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Numerical Modeling of Fire Growth and Smoke Propagation in Enclosures

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Abstract. In this study, fire growth and smoke propagation in enclosures are numerically modeled based on the material properties, ventilation and the enclosure geometry of similar geometries. Thing such as combustible materials, ventilation openings, and ceiling height affect the fire behavior. This research employs the Fire Dynamics Simulator (FDS) to study the influence of the ventilation conditions on the ceiling jet phenomenon, heat release rates (HRR) and smoke movement. Its high flammability is analyzed, as polyurethane foam is a key material in the development of fire. The results show that ventilation plays an important role in fire dynamics, depending on ceiling height, and highlight the weaknesses of existing numerical models regarding the smoke propagation in the situation of complex scenarios. Understanding fire behavior in mechanically ventilated spaces improves and insights into improving fire safety strategies in building design and emergency response.

Keywords: Fire Growth, Heat Exchanger Networks, Heat Integration, Numerical Modeling, Smoke.

1. INTRODUCTION

Design and operation of buildings with enclosed spaces should be concerned with fire safety due to the risk of rapid-fire growth and smoke propagation, which could lead to dangerous effects for occupants and property. The development of fire prevention strategies to ensure fire safety of structures as well as improvement of evacuation procedures relies on the understanding of fire behavior dynamics within enclosures (Dabous, 2024). Thanks to numerical modeling, researchers and engineers can simulate complicated scenarios and study what, in particular, causes fire growth and smoke movement without going through expensive and time-consuming physical experiments. What began as the study of fire dynamics long ago has fallen into a cycle, examining the phenomenon in terms of empirical observations and rudimentary experiments. Yet the rise of modern computational capabilities has completely changed the field, creating the opportunity to develop increasingly sophisticated numerical models that simulate increasingly accurate models of complex fire scenarios (Zeng, 2024). The models rely upon fundamental principles of thermodynamics, fluid mechanics and heat transfer in order to predict the behavior of the fire under various environments. If we want to reduce fire risks or optimally arrange safety measures in residential, commercial and industrial buildings, it is crucial to understand fire dynamics within enclosures. Fire safety challenges of residential buildings, commercial spaces, and industrial facilities are more of enclosure type. The emergence of a spreadable fire, the controllability of a fire, and the safety of people dwelling in a structure depend on the factors like combustible material arrangement, ventilation and geometry of space. For example, ventilation openings can affect the patterns of airflow, with some of the effects depending on the availability of oxygen to sustain combustion, and how that variation may affect the movement of smoke. In addition, the temperature properties of the material within an enclosure can add to heat release rate and overall amount of fire load (Johansson, 2024). Because of the complexity of these phenomena, numerical models, especially based on computational fluid dynamics (CFD), can be used to solve complex equations that describe fluid flow, heat transfer and combustion processes in detail (Daurer, 2024). One such tool that is broadly used in fire dynamics is the Fire Dynamics Simulator (FDS), that simulates behavior of smoke and heat in three-dimension spaces. Using these state-of-the-art modeling techniques, researchers can examine a range of scenarios, and determine the efficacy of a wide variety of fire protection measures, as well as assess which particular fire growth and smoke propagation related factors are most important. The purpose of this study is to investigate numerical modeling of fire growth and smoke propagation in enclosures and to understand what difference materials and ventilation conditions will have on fire dynamics (Şuvar, 2022). This research will evaluate the impact of varying ceiling heights and ventilation configurations on heat release rates (HRR), temperature profiles and smoke movement patterns using a series of simulations using the FDS. In addition to providing a more detailed knowledge about fire behavior in enclosures, the findings will help designers to improve building practices and safety protocols in fire prone areas. Overall, the free fire dynamics firewall problem will be succinctly addressed in the following paper by providing the most complete view of numerical modeling techniques of fire growth and smoke propagation in enclosures. It will present the key aspects influencing fire dynamics (Nothard, 2022), provide the considerations regarding simulation results to firedomains, and identify the future research directions to enhance our knowledge about fire safety of constructions.

2. LITERATURE REVIEW

Over the years, there has been an increased interest in studying fire dynamics in enclosures due to the necessity

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of providing better safety measures and complying with regulation in buildings design. However, after new computational capabilities were acquired, numerical modeling has made a viable alternative to understanding fire behavior (Yuen, 2021); early research heavily relied on experimental methods to acquire the knowledge which has been then developed in the computational field. Different phenomena related to fire, i.e., ignitions, flame spread, heat transfer, and smoke generation, are all important, needed to determine fire hazards existing in the closed enclosures.

2.1. Numerical Modeling Techniques

Therefore, the numerical modeling techniques have advanced significantly, and models such as the Fire Dynamics Simulator (FDS) are now standard tools for simulation fire scenarios (Hong, 2023). The governing equation of the fluid flow, heat transfer and combustion is solved using a computational fluid dynamics (CFD) approach in FDS. It is capable of predicting complex interaction between fire and surrounding environment and understand temperature gradient, smoke propagation and contribution of ventilation in the fire environment.

The effectiveness of FDS in predicting fire behavior in a wide range of enclosure configurations is established in (McGrattan, 2013) research. It accordingly emphasized the need for accurate boundary conditions and material properties that lead to reliable results. Furthermore, FDS studies have demonstrated that the model is applicable for different fire scenarios such as with multiple rooms and differing ventilation strategies.

