planned to determine the exact nature of these influencing factors.

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# BUILDING FIRE SAFETY: NUMERICAL SIMULATION AND EVACUATION PLANNING

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## ABSTRACT

Fire dynamics and fire propagation study reckon attention due to the role they play in evacuation planning and minimizing the loss of lives and properties in case of a fire breakout. For this paper, Fire Dynamics Simulator (FDS) is used to simulate a fire situation involving an air conditioning device in a two-room domain. The rooms are connected through a door. In our simulation, a window Air-Conditioner is modelled as a heat source with constant Heat Released Rate Per Unit Area (HRRPUA) to signify a fire source which in real life could be a result of AC malfunctioning. HRRPUA of AC is varied and its effects on soot flow pattern, burning rates of materials, temperature contours and gauge pressure of both the rooms are studied. Further, the Available Safe Evacuation Time (ASET) is calculated for the above cases. Using the ASET values and soot flow pattern, certain design changes in the rooms are suggested. Windows are placed at those spots on the wall where the soot hits first or shows a tendency to flow. Similarly, the exit doors are planned based on the safe zones and the ASET data. For the modified geometry, ASET is calculated which is observed to be higher than those of above cases. Reasons for this difference are suggested. Feasibility of safe evacuation is discussed for all the above cases including the calculation of Required Safe Evacuation Time (RSET). Present simulation and its findings will help in designing buildings and aid safety engineers to recognise and assess the risk of fire originating from air conditioning devices. Engineers could improvise and bring appropriate changes in their designs for systems and buildings of similar dimensions.

## INTRODUCTION

Fire is one of the major hazards featuring among the causes leading to loss of properties and lives. A major chunk of non-natural deaths worldwide features fire as one of the prominent reasons [1]. Fire could be initiated due to pantry related causes including gas-leakage, over-heating of cooking medium or electrical related causes like short circuits, overloaded circuits, leakage currents and electric sparks. In US alone, 2300 air-conditioners fires are reported annually. Each contributes to property loss of over $10,558. 86% of these fires are initiated due to mechanical failure or malfunctioning [2]. With increasing ownership of air-conditioners in India [3] and air-conditioners working at full capacity during summer [4], the chances of malfunctioning due to over-loading, clogging of drainage, improper wiring or short-circuiting have also increased. A review of accidents involving fires show that the causalities are caused mainly due to suffocation (lack of oxygen), toxic smoke inhalation or direct exposure to flame [5]. These factors have been considered while calculating ASET.

In 1982, Markatos et al. outlined the need of numerical simulations in their paper [6]. They argued that apart from the experience we gain from real fires, the major dependence was on the scaled physical models since a full-scaled model would require prohibitive human and financial resources. However, it is not possible to achieve complete similarity between the real and scaled model and a compromise is invariably reached. With the advancement in the field of digital computers and development of mathematical methodologies for fire modelling, we now have the flexibility of aptly simulating fire behaviours in different enclosed configurations, therefore overcoming the constraints in experimental and theoretical approaches [7].

Ta-Hui Lin et al. have highlighted the remarkable correlation between the full-scaled experiments and the numerical simulation [8]. In 2012, followed by a series of fire test burns carried out by Fire and Rescue New South Wales in discarded furnished room, a CFD based large eddy simulation was carried out. G.H. Yeoh et al. published the above results in their paper [9] and established the fact that if the pyrolysis and combustion rate of fuel are appropriately modelled then numerical simulations gave reasonable temperature and flow predictions. Although there have been studies validating the numerical simulations; studies with parametric variations are still unexhausted.

Owing to the sudden nature of fire breakout, we cannot guess its intensity beforehand. There appears to be very less experimental work on electric fires caused due to air conditioner malfunctioning. In this paper, we have modelled the air conditioner as a heat source with constant HRRPUA, which is varied in subsequent cases to cover a wide range of possibilities, which could be encountered during fire hazard.

