver and Pressure Utilization*

A louver is a combination of an orifice and a mechanical system to force ventilation from one side to the other. Normal placements of a louver are at an elevated height from the ground floor at the wall, usually at the kitchen, to exhaust unwanted fumes and odour out of the house. In addition, a louver can reverse its poles, allowing external air to flow into a room. The purpose of including a louver is to counteract the depressurization of a room by the ACMV system and to keep the value constant; hence, the pressure sandwich will be localised theoretically from an entire floor to one room or corridor [18]. Louver sizes are customisable as long as an exhaust fan size is available. The fan capacity and louver size will determine the inflow rate (from outside of the building into the targeted floor), while the outflow rate (from the fire outbreak floor out of the building through exhaustion) is determined by the vent size of ACMV. Eq. (1) shows the ideal gas law to determine the desired mass of air needed to evacuate for a 50 Pa pressure differential (as recommended by The Institution of Fire Engineers Malaysia Branch) [19].

$$Mass\ for\ exhaustation, m = pv/RT \tag{1}$$

where P is pressure (kPa), V is volume ($m^3$), R is gas constant (J/K.mol), and T is temperature (K). The starting resulting mass equates to 1.46 kg for one room, and 10.77 kg for the corridor for exhaustion to achieve 50 Pa difference in 298 K temperature.

In summary, in the field of building smoke control strategy, the identified literature reviewed focus the research on the application of stairwell and elevator shaft pressurisation [10], ACMV system with air supply system, mechanical smoke exhaust system [13], air curtain to confined the induced smoke [20], stand-alone louver system and chimney system, respectively [21], and location of the mechanical exhaust vents and its rate [22]. However, there is little or no research on the effect of utilizing ACMV system coupled with an automatic louver on smoke control over a building. Thus, the current study aims at providing an insight to a non-dedicated smoke control approach with an automatic louver.

## 2. Methodology

The research method in this section aims at evaluating the effectiveness of the proposed integrated ACMV system in comparison with the current conventional designs. Figure 2 shows the plane view of a studied standard office layout with twelve (12) rooms per floor: Each of the eight levels of the building will be connected through a stairwell and two elevator shafts; each room will have dimensions of 24.5 $m^3$ and the corridor will take up 177.8 $m^3$; the distance between each floor is 4.5 m, inclusive of 0.3 m concrete floor and 1.2 m of plenum or ceiling space. Moreover, the rooms are separated with 0.14 m thick of gypsum board, while the exterior wall is made of concrete and plaster totalling up to 0.155 m. The simplification of the design is done by studying the top three floors, as the design of each floor is identical. For a fair comparison of the simulation, both designs will have the same building layout but, in one using an integrated ACMV and louver, and in the other using conventional system. Note that both ACMV and conventional system ducts are placed at the same vent but with different functionality.