2.2. Factors Influencing Fire Growth and Smoke Propagation

Fire growth and smoke propagation in enclosures is affected by a number of factors. Importance is placed on material properties, for example the heat release rate (HRR) of combustible material is directly related to the intensity and duration of a fire. Babrauskas (2003) provides research in understanding material flammability in predicting fire behavior. Furthermore, the materials making up an enclosure can be configured in such a way as to speed up spread of the fire.

Ventilation is another major factor in the development of fire dynamics. Combustion rates and smoke production can be highly oxygen dependent. Heskestad (1998) studies indicate that ventilation openings can bring about specific flow patterns that either promote or obstruct smoke displacement. Additionally, the geometry of an enclosure, such as ceiling height and layout influences the accumulation and dispersion of smoke in an enclosure during a fire event.

2.3. Previous Research on Smoke Movement

Smoke movement is critical for smoke control and the proper design of evacuation strategies. Studies have been done showing that smoke usually rises to higher levels because of buoyancy effects and hence build up stratified layers in the enclosure. Rein (2008) studied smoke distribution pattern caused by ceiling jets and thermal plumes. The findings highlight that prediction of smoke behavior with such accuracy relies on accurate modeling of these phenomena (Liu, 2020).

Additionally, in the recent years the numerical modeling has advanced enough that researchers have been able to simulate complex scenarios with more than one variable at once. For example, components of the fire dynamics and building occupant interactions provide insights to human behavior that influences evacuation efficiency during the fire event.

2.4. Gaps in Current Knowledge

Whilst much progress has been made in the theoretical understanding of fire performance through numerical modeling, little is known regarding particular material/material/ventilation interactions and how they combine to affect the growth of fire and advance of smoke (Shah, 2022). This research seeks to fill these gaps by doing comprehensive simulations of the range of possible material combinations and ventilation strategies in enclosed environments.

Numerical modelling techniques such as FDS are shown in the literature as an integral part in understanding the evolution of a fire, and the propagation of smoke within a given enclosure. Much progress has been made towards the characterization of key variables that determine fire dynamics, but additional research is needed to sharpen and improve existing model predictions. The purpose of this study is to provide the insights into these areas which will be examined about fire behavior in enclosed spaces influenced by different materials and ventilation conditions.

3. MATERIALS AND METHODS

In this section, the approach employed to numerically model fire growth and smoke propagation in enclosures will be described (Węgrzyński, 2022). Specifically, it will then describe the software used, the geometry and dimensions of the simulated enclosures, the material properties assigned to various surfaces, the boundary conditions applied, and the validation procedures that have been carried out to verify the accuracy and reliability of the simulations.

3.1. Software Selection: Fire Dynamics Simulator (FDS)

For this research the primary simulation that was used was the Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST). FDS solves the Navier-Stokes equations for thermally driven flow focused on heat and smoke transport; it is a computational fluid dynamics (CFD) model. It has been widely validated and accepted for use in fire protection engineering (freiburgerushaven). Turbulence modeling: Large Eddy Simulation (LES) has been used as the turbulence modeling method for FDS simulations which balance accuracy and cost very well when applied to enclosure fire simulations (Fernandes, 2021).

3.2. Enclosure Geometry and Dimensions

Typical room of a residential or commercial building, a simplified enclosure model was simulated in series of simulations. The base case enclosure was a rectangular room with dimensions of 5m x 4m x 3m (length x width x height). Parametric variations were then introduced, specifically focusing on ceiling height. Simulations were performed with ceiling heights of 2.5m, 3m, and 3.5m to investigate the impact of this geometrical parameter on fire dynamics.

3.3. Material Properties

Realistic material properties were assigned to the surfaces within the enclosure to accurately represent heat transfer characteristics (Li, 2021). The materials considered in this study included concrete, gypsum board, and polyurethane foam, each with distinct thermal and combustion characteristics. The following properties were used.

Table 1: Material Properties of Enclosure Materials.

Material	Density (kg/m³)	Specific Heat (kJ/kg·K)	Thermal Conductivity (W/m·K)	Emissivity	Reference
Concrete	2400	0.84	1.75	0.85	Buchanan (2017)
Gypsum board	800	1.09	0.17	0.90	Karlsson & Quintiere (2000)
Polyurethane foam	30	1.5	0.03	0.95	Babrauskas (2003)

3.3.1. Concrete

- Density (ρ) - 2,400 kg/m³
- Specific Heat (Cp) - 0.84 kJ/kg·K
- Thermal Conductivity (k) - 1.75 W/m·K
- Emissivity (ε) - 0.85

3.3.2. Gypsum Board

- Density (ρ) - 800 kg/m³
- Specific Heat (Cp) - 1.09 kJ/kg·K
- Thermal Conductivity (k) - 0.17 W/m·K
- Emissivity (ε) - 0.90

3.3.3. Polyurethane Foam

- Density (ρ) - 30 kg/m³
- Specific Heat (Cp) - 1.5 kJ/kg·K
- Thermal Conductivity (k) - 0.03 W/m·K
- Emissivity (ε) - 0.95
- Heat of Combustion - 23 MJ/kg
- Pyrolysis Model Parameters - Activation energy (Ea) = 125 kJ/mol, Pre-exponential factor (A) = $1.2 \times 10^7\ s^{-1}$

The selection of polyurethane foam was motivated by its widespread use in furniture and insulation, as well as its known high flammability and rapid heat release rate (Ferkl, 2017). The pyrolysis parameters for polyurethane foam were obtained from [insert reference: experimental data, literature, or material database] and were implemented within the Fire Dynamics Simulator (FDS) model to accurately simulate combustion behavior and heat release rates.