Table 1: NOMENCLATURE

| | | |
|---|---|---|
| ASET | [s] | Available Safe Evacuation Time |
| RSET | [s] | Required Safe Evacuation Time |
| $D$ | [m$^{-2}$] | Occupant density |
| $D^*$ | [m] | Characteristic Fire Diameter |
| $C_p$ | [J/(kgK)] | Specific Heat |
| $\rho$ | [kg/m$^3$] | Density |
| $g$ | [m/s$^2$] | Acceleration due to gravity |
| $h_s$ | [J/kg] | Sensible Enthalpy |
| $H$ | [J/kg] | Stagnation enthalpy |
| HRRPUA | [W/m$^2$] | Heat Release Rate Per Unit Area |
| $\overline{M}$ | [kg] | Average mass |
| $\overline{P}$ | [Pa] | Background pressure |
| $\dot{Q}$ | [W] | Heat Release Rate |
| $\dot{q}'''$ | [W/m$^3$] | Heat release rate per unit volume from a chemical reaction |
| $\dot{q_b}'''$ | [W/m$^3$] | Rate of energy transfer to sub grid scale droplets and particles |
| $\dot{q}''$ | [W/m$^2$] | Conductive, diffusive and radiative heat fluxes |
| $S$ | [m] | Evacuation Distance |
| $T$ | [K] | Temperature |
| $t$ | [s] | Time |
| $t_d$ | [s] | Delay between fire ignition and detection |
| $t_e$ | [s] | Delay between fire detection and escape initiation |
| $t_r$ | [s] | Time required to reach safer place |
| $\boldsymbol{u}$ | [m/s] | Velocity field |
| $V$ | [m/s] | Evacuation speed |
| $w$ | [m] | Width of exit point |
| $X$ | [-] | No. of persons |
| $x$ | [-] | No. of exit points |
| Subscripts | | |
| $\infty$ | [-] | Ambient properties |

The main aim of this paper is to compare the ASET and RSET values and to suggest design changes to increase ASET and decrease RSET in order to ensure safe evacuation in case of fire breakout.

## MODEL DESCRIPTION

For the purpose of our study, we have chosen Fire Dynamics Simulator, an open source Computational Fluid Mechanics (CFD) code developed by NIST (National Institute of Standards and Technology) lab, USA. FDS is a fire driven fluid flow model. The model numerically solves a form of the Navier-Stokes equation appropriate for low-speed, thermally driven flow with an emphasis on smoke and heat transport due to fire. Version 6 of FDS is used for our simulations. The continuity equation solved in FDS is:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \boldsymbol{u}) = \dot{m_b}''' \qquad (1)$$

where the source term, $\dot{m_b}'''$ denotes the addition of mass from the evaporating droplets or other sub-grid scale particles such as sprinklers, fuel spray etc. These objects are assumed to occupy no volume and thus feature as point source of mass in continuity equation. The momentum transport equation employed in FDS is

$$-\nabla^2(H) = \frac{\partial(\nabla \boldsymbol{u})}{\partial t} + \nabla \boldsymbol{F} \qquad (2)$$

where $\boldsymbol{F}$ represents the net force per unit mass, including body forces and surface forces. Energy conservation equation solved in FDS is:

$$\frac{\partial(\rho h_s)}{\partial t} + \nabla.(\rho h_s \boldsymbol{u}) = \frac{D\overline{P}}{Dt} + \dot{q}''' - \dot{q_b}''' - \nabla.\dot{q}'' \qquad (3)$$

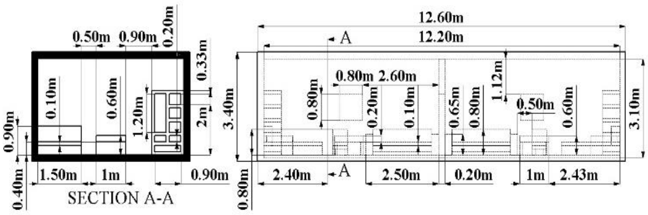
The equation of state used in FDS:

$$\overline{P} = \frac{\rho R T}{\overline{W}} \qquad (4)$$

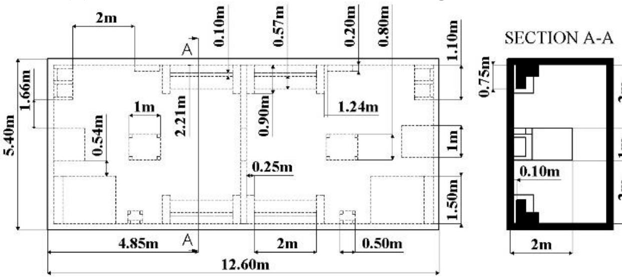
The background pressure, $\overline{P}$ features in the energy conservation equation (3) and the equation of state (4) whereas the perturbation pressure term is present in the momentum transport equation (2).

The partial derivatives in the equations for the mass, energy and momentum are approximated by finite differences and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Equations (1), (2) and (4) are solved simultaneously to calculate the properties such as pressure, velocity vector field and temperature. These variables are advanced in time using an explicit second-order predictor/corrector scheme [10]. FDS uses the energy conservation equation (3) to keep a check on the solution. The left hand side and right hand side of the equation (3) can be calculated independently if all the state properties are known. Their equality serves as the convergence criteria during simulation.

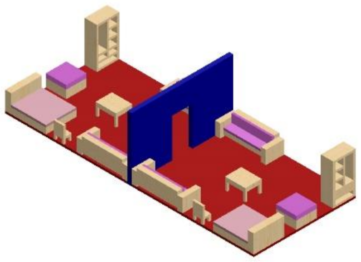
## WORKING DOMAIN DESCRIPTION




(a) Front view with section showing the left wall




(b) Top view with section showing the partition wall



(c) Isometric view with all walls removed

*Figure 1: The Working Domain*

Each room is 6 m long, 5 m wide and 3 m high. They are connected through a door of height 2 m and width 1 m. The entire domain is kept in a box of dimension 12.6 m x 5.4 m x 3.4 m. Air conditioners are situated at the centre of the back wall. Fire starts at the AC situated in room 1 (left room in *Figure (1))* and propagates through the furnished rooms. The walls of the rooms are covered with wallpapers and the floor is carpeted. The properties and application of materials are summarized in *Table (3).* These materials can be grouped into two types. First for whose combustion a definite model or formula is available such as foam, fabric, wood [9] and second, like wallpapers for whose combustion heat release rate data exist but no proper model has been developed. HRRPUA of wallpaper is determined using an empirical formula given by Dougal Drysdale [12]. Interaction of the above domain with the surroundings is of critical importance. Ambient pressure is taken as 101.325 kPa and ambient temperature as 25°C. At t=0, air speed is 0 m/s and smoke concentration in the domain is zero. The gaseous fuel used is $C_{6.3}H_{7.1}O_{2.1}N$. HRRPUA of AC is varied from 250 kW/m$^2$ to 1000 kW/m$^2$ as summarized in *Table (2).*

*Table 2: HRRPUA Variation*

| Case | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| HRRPUA of AC (kW/m$^2$) | 1000 | 750 | 500 | 300 | 250 |

*Table 3: Properties of materials used for simulation*

| Material | Polyurethane foam [9] | Fabric [9] | Carpet [11] | Wood [9] | Gypsum plaster [9] | Wall Paper [13] |
|---|---|---|---|---|---|---|
| Applied for | Mattress of bed and sofa | Mattress covering | Carpet on floor | Furniture mainframe | Wall | Wall covering |
| Specific heat, kJ kg$^{-1}$ K$^{-1}$ | 1.0 | 1.0 | 1.7 | 1.38 | 0.84 | 2.5 |
| Conductivity W m$^{-1}$ K$^{-1}$ | 0.05 | 0.1 | 0.25 | 0.14 | 0.48 | 0.22 |
| Density kg m$^{-3}$ | 40 | 100 | 1130 | 489 | 1440 | 690 |
| Heat of combustion, kJ kg$^{-1}$ | 33280 | 15000 | 22300 | 14500 | NA | NA |
| Arrhenius Pre exponential factor, s$^{-1}$ | 1.69 x 10$^8$ | 4.28 x 10$^{14}$ | NA | 1.89 x 10$^{10}$ | NA | NA |
| Activation Energy, kJ/mol | 1.35 x 10$^5$ | 2.02 x 10$^5$ | NA | 1.51 x 10$^5$ | NA | NA |
| Heat of Reaction kJ kg$^{-1}$ | 1750 | 3000 | 2000 | 430 | NA | NA |