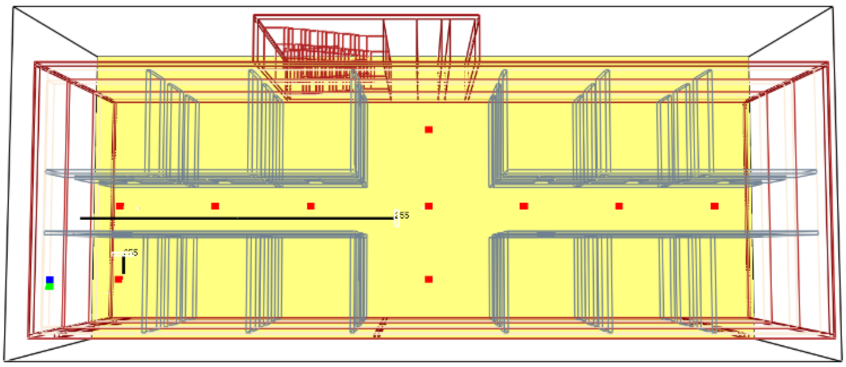

**Fig. 2.** Plane view of structural design

### *2.1 Fire Placement and Capacity*

The fire model for both set-ups is identical and simulated with large eddy simulation (Eq. (2)), whereby a fire with the surface area of 1 m by 1 m is placed in the middle of the furthest room. The total simulation time is set to a maximum value of 200 seconds, which is adequate for a small fire in a high-rise building. Moreover, the heat release rate of the fire (Eq. (3)) is set to a maximum value of 200 kW per unit area; the growth rate of fire to reach maximum value is instantaneous at the start of the simulation, and linear decay will start from 55 seconds to 100 seconds, until the fire depletes. The fire fuel will be a simple heptane combustion consisting of soot and carbon monoxide production of 0.006 % and 0.015 %, respectively. Furthermore, after the depletion of fire, there will be an additional 100 seconds of run time to evaluate the effectiveness of both systems, and to compare the smoke obscurity value by the path obscuration meters.

$$\bar{\phi}(x,y,z,t) \equiv \frac{1}{V_c}\int_{x-\delta x/2}^{x+\delta x/2}\int_{y-\delta y/2}^{y+\delta y/2}\int_{z-\delta z/2}^{z+\delta z/2}\phi(x',y',z',t)\,dx'\,dy'\,dz' \quad (2)$$

where $V_c$ is cell volume; $\phi$ is filtered field.

$$\dot{q}^m = -\sum_\alpha \dot{m}_\alpha{}''' \Delta h_{f,\alpha} \tag{3}$$

where $\dot{q}^m$ is heat release rate per unit volume; $\dot{m}_\alpha{}'''$ is mass production rate per unit of species $\alpha$ by evaporating droplets/particles; $\Delta h_{f,\alpha}$ is heat of formation of species $\alpha$.

### *2.2 Placement of Vents, Smoke Detectors, Louver*

As aforementioned, both systems contained an equal number of positions of vents (highlighted in red colour in Figure 2) for smoke exhaustion. The vents at the corridor is distanced from each other by every 5 m. The control logic for each vent will vary across both designs, which will be discussed in the next section. In addition, smoke detectors are placed in strategic locations near the fire to activate the smoke control systems easily. The general activation value will be at 3.2 %/m for smoke detectors. The last device included in this simulation is a two-way obscuration meters (to provide the smoke obscurity level): one is placed in the room of fire outbreak, and another along the corridor. However, both will have an elevation of 1.7 m at average eye level. The addition of an automated louver, with the dimension of 0.254 m by 0.254 m (as provided by FDS), will be only available for the integrated ACMV design to allow a constant negative pressure operation. Furthermore, each room will have a louver on the top left corner whereas the corridor will have two; each automated louver will have an intake velocity of 1.78 m/s due to the 50 % free area replication. The 50 % automated louver free area here refers to the 50 % of usable space, as the rest will be obstructed by the damper itself.

### *2.3 Design Sequence for Both Systems*

This section illustrates the design sequence for the conventional smoke control system and the integrated ACMV smoke control system.

#### *2.3.1 Conventional smoke control system*

Firstly, the simulation starts and the fire begins to produce heat and soot. The smoke detector activates when a certain obscurity level is met. The exhaust shaft for the entire floor will switch on and depressurisation occurs. Observe the smoke propagation of the simulation until 200 seconds. Finally, record data for devices and path obscuration meter.

#### *2.3.2 Integrated ACMV smoke control system*

Firstly, the simulation starts and the fire begins to produce heat and soot. The smoke detector in the room will activate exhaustion of that particular room instead of the entire floor. The automated louver will switch on after 11 seconds of delay, allowing depressurisation of compartment to occur. The smoke detectors along the corridor will activate different areas of the ACMV to create depressurisation in the event of smoke propagating out of the room. Observe the smoke propagation of the simulation until 200 seconds. Finally, record data for devices and path obscuration meter.

## 3. Results

The section will present the results and discussion for path obscuration in room and corridor, and temperature rise outside the room.