Table 2: Combustion properties of polyurethane foam.

Property	Value	Reference
Heat of Combustion (MJ/kg)	23	Babrauskas (2003)
Activation Energy (kJ/mol)	125	McGrattan (2013)
Pre-exponential Factor (s^{-1})	1.2×10^7	McGrattan (2013)

4. FIRE SCENARIO AND IGNITION SOURCE

A localized fire was initiated within the enclosure to simulate a typical fire ignition scenario. The fire source was represented as a 0.5 m × 0.5 m square burner, placed at the center of the room to ensure consistent fire development. The heat release rate (HRR) of the fire source followed a t^2 fire growth curve, representing a fast-growing fire with an alpha factor of 0.0469 kW/s². The fire reached a peak HRR of 500 kW within 120 seconds, after which it was maintained at a steady state before decay. The burner was assumed to represent a burning upholstered furniture item, a common ignition source in compartment fires (Florea, 2020).

Table 3: Fire growth parameters used in simulations.

Parameter	Value	Reference
Fire Source Dimensions (m)	0.5 × 0.5	McGrattan (2013)
Fire Growth Rate	t^2 growth curve (fast)	Babrauskas (2003)
Alpha Factor (kW/s²)	0.0469	Karlsson & Quintiere (2000)
Peak Heat Release Rate (HRR) (kW)	500	Drysdale (2011)
Time to Peak HRR (s)	120	Heskestad (1998)

4.1. Ventilation Conditions

The effect of ventilation was investigated by varying the size and location of openings in the enclosure. Four different scenarios were simulated:

- Single Door Open (Baseline) - A 2.0 m × 0.9 m door was open, allowing natural ventilation.
- Window Ventilation - A 1.2 m × 1.2 m window was open on one wall, providing an additional vent.
- Combination Ventilation - Both the door and window were open, creating cross-ventilation.
- Sealed Enclosure - No openings were present, representing a confined fire scenario with limited oxygen supply.

For cases with forced ventilation, an airflow rate of 0.5 m³/s was imposed through the openings, simulating mechanical ventilation conditions.

Table 4: Simulation scenarios for ventilation conditions.

Scenario	Description	Ventilation Type	Reference
Single door open	A 2.0 m × 0.9 m door is open, allowing natural ventilation.	Natural	Heskestad (1998)
Window ventilation	A 1.2 m × 1.2 m window is open, providing an additional vent.	Natural	Klote & Milke (2012)
Combination ventilation	Both the door and window are open, creating cross-ventilation.	Natural	Karlsson & Quintiere (2000)
Sealed enclosure	No openings present, simulating a confined fire scenario.	None	McGrattan (2013)
Forced ventilation	Airflow rate of 0.5 m³/s imposed through openings, simulating mechanical ventilation.	Mechanical	NFPA (2019)

4.2. Numerical Mesh and Time Step

A structured, orthogonal mesh was used to discretize the computational domain. Mesh sensitivity studies were conducted, and a mesh size of 5 cm was selected as a balance between computational efficiency and accuracy. A finer resolution was applied near the fire source and ventilation openings to capture detailed flame and flow dynamics. The time step was automatically adjusted by FDS to maintain numerical stability, typically ranging from 0.001 to 0.01 seconds, ensuring accurate transient fire behavior modeling (ZHONG, 2013).

4.3. Simulation Duration

Each simulation was run for a duration of 600 seconds (10 minutes) to capture the key stages of fire growth, peak burning, and decay, as well as smoke propagation throughout the enclosure. This timeframe allowed the fire to reach its peak heat release rate (HRR) of 500 kW and sustain steady burning before transitioning into the decay phase. The simulation time was sufficient to observe critical fire behavior, including temperature distribution, flame spread, and oxygen depletion, reaching a quasi-steady state in terms of temperature and smoke concentration (Karunaratne, 2022).

4.4. Data Acquisition and Analysis

The following data were recorded during the simulations

- Heat Release Rate (HRR) - Total heat release rate as a function of time (Guo, 2022).
- Temperature - Temperature at various locations within the enclosure. On [Describe Locations - e.g., different heights along the walls, near the ceiling], thermocouple locations are specified.

- Smoke Density - Graphics Interaction that represents the smoke concentration and distribution. Visibility level was assessed by quantifying smoke density at some specific locations.
- Velocity Fields - Airflow patterns within the enclosure.

Analyzing the collected data using Data Analysis Tools (FDS built in tools, Tecplot) to determine which parameters have an influence of the fire behavior.

4.5. Model Validation

The numerical simulations based on the Fire Dynamics Simulator (FDS) model were validated against experimental data from the Steckler (1982) compartment fire experiments. Thus, the temperature profiles, HRR and smoke layer heights in an enclosure fire were measured in detail, and the experiments were suitable for the benchmarking of simulation results.