* NA- Not Applicable

## GRID INDEPENDENCE STUDY

Cubical cells are used in the domain. To get the approximate grid size, the characteristic diameter of fire is calculated using the following equation: [14]

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

The value of $D^*/\delta x$ must lie between 4 and 16 for reliable results. In preliminary simulations, for an average heat release rate of 5000 kW, $D^*$ is calculated to be 2 m. Therefore, $\delta x$ is predicted to be 0.2 m. However, since the heat release rate varies during the simulation, the grid independence test is carried out for a wide range of cell sizes.

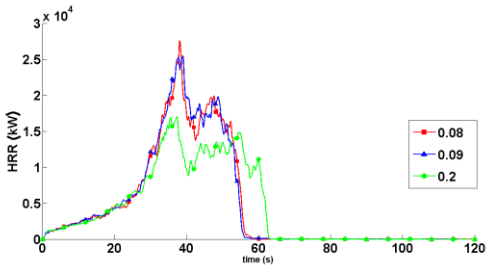



*Figure 2: Comparison of Grids using HRR*

As the cell size approaches around 0.09 m, saturation in the results is achieved. In *Figure (2),* Heat Released Rate (HRR) due to fire is plotted against time for three representative grids, with cell sizes of 0.2 m, 0.09 m and 0.08 m. It is found that the average difference between the values of HRR for grids with cell sizes of 0.09 m and 0.2 m is 8.21% whereas the difference is only 0.21% for grids with cell sizes of 0.09 m and 0.08 m. The grid with cell size 0.09 m is deemed to be more effective for the numerical simulation and hence it is selected for further simulation and studies.

## RESULTS

As HRRPUA of AC is varied, differences in several parameters such as gauge pressure of the rooms, burning rates, smoke flow pattern are observed. Following is an account of the observations.

### Soot flow pattern in the considered cases

The soot flow is fastest in the first case and it gets slower in the consecutive cases (with decreasing fire intensity). The soot flow is slowest in case (5). This is illustrated in *Figure (3).* It is also found that due to lack of ventilation, the soot concentration inside the room increases throughout the burning phase as shown in *Figure (3).* This leads to depletion of oxygen in the domain which results in a sudden death of the burning flame. The burning flame contour for case (1) is shown in *Figure (6)* after the discussion on the variation in burning rate of combustible substances in the domain.

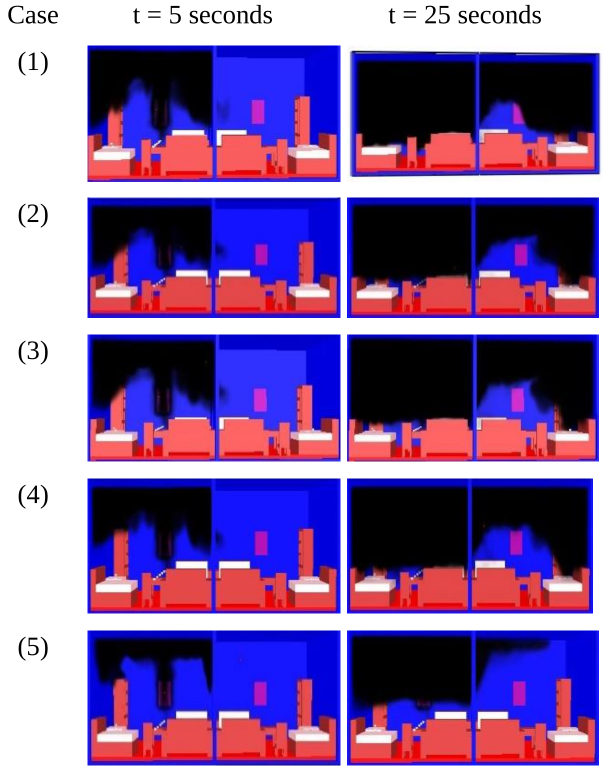



*Figure 3: Soot flow pattern for different HRRPUA (front wall made invisible for clarity)*

