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Investigating the Actuation of Sidewall Sprinkler in an Atrium Using CFD Simulation

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ABSTRACT

This study investigates the actuation of sidewall sprinklers in large-scale buildings with high-ceilinged atriums, addressing the challenges of unique architectural configurations. Compliance with NFPA 101 requires automatic sprinkler systems, including atrium areas, in these buildings. To maintain aesthetic considerations, design engineers, particularly in the middle east, often propose sidewall sprinklers as an alternative to traditional ceiling sprinklers. This research assesses whether the sidewall sprinklers would actuate during a fire using Fire Dynamic Simulator (FDS). The findings indicate that sidewall sprinklers will fail to actuate if the fire is located at the centre of the atrium, even if the edge of the fire area is below the sprinklers. Furthermore, the study emphasizes the importance of using an FDS mesh resolution (D*/dx) of 6 or finer resolution when measuring temperatures near the flame or fire plume to ensure accurate evaluations of sprinkler activation. These findings provide valuable insights for design engineers and authorities, assisting in decision-making processes related to fire safety measures, system designs, and regulatory compliance.

1. Introduction

An atrium is a large space built by a series of floor openings joining two or more floors enclosed at the top of the openings and intended to be used other than mechanical, electrical, or plumbing shaft (NFPA 101, Life Safety Code). Atria is a common design feature nowadays as they offer humongous space and let natural light enter, which provides a feeling of freedom for the occupants or visitors. Hence, architects and building owners desire this architectural feature in the buildings. Having enough natural light from the sun makes it generally more beneficial for the building owners to turn off their lights during daylight, hence reducing the electricity cost. Although the atrium offers numerous advantages, it poses challenges for fire protection engineers regarding smoke management and fire control. This large shaft that is unenclosed by fire-resisting construction, which extends up to several stories, contradicts the principles and practice of compartmentation that could potentially endanger the lives of the occupants.

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Building and life safety codes adopted in the United Arab Emirates and Qatar are NFPA 101; NFPA 5000, Building Construction and Safety Code; and the International Building Code (IBC). NFPA 101 Section 11.8.3.1 requires high rise buildings to be protected with automatic sprinkler systems and shall follow the installation requirements of NFPA 13, Standard for the Installation of Sprinkler Systems. In the context of NFPA 101, high rise building refers to a structure where the highest habitable height equals or exceeds 23 m (75 ft). The exact requirement is represented in IBC section 403.3. Accordingly, NFPA 13 section 8.1.1 (1) requires full protection of sprinklers in all areas, including the atrium space. With the aforementioned code requirement, authorities having jurisdiction has to enforce sprinkler protection throughout building premises. However, the installation of sprinkler heads in the atrium creates two major concerns. The first is that architects and building owners want to avoid installing sprinkler heads on the ceiling of the atrium as they damage the aesthetics of the ceiling, especially if it is made of decorative glass. Secondly, the question arises whether the ceiling sprinkler will activate or not. Several factors influence the activation time of sprinklers are the fire characteristics; the convective heat transfer processes which greatly influence the rate at which the sprinkler head reaches its activation temperature; the response time index (RTI) represents the sprinkler’s sensitivity to heat; the clearance between the top of the fuel and the location of the sprinkler under the ceiling; and the temperature rating of the sprinkler. In addition, when the fire occurs at the ground floor level of the atrium, the hot dense plume rises to the ceiling while continually entraining air as it moves towards the highest level of the atrium space; this causes the density, the buoyancy, and the smoke temperature decreases causing a delay in activation time of sprinkler or sprinkler may not activate at all.

Since sprinkler activation depends on several factors, engineers are gearing toward using a performance-based approach, which is an alternative engineering-based approach. Unlike the prescriptive approach, which dictates what needs to be followed without giving a specific goal, the performance-based approach uses engineering calculations and judgment to allow engineers to deterministically assess a certain scenario based on the agreed fire safety goal. As such, this approach can be used to determine if the sprinkler will actuate or not. Examples of known buildings in the United Arab Emirates where automatic ceiling sprinklers were not installed at the ceiling of the atrium are the Ferrari World, Dubai Mall, and Khalidiya Rotana Hotel.