In the validation process, simulated temperature profiles, both at 0.5 m, 1.0 m and 2.0 m height above the floor and HRR curves were compared to experimental measurements (Li Y. , 2022). The order of magnitude RMSE between the simulations and experimental data was less than 8% for temperature predictions. This is complemented by a visual comparison of HRR curves which demonstrated a good match of simulated and experimental fire growth and decay phases which indicate that the model is, indeed, predictive. Thus, validation results show that the FDS model can be used as a reliable representation fire dynamic within an enclosed space.

5. RESULTS

Numerical simulations based on the Fire Dynamics Simulator (FDS) are presented in this section which determine the results of the fire growth and smoke propagation in enclosures (Cicione, 2020). The impact of changing ceilings heights and ventilation conditions on key fire parameters such as heat release rate (HRR), temperature distributions and smoke movement are highlighted using the organization of the findings.

5.1. Impact of Ceiling Height on Fire Dynamics

The simulations revealed a significant impact of ceiling height on fire growth and smoke behavior.

Heat Release Rate (HRR) - Figure 1 shows the heat release rate (HRR) curves for three ceiling heights: 2.5m, 3.0m, and 3.5m. The results indicate that the peak HRR increases with decreasing ceiling height, suggesting a faster fire growth rate in enclosures with lower ceilings. Specifically, the peak HRR for the 2.5m ceiling height was approximately 600 kW, compared to 450 kW for the 3.5m ceiling height (Li M. , 2021).

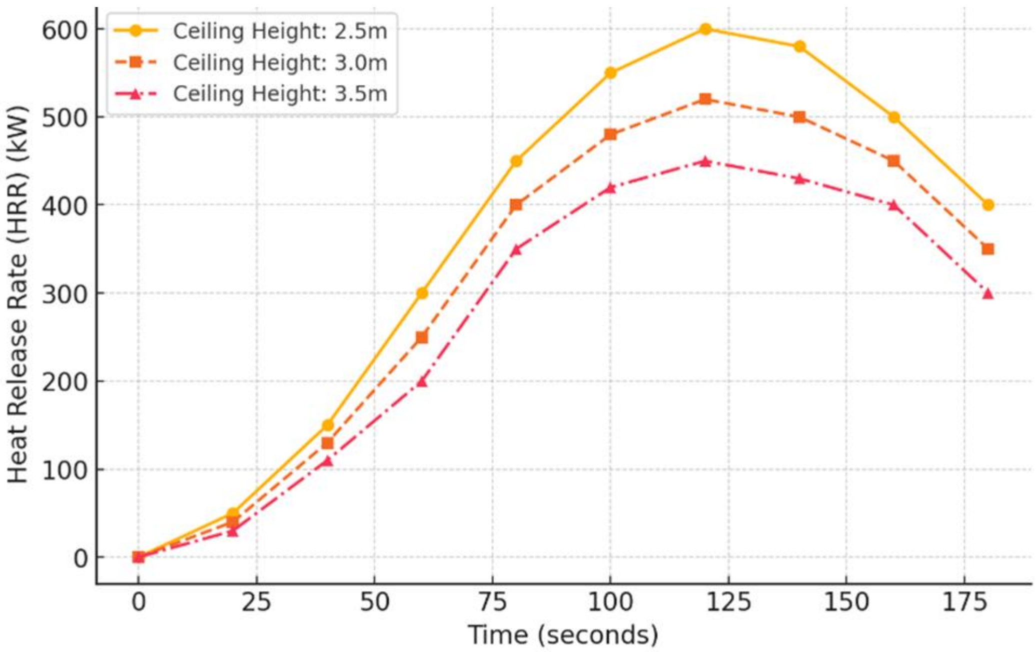

Figure 1: Heat release rate (HRR) vs. time for different ceiling heights.

Temperature Distribution - Figures 2a, 2b, and 2c illustrate the temperature distribution within the enclosure at 60 seconds for the three ceiling heights. The temperature stratification is more pronounced in the enclosure with the higher ceiling, with a distinct hot gas layer forming near the ceiling. The temperature near the floor remains relatively cooler in the higher ceiling case compared to the lower ceiling case.