### Variation of the gauge pressure

The gauge pressure *vs* time plots (*Figure (4)*) for both the rooms are found to be identical. This is attributed to the fact that they share a common interface by virtue of the door connecting them.

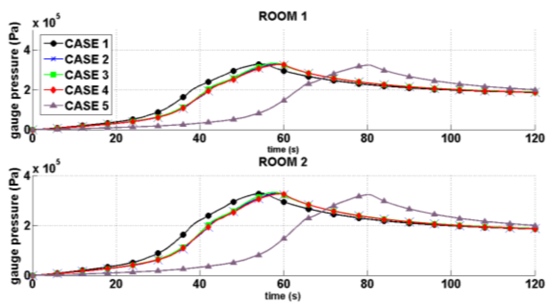



*Figure 4: Variation of Gage pressure at different HRRPUA*

The general trend observed for the gauge pressure is that the pressure increased initially up to maximum as the soot concentration in the rooms increase. As the soot started to settle down, decrease in the pressure is observed and finally the gauge pressure becomes constant at about 0.2 MPa. As HRRPUA of the AC is varied, no change in the peak value of the gauge pressure is observed. However, time taken to reach this maximum value increases with decreasing

HRRPUA. The maximum shift in this time instant is observed in the case (5) with HRRPUA=250 kW/m$^2$.

### Variation of the burning rate

Burning rate of the combustible substances in the domain serves as an important parameter to judge fire behaviour. Cases with different HRRPUA of AC follow a comparatively similar profile for burning rate plots. Starting with the value of zero, burning rate increases to a maximum value before decaying to reach a constant value of 2.6 kg/s (*Figure (5)*). This decay is because the fire flame dies out due to lack of oxygen. *Figure (6)* shows the flame contour for case (1) depicting the extinction of flame at t = 58 seconds.

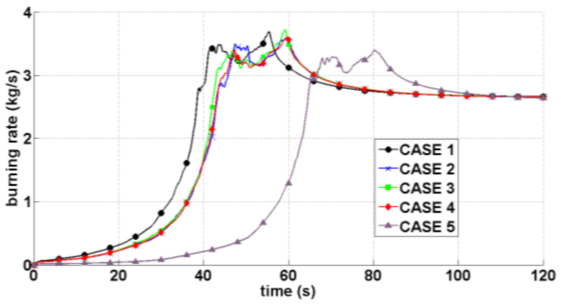



*Figure 5: Variation of Burning rate of combustible substances at different HRRPUA*

As shown in *Figure (5), a* forward shift in the burning rate *vs* time graph with decreasing HRRPUA is observed. Case (1) and case (5) form the left-most and right-most boundaries of the curve respectively.

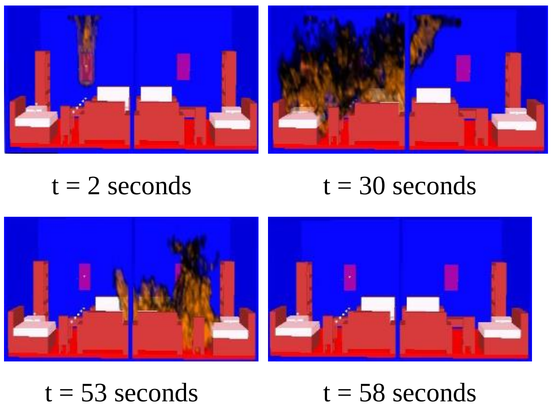



*Figure 6: Flame contour for case (1) front wall and soot made invisible for clarity*

### Variation in the wall temperature contours

Temperature contours of the walls of the domain are illustrated in *Figure (7)* for four time instances. The two extreme cases, (1) and (5) are considered for this. It is observed that the fire propagation is faster in case (1) than that in case (5). Peak temperature near 500ºC is observed at the burning surfaces. However, during the initial moments of fire breakout the spread is localised until all the combustible furniture in the domain starts burning.