In response to the code requirement for full sprinkler protection in atrium spaces, some design engineers argue that the absence of sprinkler protection would leave people exposed to the hazards of fire, potentially violating fire safety regulations. To address this concern, engineers in the Middle East and other parts of the world have adopted the practice of installing sidewall sprinklers on each balcony floor level of the atrium.

The installation of sidewall sprinklers in atriums has become a standard design practice in many Middle Eastern buildings. This approach is based on the belief that these sprinklers will activate in the event of a fire, providing fire control. Sidewall sprinklers are considered less visually obtrusive compared to traditional ceiling-mounted sprinklers. They can be installed in a manner that blends with the architectural design of the atrium, offering a more aesthetically pleasing fire protection solution.

By installing sidewall sprinklers, design engineers aim to address both the code requirements for full sprinkler protection in atrium spaces and the desire to maintain the visual appeal of the atrium.

The photos in Figure 1 to Figure 4 show sidewall sprinklers (circled in red) installed in the atrium instead of ceiling sprinklers.

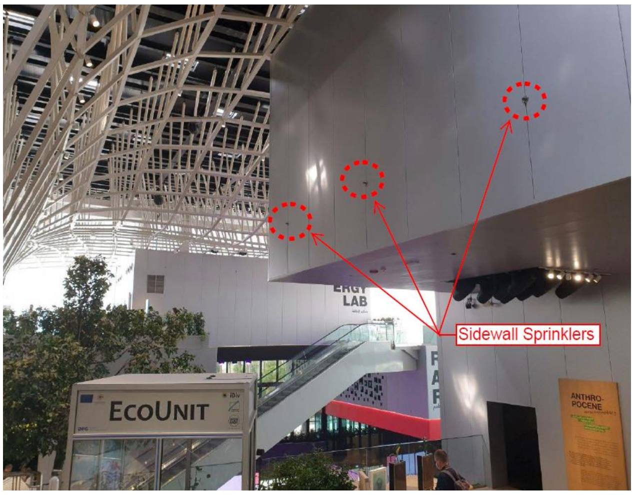

Fig. 1. German Pavilion, EXPO 2020, Dubai, United Arab Emirates (UAE)

Fig. 2. Al Wahda Mall, Abu Dhabi, UAE

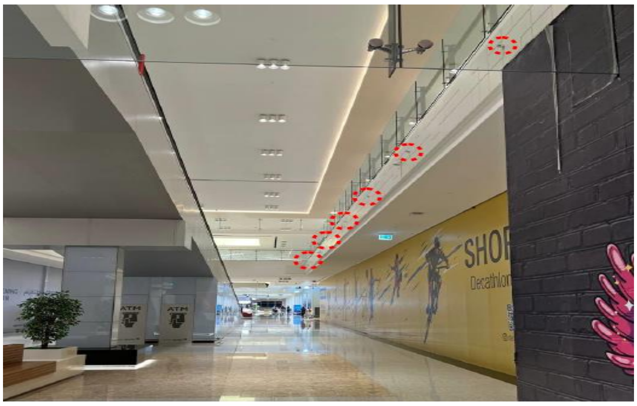

Fig. 3. Reem Mall, Abu Dhabi, UAE

Fig. 4. Galleria Mall, Tbilisi, Georgia

The study seeks to determine the activation potential of sidewall sprinklers in atriums during fires, utilizing the FDS via Pyrosim software for computational fluid dynamics (CFD) simulations. Crucial for assessing the standard design practice of installing these sprinklers, the investigation targets three scenarios: fire ignition at the atrium center, near a sidewall sprinkler, and directly below the sprinkler. By addressing conflicting engineer opinions, the research aims to provide objective insights into sidewall sprinkler necessity on atrium balcony levels, potentially influencing facility costs, fire safety, and operational efficiency. The findings will provide valuable reference to the regulatory bodies like the UAE Civil Defense and Qatar Civil Defense in updating guidelines for atrium sprinkler system design.