### *3.1 Path Obscuration in Room and Corridor*

From the observation of the two simulation results (Figure 3), both the integrated ACMV system and the conventional system have yielded similar patterns and percentage in terms of smoke obscuration. Figure 3 shows the path of obscuration percentage in the room for both systems; noticeably, there is slightly less peak path obscuration percentage from the integrated system, and overall lower percentage, as compared to the latter. The peak value is at 28.4 % and at 29.2 % for the integrated ACMV and the conventional system, respectively. However, the results show a much steeper decline in the obscuration percentage for the integrated ACMV system, after the fire has depleted at 100 seconds, because of the localising of depressurisation of the room, which will inhibit smoke propagating out of the fire outbreak room [23]. Conversely, the conventional system performed slightly less effective in exhausting smoke out of the fire outbreak room, which showed a higher obscuration value. One of the reasons that the conventional system shows a higher overall path obscuration value is the flow rate difference in the room itself. As mentioned in previous sections, activation of vents is independent when it comes to the integrated ACMV system, which means that for every ventilation orifice to be activated, the adjacent smoke detectors to the vents will need to be activated; whereas, any smoke detector in the conventional system will activate the vents of the entire floor. Therefore, in the event of a fire outbreak, the integrated ACMV system will perform more effectively than the conventional system, and this, precisely, because of ability of the integrated ACMV system to localize depressurization to a desired location, instead of the entire floor.

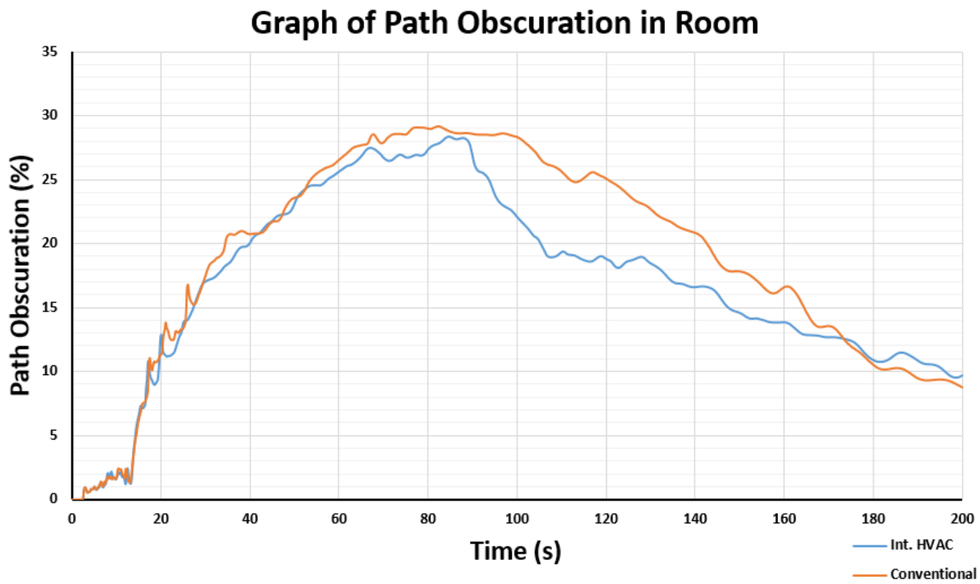


**Fig. 3.** Time series for obscuration percentage in room for both systems

The observation through the Smokeview application in FDS has shown that the amount of time taken for the residual smoke to reach the end of the corridor for both the conventional system and the integrated system is at 105 seconds and at 120 seconds, respectively. The result of delayed smoke propagation is due to the more effective localising of pressure, which is elaborated further in Figure 4.

The path obscuration device was placed along the corridor outside of the room up to the middle of the building, with an elevation of 1.7 m. The purpose of this placement is to understand the smoke propagation out of the room and along the corridor. As aforementioned, the time taken for smoke to reach the end of the corridor is at 105 seconds and at 120 seconds for the conventional system and integrated ACMV system, respectively. In Figure 4, both systems show similar pattern for smoke obscuration percentage in the first 70 seconds before they diverged significantly, with the integrated ACMV system averaging higher values than those of the conventional design.