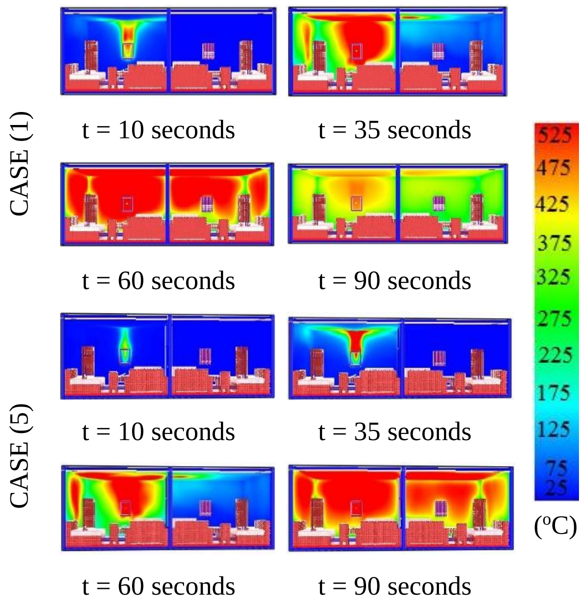



*Figure 7: Wall temperature contours (front wall made invisible for clarity)*

### Calculation of Available Safe Evacuation Time

ASET is critical time limit before which every person must evacuate the affected region. Main concerns during fire in closed environment (like rooms) are (I) Toxic smoke inhalation (ii) Light shielding effect of smoke and (iii) Exposure to unbearable temperatures [5]. (i) and (ii) are related to each other in a sense that if the smoke concentration will increase in a room; there will be more shielding effect and the toxic contents concentration in the room will also increase.

In India, average height of a male is 1.65 m and that of a female is 1.52 m [15]. Since the smoke assumes a horizontal profile settling from roof to floor, the average visibility is calculated for the region 1.71 m to 1.80 m. In FDS, visibility is calculated on a scale of 0 to 30 m with 30 being best visible. A visibility threshold of 20 m (33.3 % decrease from the maximum) is considered in ASET calculation. 60ºC is taken as the maximum tolerable temperature [5] in the same height region. The minimum of the time taken for visibility to fall below 20 m or temperature to rise above 60ºC is ASET. ASET values of the rooms are summarised in *Table (4)*. It is found that higher the intensity of fire, lower is the ASET value. Further, by observing the wall temperature contours and the soot flow pattern it can be inferred that the soot flows faster as compared to the speed of fire propagation, during the initial moments of fire breakout. This fact can also be established by noticing the dominating factor during ASET calculation for room 1.

*Table 4: ASET values*

| Case | Room1 | Room2 |
|---|---|---|
| | Dominating factor : Temperature / Visibility | |
| 1. | 8.625 s (Visibility) | 21.234 s (Temperature) |
| 2. | 9.853 s (Visibility) | 24.51 s (Temperature) |
| 3. | 9.971 s (Visibility) | 24.1 s (Temperature) |
| 4. | 9.449 s (Visibility) | 24.311 s (Temperature) |
| 5. | 18.951 s (Visibility) | 41.455 s (Temperature) |

**Calculation of Required Safe Evacuation Time**

RSET is the maximum time required for the safe evacuation from the accident site. RSET must be less than ASET to avoid causalities.

$$t_d + t_e + t_r \leq ASET \tag{6}$$

The sum of terms on the left hand side of equation (5) is equal to RSET. Time delay between fire ignition and fire detection $(t_d)$ and time delay between fire detection and onset of escape activities $(t_e)$ are assumed to be zero; that is evacuation is assumed to begin as soon as the fire breaks out. To account for the above assumptions, safety factor of 1.5 is incorporated during the calculation, in RSET value.