2. Methodology

The study aims to determine whether the sidewall sprinklers installed in the atrium will activate during a fire. To achieve this objective, the researchers will utilize the FDS using Pyrosim software, a CFD software, for conducting simulations.

By using CFD simulations, the researchers can model the complex interactions between the fire plume, smoke layer, and airflow within the atrium. This enables engineers to assess how these factors influence sprinkler activation times. The simulations take into account the geometry and characteristics of the atrium, providing valuable insights into the behavior of the fire and smoke in the space.

The selection of input data, such as design fire load, will be based on the most conservative value between the previous researcher's fire load survey and the UAE fire and life safety code of practice requirement. The study will also obtain other input data from the actual fire experiments conducted by National Institute for Standards and Technology (NIST).

2.1 Comparison of FDS Predictions to Real-Scale Fire Test

The field model separates a compartment into thousands or millions of cells depending upon the user inputs. This field model calculates each cell using partial differential equations to relate the flow of fluids and energy transfer. The law of momentum, energy, and mass conservation are applied to each cell and balanced with all adjacent cells.

The general form of the Navier-Stokes governing equation of the natural buoyant airflow is as follows:

$$\nabla \cdot (\rho \phi V) = \nabla \cdot (\Gamma \phi \nabla \phi) + S\,\phi \tag{1}$$

A general form of the energy equation is as follows:

$$\nabla \cdot (V(Pe + \rho)) = \nabla \cdot (k \nabla T - \Sigma h_i J_i) \tag{2}$$

Where ϕ represents the variable of interest; ρ is the density; Γ is the diffusion coefficient; $S\,\phi$ is the source rate per unit volume; k is the thermal conductivity; T is the dry air mixture temperature; Ji is the diffusion flux of species i.

Tilley *et al.,* [1] used the fire dynamics simulator to enhance existing correlations with regard to the smoke and heat control system of the atrium. An extensive number of simulations were performed to study the existing equations or correlations for smoke and heat removal. They have also conducted another experiment on an atrium space and tunnels to validate the physics of the fire dynamics simulator in comparison with the scaled fire model. Sixteen simulations have been performed, and four different heat release rates (HRR) were studied. The Smagorinsky LES turbulence and Prandtl number used in the calculation are 0.2 and 0.7, respectively. A grid cell of 2.5 cm was used. The result shows for the atrium space that numerical results using the fire dynamics simulator are in very good agreement with the experimental data. It was concluded that the prediction of the quasi-steady state smoke region by the fire dynamics simulator is good.

Ayala *et al.,* [2] performed full-scaled fire experiments in an atrium space with a dimension of 19.5 m x 19.5 m x 17.5 m using 1.36 MW and 2.34 MW pool fires with different roof geometries, and the results were compared to the result of the fire dynamics simulator. The result shows good agreement between the result of FDS and the experimental result. The difference between mathematical and physical models is less than 10% only in all test cases. They also found out that the far-field temperatures are not significantly impacted by the atrium geometry or the geometry shape of the roof.

Al Waked *et al.,* [3] have investigated a residential building atrium to improve the smoke and heat removal of several fire scenarios and to determine where strategically the smoke and heat vent should be placed using the fire dynamics simulator. The HRR used in the design fire is 1.52 MW which was assumed to result from the burning sofa chair with a rapid growth fire coefficient of 0.04689 Kw/m^2.

Lei Xu *et al.,* [4] performed a numerical simulation using FDS to study the smoke spread process of a thin, tall atrium, which is essential to the design of a smoke control system. The ceiling height of the atrium is 12.0 m, and the result shows that the smoke temperature did not reach 74°C.

Nowadays, with the advancement of computer power, the fire hazard assessment in atria can be performed with relative ease with the use of the CFD fire model, such as the fire dynamics simulator. Montes *et al.,* [5] performed fire experiments in the Murcia Test Facility, which has a dimension of 19.5 m x 19.5 m x 17.5 m, to validate the fire dynamics simulator result. In general, the fire dynamics simulator shows good agreement with the experiment. The result shows that the fire dynamics simulator over predicts the plume temperature by 10 to 25% above 9.0 m.