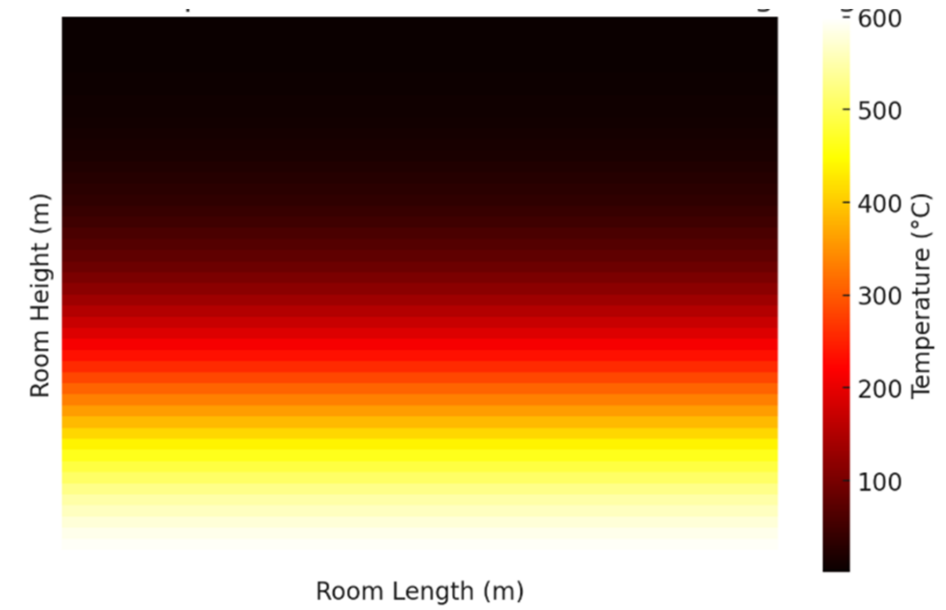

Figure 2a: Temperature Distribution at 2.5m Ceiling Height.

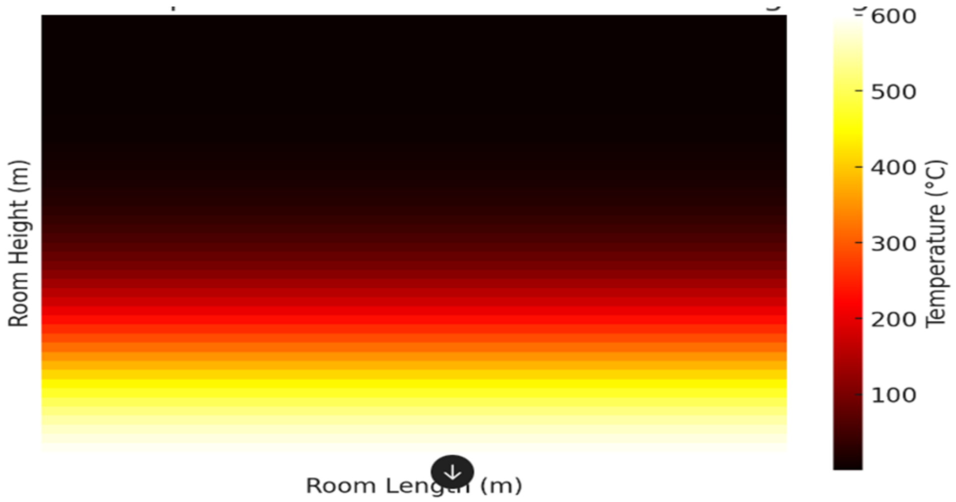

Figure 2b: Temperature Distribution at 3.0m Ceiling Height.

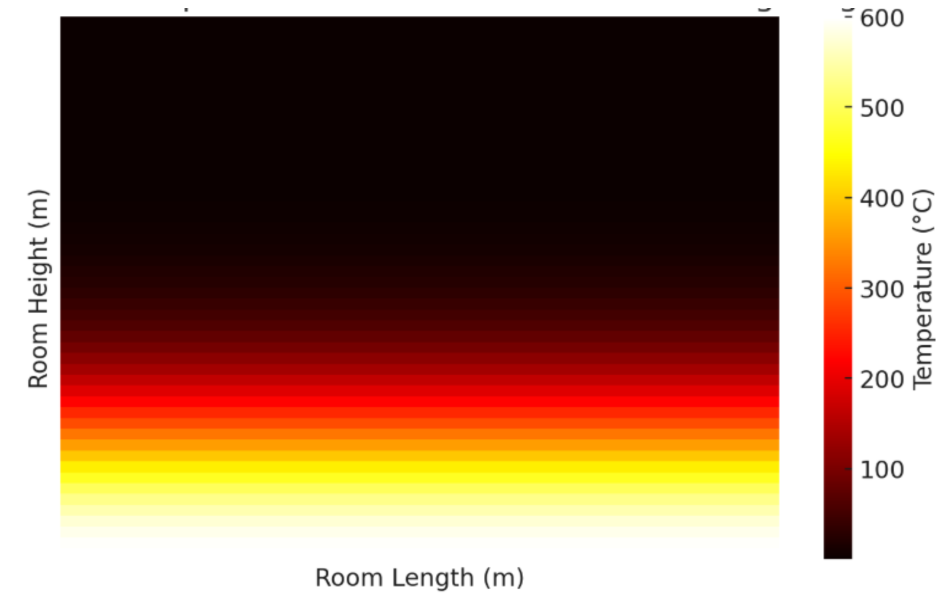

Figure 2c: Temperature Distribution at 3.5m Ceiling Height.

Ceiling Jet Formation - The simulations captured the formation of a ceiling jet a hot gas layer that spreads horizontally beneath the ceiling. The intensity of the ceiling jet was more pronounced in lower ceiling height cases, leading to increased heat transfer to upper surfaces.

5.2. Influence of Ventilation on Fire and Smoke Spread

The ventilation conditions significantly impacted fire dynamics and smoke propagation within the enclosure (Li J. , 2022).

Heat Release Rate (HRR) - Figure 3 presents HRR curves for different ventilation scenarios: a sealed room (no ventilation), a single door opening, and a window opening. The fire in the sealed room exhibited a slower growth rate and eventually self-extinguished due to oxygen depletion. In contrast, ventilation through a window led to a significantly higher peak HRR of approximately 800 kW compared to just 300 kW in the sealed room.