The time required to reach a relatively safer place $(t_r)$ is given by:

$$t_r = \frac{RSET}{1.5} = \frac{(l+b) + \frac{X}{x}}{V} \tag{7}$$

where $(l+b)$ is the sum of length and breadth of the room; that is the longest distance that a person will have to travel to reach the escape door.

$\frac{X}{x}$ corresponds to the passage of $X$ persons through $x$ exit units. It has been found that it takes approximately 1 second for a person to go through the door opening while evacuating at normal walking speed. This part of equation therefore translates the passage of one person per second into a walking distance of about 1 m. Occupant density of 0.05 persons per square metres is chosen as a standard for houses and hotels [16]. To consider the most extreme case, we have assumed the occupant density as 0.2 persons per square metres which may correspond to a small social gathering. Total number of persons, $X$ is therefore equal to 12, that is 6 persons in each room. $x$ is the total number of effective exit points. Each exit point is recognised as an useful width of 0.6 m (with 0.2 m is the loss at each exit point). Moreover large gates, which are normally closed are taken as one exit point, irrespective of their width [16]. So for an exit point with width $w_i$

$$x_i = \frac{w_i - 0.2}{0.6} \tag{8}$$

The value of $x$ for a domain with $n$ exit points is:

$$x = \sum_{i=1}^{n} x_i \tag{9}$$

Evacuation speed $V$ is given by empirical formula [16]:

$$V = k(1 - 0.266D) \tag{10}$$

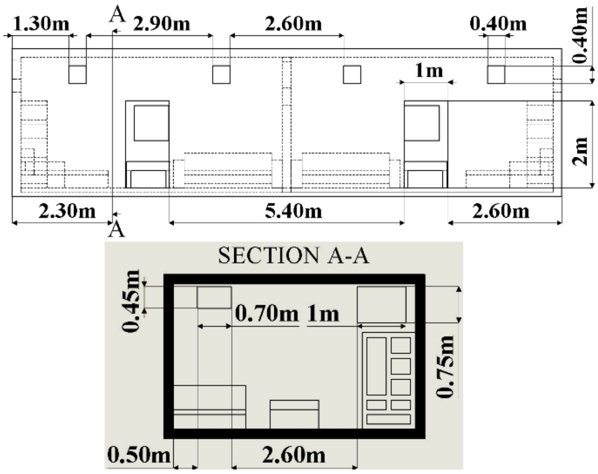
Where $D$ is occupant density in persons per square metres and $k$ for horizontal escape routes is 1.26 m/s. For our simulation, evacuation speed is calculated to be 1.193 m/s. The door connecting the rooms is the only exit point for room 1 and it is assumed that there is a door in room 2, which is opened every time a person approaches it (this makes the number of effective exit point in room 2 equal to 1 irrespective of width of the door). RSET for room 1 is found to be 19.48 seconds and for room 2 as 28.9 seconds. It is observed that only in case (5), for room 2, value of ASET is greater than RSET. In all other cases, there is no chance of safe evacuation. In the next section, we have proposed some design changes to ensure safe evacuation.

## PROPOSAL OF HOUSE DESIGN

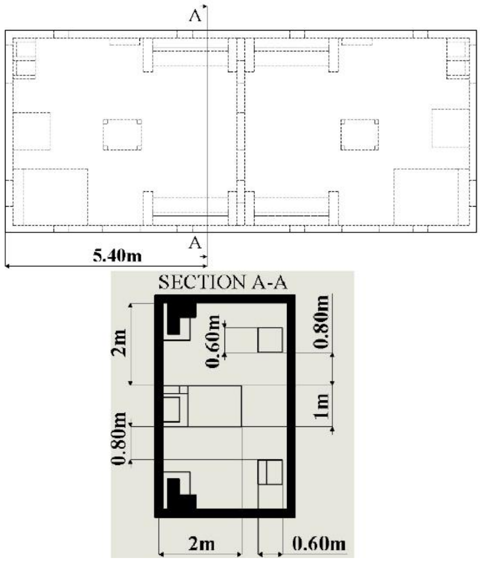
We can ensure safe evacuation either by increasing the ASET value or by decreasing the RSET value. Therefore, ventilation windows are provided in the rooms especially at places where soot reaches first at the sidewalls. These windows are assumed open as soon as the fire starts. We have also employed exit doors, which are assumed open throughout the accident time. Ventilation has is provided between room 1 and room 2 to allow soot to escape effectively from room 1. In view of mentioned assumptions, the factor of safety incorporated in the RSET value is increased to 2. *Figure (8)* illustrates the modifications suggested in the domain.