In addition, the peak value for the integrated ACMV system shows a 24.9 % obscuration, and the conventional system yields a 23.3 %, indicating that a higher path obscuration percentage is due to the activation of the first three vents along the corridor before the rest is activated. Furthermore, the results indicate further difference reading after 140 seconds, whereby the integrated ACMV system shows consistently higher path obscuration. In other words, more smoke is contained at the room, and along the corridor outside of room, because of the selective activation of vents. Such a type of depressurisation is also one of the reasons for the delayed propagation, as compared to the conventional system.

During the end of the simulations, observation for both was made in real time review to compare the propagation of smoke to the entire floor: There have been no signs of infiltration into the stairwell for both tests. However, there is propagation of smoke into four of the rooms in the conventional system but none on the integrated ACMV system. In the conventional system, due to the lower pressure of the entire floor, smoke propagates easily around the same level unless it is near the vents.

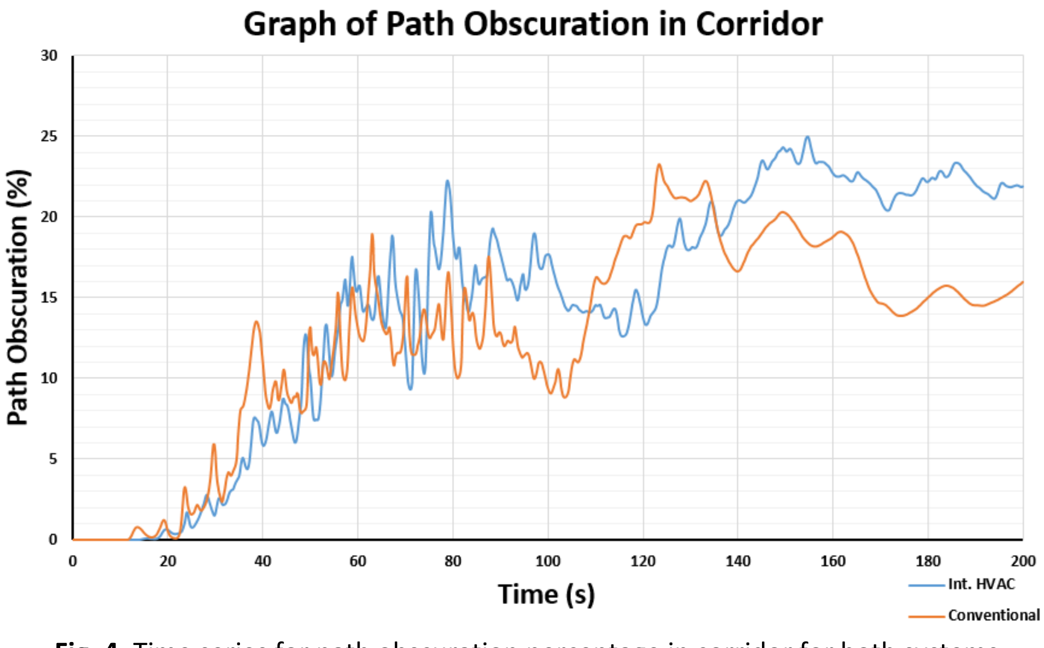


**Fig. 4.** Time series for path obscuration percentage in corridor for both systems

### *3.2 Temperature Rise Outside the Room*

In the same simulation, the input code has been set to determine the boundary temperature of the building, where the conductivity, the specific heat, and the density of each component were set to values. The few simulated components are plaster, concrete, inner wall, and door values (Table 1).

This subsection discusses the effects of smoke propagation out of fire outbreak room in terms of boundary temperature rise.

**Table 1**
Thermal properties of simulation components

| Type of Material | Concrete | Plaster | Door | Ceiling | Ground |
|---|---|---|---|---|---|
| Thermal Conductivity, (W/m.K) | 0.6 | 0.48 | 0.22 | 0.055 | 0.6 |
| Density, (kg/m$^3$) | 2400 | 849 | 750 | 375 | 2400 |
| Specific Heat, (kJ/kg.K) | 1.55 | 0.84 | 1.85 | 1.09 | 1.55 |
| Thickness in simulation, (m) | 0.115 | 0.02 | 0.035 | 0.012 | 0.3 |