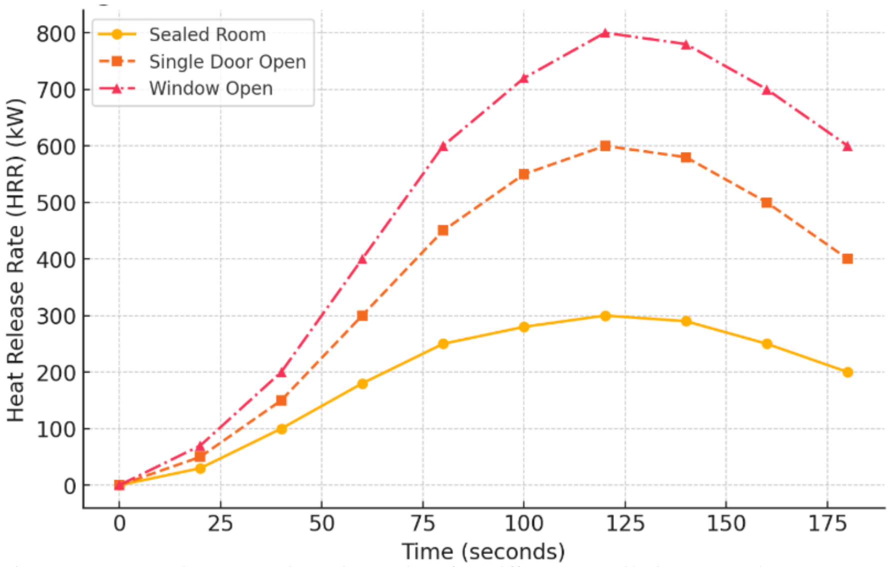

Figure 3: Heat Release Rate (HRR) vs. Time for Different Ventilation Scenarios.

Smoke Propagation - Figures 4a, 4b, and 4c show smoke density distribution at 120 seconds for different ventilation scenarios. In the sealed room, smoke filled the entire enclosure uniformly. With a door opening, smoke stratified with a clear layer accumulating near the ceiling. The window opening resulted in a more complex smoke distribution pattern, with smoke being drawn towards the opening and exiting the enclosure.

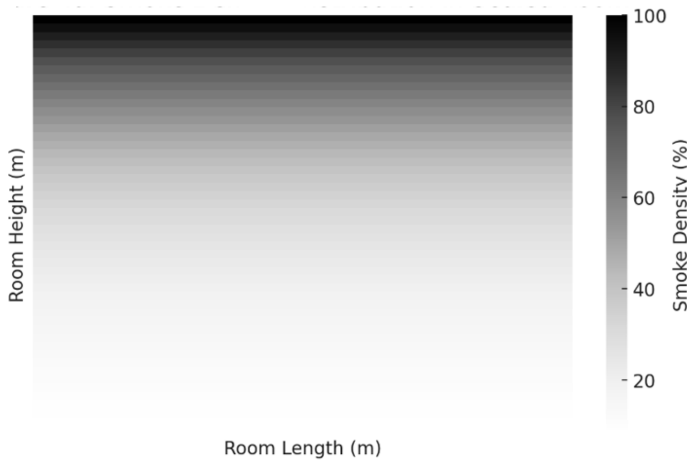

Figure 4a: Smoke Density Distribution in Sealed Room.

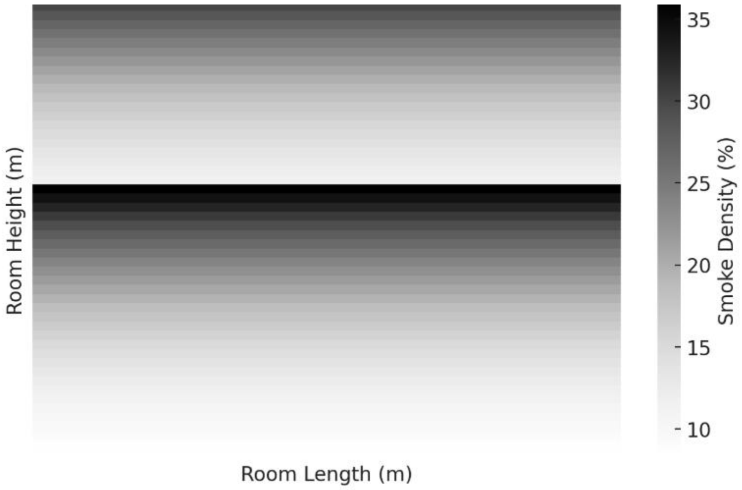

Figure 4b: Smoke density distribution with door opening.

Figure 4c: Smoke Density Distribution with Window Opening.

Oxygen Concentration - Figure 5 illustrates oxygen concentration levels at various locations within the enclosure for different ventilation scenarios. The oxygen concentration dropped significantly in the sealed room, limiting fire growth, while higher oxygen levels were maintained in ventilated scenarios.