ASET for case (1), with HRRPUA of AC equal to 1000 kW/m$^2$ is the lowest. Therefore, if we could secure this case, same modification can be employed for other cases for which ASET values increase with decreasing intensity of fire. It is observed that after including the above modifications, the ASET of room 1 increases by 238.8% and that of room 2 by

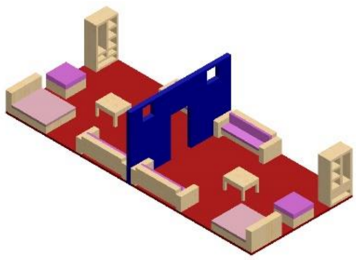
93.7%, as the windows provided escape route to the soot, therefore delaying the fall observed in visibility.




(a) Front View with section showing the left wall




(b) Top view with section showing the connecting door



(c) Isometric view with all walls removed

*Figure 8: The modified domain*

*Table 5: Probable escape scenarios*

| Case | Remark | $x$ in room 1 | $X$ in room 2 |
|---|---|---|---|
| (A) | Every person from room 1 went to room 2 | 1.33 | 12 |
| (B) | Each gate is equally likely to be used by each person of room 1 | 2.67 | 9 |
| (C) | No person from room 1 went to room 2 | 1.33 | 6 |

For the calculation of RSET, any one of the three scenarios listed in *Table (5)* is possible. In any other scenario, only the number of persons in room 2 will vary and will lie between the values corresponding to scenario (A) and scenario (C). The evacuation speed remains same, equal to 1.193 m/s. The RSET values are summarized in *Table (6)* and it is found that in all the considered scenarios, the RSET value is less than the ASET value. This implies safe evacuation from both the rooms.

*Table 6: ASET and RSET comparison for modified design*

| Case | Room | RSET | ASET |
|---|---|---|---|
| (A) | 1 | 26 | 29.224 |
| | 2 | 33.56 | 41.134 |
| (B) | 1 | 22.21 | 29.224 |
| | 2 | 29.78 | 41.134 |
| (C) | 1 | 26 | 29.224 |
| | 2 | 26 | 41.134 |

## CONCLUSION

Fire behaviour and propagation is studied using numerical simulations. To vary the intensity of fire in two-compartment domain interconnected by a door, HRRPUA of AC, which is the source of fire, is varied. Mass, momentum and energy equations are solved in three-dimensional domain along with necessary chemical kinetics. It is found that higher is the intensity of ignited fire, faster is the soot flow and fire propagation. Gauge pressure and burning rate reach a maximum before falling to a constant value (0.2 MPa and 2.6 kg/s respectively) which is unaffected by fire intensity. The time taken to reach the maxima does increase with decreasing HRRPUA of AC. During the initial phase of fire breakout, fire spreads slower than soot. Due to this, the dominating factor for ASET calculation of room 1 (where fire starts) is fall in visibility. Even though continuous increase in the soot concentration and lack of ventilation leads to eventual death of flame, ASET values are very small as compared to the time taken for flame extinction. Efforts have been made to design the house from the knowledge of numerical findings, so that maximum ASET is achieved. Further, to ensure safe evacuation, exit doors are planned to decrease RSET. The design changes that are suggested are successful in increasing ASET in case with maximum fire intensity by 238% in room 1 and 93.7% in room 2. The method used in this paper can be used by safety engineers to assess their design for proper evacuation assurance during fire breakout.

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