Figure 5 and 6 represent the view at the corridor observing the room fire from in front of the emergency staircase with the integrated ACMV and the conventional design, respectively. Similarly, both simulations show maximum temperatures of 29.5 °C outside of the room for the entirety of 200 seconds. Moreover, both simulations yield the maximum spread of peak temperature at around 115 seconds. However, there is a notable difference in the peak temperature spread for both designs. To illustrate, both figures act as a visual illustration for temperature rise from blue to red, which is 25.0 °C to 29.5 °C. Even with a small fire and fast depletion time, the propagation of high temperature smoke for the conventional design reaches 29.0 °C on the second vent (its location is closer to the emergency staircase); whereas, the integrated ACMV system shows a full drop of 1.0 °C at the same point, which is approximately 28.0 °C. The convection heat transferred (Q) caused by the propagation of smoke is determined through the convection heat transfer calculation. The 0.1 m by 0.1 m area on the left and the right sides of the second vent for both simulations are used to determine the average heat transfer through convection done to the ceiling. The Q value for the integrated ACMV system is 14.71 kJ, and it is 19.62 kJ for the conventional system. Even with a short fire growth and decay, the integrated ACMV system managed to reduce the spread of heat. To further this point, it can be seen that the maximum temperature of 29.5 °C for the integrated ACMV system is only up to the first vent that is right outside the fire outbreak room; whereas, the same temperature for the conventional system has managed to reach parts of the second vent, which is 5 meters of extra spread.

Moreover, after peak spread of heat transfer for both simulations at 115 seconds, the overall boundary temperature continues to change according to the presence of smoke. Hence, the decrease in temperature depends on the effectiveness to exhaust smoke out of the building. At the end of the simulation run, it can be observed that the lower spread of smoke along the stretch of the corridor system has allowed faster cooling with a maximum reading of 28.5 °C (Figure 7) on the doorframe in the case of the integrated ACMV, as compared to 29.5 °C (Figure 8) in the case of the conventional system.