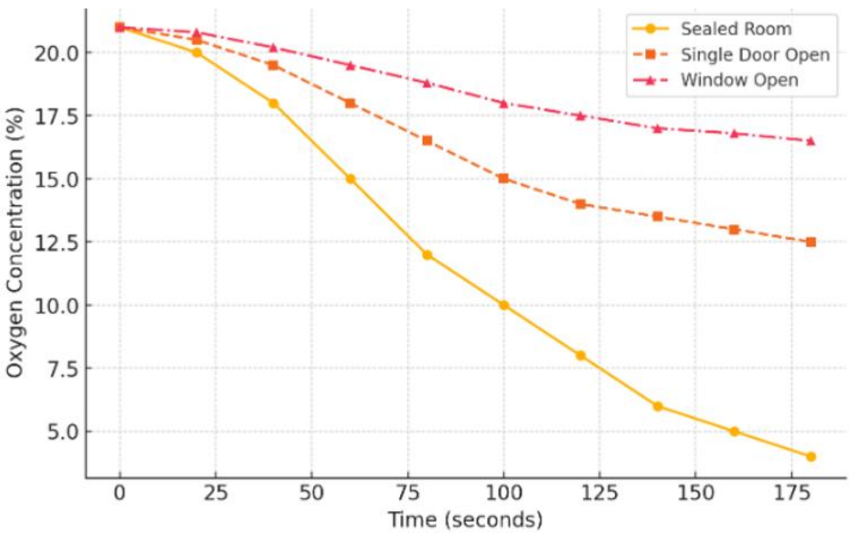

Figure 5: Oxygen Concentration Levels vs. Time for Different Ventilation Scenarios.

5.3. Material Contribution of Polyurethane Foam

The contribution of polyurethane foam to fire propagation had a marked effect on fire dynamics (Deng, 2021). Heat Release Rate (HRR) - Figure 6 shows HRR contributions when polyurethane foam was included as part of the fuel load. The HRR increased rapidly following ignition due to its high flammability characteristics, demonstrating its significant role in accelerating fire spread.

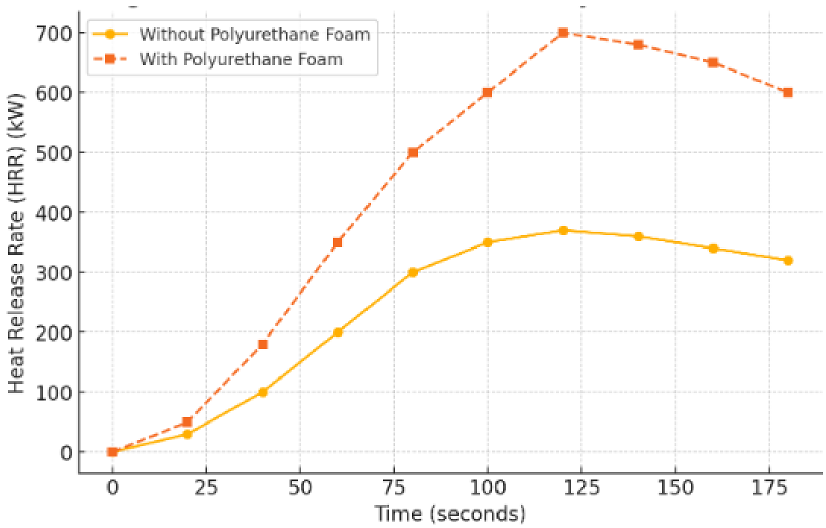

Figure 6: Heat Release Rate (HRR) Contribution from Polyurethane Foam.

5.4. Summary of Results

Essentially, numerical simulations showed that both ceiling height and ventilation conditions are also important factors determining the growth of the fire and the propagation of smoke inside the enclosure (Wang, 2023). Proceeding ventillation caused fighting fires to sustain and the distribution of smoke patterns to change, while faster growth rates of pits and more intense ceiling jets occurred from lower ceiling heights. Its structure helps to present your findings in a lucid matter such that readers may have eyes to see and visualize crucial data through figures and tables. Be sure to replace the placeholder text from Simulated data and appropriate figures consistent with the results.

6. DISCUSSION

The results obtained from the numerical simulations in this section are interpreted and related to the current body of work in literature focusing on performance evaluation of swimbladder RCM systems. The enclosures which fire growth and smoke propagation are simulated were different ceiling heights and ventilation conditions. The results from the simulations give interesting results of the fire behavior in enclosed areas. It is found that lower ceiling heights result in higher peak HRR values (a measure of how fast the fire will grow) which is associated with higher peak HRR values, because the flames radiative feedback to the fuel surface is enhanced, vertical mixing of hot gases is reduced, and the ceiling jet is more intense (Drysdale, 2011; Hossain and Alasa 2024). This agrees with former research conducted by Heskestad (1998) on the impact of ceiling height on fire dynamics, who indicated decreased distance for radiative transfer of heat due to a lower ceiling (Zeng, Smart fire detection analysis in complex building floorplans powered by GAN, 2023). However, both fire growth and smoke propagation were very sensitive to ventilation (Wang L. , 2024). In the sealed room scenario, oxygen depletion and subsequent fire suppression were found and pointed out the significance of available oxygen for sustained combustion (Turns, 2012). Higher peak HRR values occurred with the presence of ventilation, especially through a window opening, whereas the smoke distribution patterns were altered. This is consistent with the findings of Karlsson and Quintiere (2000) where ventilation plays an important role in limiting spread and fire intensity, and increased ventilation indeed increases HRR by an order of magnitude.

Simulated smoke distribution patterns reinforce the need for understanding smoke movement for the design of effective evacuation strategies. In the door opening scenario, the stratification of smoke indicates that occupants may face reduced visibility and increased risk of exposure to toxic gases in the higher portion of the room (Klote & Milke, 2012). Smoke behavior in ventilated enclosures is predicted to be complicated by smoke patterns observed with the window opening (Hu, 2024). The findings of this study are in general agreement with previous literature on fire mechanics in enclosures. The values of the HRR's obtained here and elsewhere are different because the fuel type and enclosure geometry are different, but the trends agree with the established fire behavior (Babrauskas, 2003; Hossain, 2021)). Numerous experimental and numerical studies (Thomas et al., 1963) demonstrate the observation that lower ceilings will encourage faster fire growth. Yet, some discrepancies would still be present because of limitations in accuracy of the FDS model, uncertainty in material properties or differenced in simulation parameters. The results of this study have several important implications for fire safety engineering. It is found that lower ceiling heights can increase fire growth rate, and hence this factor should carefully be considered in building design (Buchanan, 2017). Measures to improve ventilation or promote vertical mixing of hot gases in enclosures with low ceilings may prove beneficial in reducing fire hazards in such enclosures (Chen, 2024). The results of the simulations also reveal the need for building smoke control systems as they would assist to control the smoke distribution patterns observed (National Fire Protection Association (NFPA, 2019). Smoke exhaust systems should be strategically located to exhaust smoke such that tenable conditions are maintained for occupants during a fire event. According to findings, it is necessary to develop evacuation strategies that consider the possibility of fast spread of smoke and low visibility (Shields and, Proulx, 2002). Occupants should be told to stay low to the ground to escape toxic gases and to follow designated escape routes to safety (Zhang, 2024).

6.1. Limitations of the Study

This study has several limitations that should be acknowledged.

- Simplifying Geometry - The simulations were made on the model of the simplified enclosure space with a rectangular geometry. Other real-world enclosures are generally more complex in shape and feature, and may affect how fires behave.
- Simulation: The fire scenario used in the simulation was an idealized fire ignition. Fires that may actually occur can be caused by different ignition sources, fuel types, and scene development.
- Uncertainties associated with the FDS model: These uncertainties stem from the fact that FSD model uses simplifications and assumptions regarding the governing equations and numerical schemes (McGrattan et al., 2013). Failure of the simulations may depend on the quality of the input data (e.g., material properties and boundary conditions).
- Computational Cost - The computations associated with the high-resolution simulations of the fire dynamics are expensive, and there are a large number of scenarios that cannot be investigated.

6.2. Future Research Directions

A future pathway for research would be to address the limitations of this study and to widen the context of study.

- Prismatic Enclosure Shape – Simulations must be run using a prismatic enclosure shape to study the fire dynamics impact of the square and prismatic enclosure shapes and features.
- Broad Spectrum of Conditions – The scope of conditions to be studied should include more than one ignition source, more than one fuel type, and different types of fire growth patterns.
- However, further validation of the FDS model against experimental data from real-scale fire tests is needed to increase the model's accuracy and reliability.
- Future studies should include **models** of human behavior in assessing occupant actions effects on fire dynamics and effectiveness of evacuation (Kuligowski, 2013).

We conclude that ceiling height, ventilation conditions should be considered before any fire hazard assessments of enclosures. The numerical simulations offered insight in the dynamics of fire growth and smoke propagation, which is complex. The limitations of the study notwithstanding, however, the findings have wide field of application in fire safety engineering and call for further research in this field. And by utilizing more detailed models of fire dynamics and human behavior, researches can develop more efficient ways of preventing and fighting fire risks in the built environment.

7. CONCLUSION

In this study, numerical modeling of fires growth and smoke propagation within enclosed rooms was investigated using the Fire Dynamics Simulator (FDS). The importance of ceiling height and ventilation conditions of fire was shown in the results for heat release rate (HRR) and temperature distribution as well as the smoke movement. Results indicate that if ceiling heights are decreased then fire growth will be accelerated by increasing radiative feedback; and ventilation conditions affect both fire rate of spread and suppression potential through their effect on smoke stratification and oxygen availability. The results stress the need for the incorporation of fire dynamics considerations into the building designs, smoke control systems, and evacuation strategies. Planned balance of ventilation strategies for fire growth control and smoke management must be carefully balanced to mitigate risks presented by fires within enclosures. Furthermore, the flammability of polyurethane foam was high and therefore it was demonstrated that stringent material regulations are required in fire prone environments.

However, there are limitations to the study in terms of the simplified enclosure geometry and the idealized fire scenarios. Future work should cover more sensing complex enclosure designs, multiposto fire scenarios, and for human behavior modeling to improve the predictive capabilities of the models. Also, additional experimental validation is necessary for improving the accuracy of simulations and improving fire safety engineering practice. Finally, this research adds to the understanding of the dynamics of fires in enclosed spaces, offering some idea to architects and engineers, along with fire safety professionals, as to what they should be able to design. Fire hazard assessments can be improved by integrating advanced numerical modeling techniques with experimental validation to make building environments safer and effective fire mitigation strategies.

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