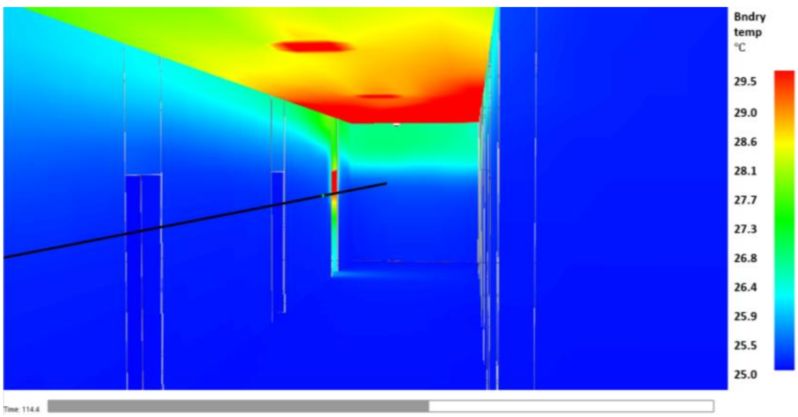


**Fig. 5.** Corridor temperature – Integrated ACMV system

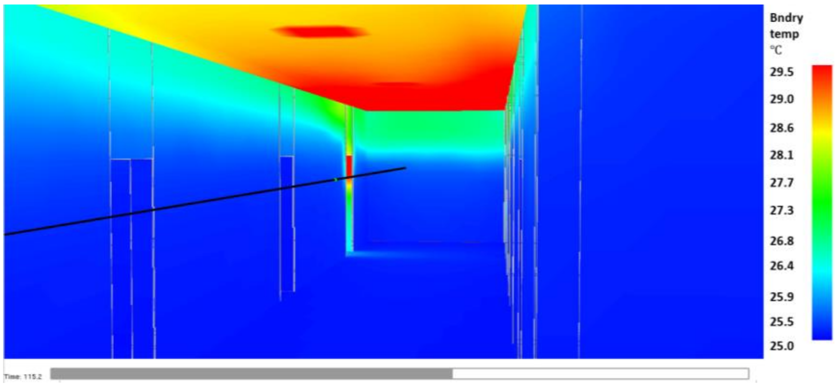


**Fig. 6.** Corridor temperature – Conventional system

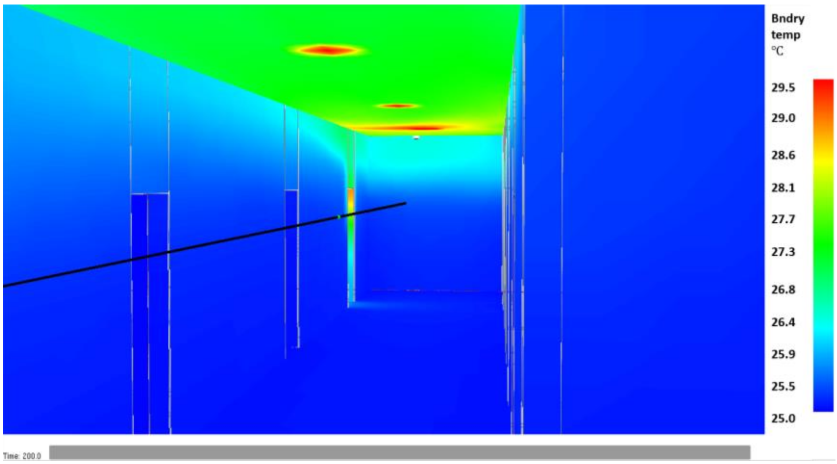


**Fig. 7.** Temperature profile at 200 seconds – Integrated ACMV system

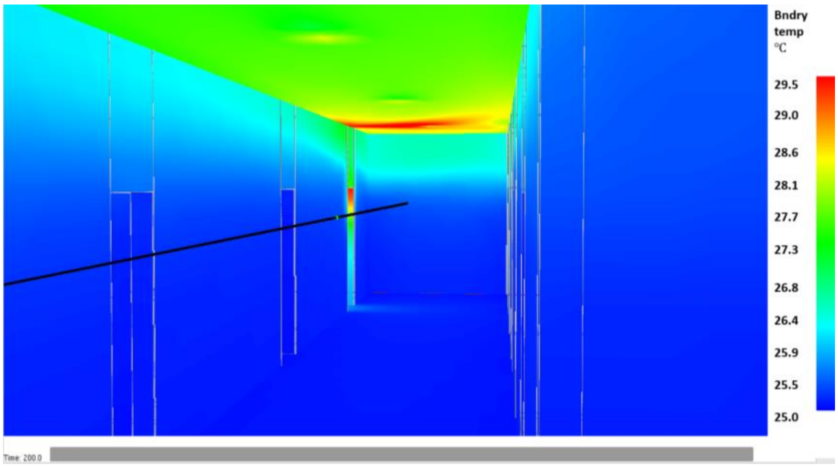


**Fig. 8.** Temperature profile at 200 seconds – Conventional system

## 4. Conclusions

This study is aimed at determining the effectiveness of alternative smoke control approach, mainly the integrated ACMV with additional louver, along with the comparison of the current conventional design. Both designs have gone through 200 seconds of simulation run time to compare between the path obscuration in the room with the corridor, and the boundary temperature along the corridor.

The path obscuration for the conventional system in the room showed a lower final value of 8.77 %, as compared to 9.71 % for the integrated ACMV system, due to the greater propagation of smoke out of the room. The results are explained further with the higher levels of path obscuration reading for the integrated ACMV system along the corridor at 21.90 %, as opposed to 16.00 % for the conventional system. A lower spread of smoke tends to lead to a higher reading of obscuration outside of the fire outbreak room. Even with a fire of 12 MJ for both simulations, the less propagation of smoke for the integrated ACMV system has led to a lower temperature rise across the corridor with a noticeable difference of 1.0 ℃ at the vent, which is closer to the emergency staircase. In addition, there is a noticeably faster subsiding of hot air for the integrated ACMV system than that of the conventional system, after the peak temperature spread of 115 seconds. Therefore, the current study concluded that the proposed integrated ACMV system with additional louver is more effective for smoke control than the conventional design.

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