Fire experiments were conducted by Hostikka *et al.,* [6] at VTT, Finland, in a 19.0 m tall hall and found well agreement between the fire dynamics simulator and the experiments (see Figure 5).

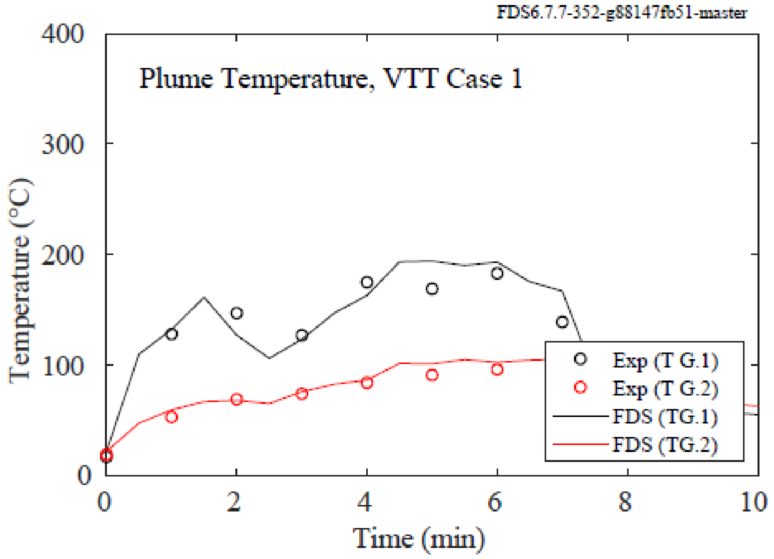

Fig. 5. VTT experiments, plume temperature

2.2 Sprinkler Protection and Activation

A fire sprinkler is a thermal device that either contains a liquid on its bulb or a sensitive soldered metal that, when heated, will trigger its activation. The sprinkler is mainly activated by heat conduction, which renders them ineffective in a scenario where a hot fire plume or ceiling jet is not in direct contact with the sprinkler. Hence, for a sprinkler to actuate, there should be enough combustible load and HRR to heat up the surrounding air, create a hot gas plume and have direct contact with heat responsive element of the sprinkler. Nam [7] conducted a series of experiments in a high-ceiling warehouse facility to determine if sprinklers would actuate or not. The test site has a ceiling height of 18.3 m, and the fire load is based on FM Global Class 2 commodity with some plastic fuels. The sprinkler temperature rating is 74 °C, and the response time index is 138 $(m\text{-}s)^{½}$. The result shows that the sprinkler would still actuate even at relatively high clearance. The main reason for this is due to the high amount of heat load and the high HRR of the burning commodities. The result of the experiment is somehow expected as a warehouse typically contains a relatively high number of combustible materials that are either piled on top of each other or placed in a warehouse rack; however, this study will focus on typical fire loads found in commercial and mercantile buildings such as mall and alike which has relatively lesser amount of combustible loading and different HRR compared to a warehouse fire.

Sidewall sprinklers will be positioned on each side and level of the balcony. Nevertheless, due to the atrium's square opening shape and the assumption that the gas temperature on one side will be approximately the same on the opposite side when the fire is at the center of the atrium, the simulation will only consider two sides. In case of a fire at the atrium's center, only the topmost level sprinklers will be taken into account. However, if the outcome indicates at least one sidewall sprinkler activation, the simulation will be reperformed to consider the potential activation of other sidewall sprinklers. For the second and third fire scenarios, where the fire is closer to the sidewall sprinkler, all sprinklers on each level will be considered to observe the temperature rise.

Per SFPE handbook, 2016 edition, the spray density value will be 0.1 gpm/ft^2 or 7.0 x 10-5 m/s, which is the minimum density of a sprinkler system. However, the effect of sprinkler spray on the fire will not be studied in this paper but will focus on whether the sidewall sprinkler will activate or not.

2.3 Design Fire Size

When performing fire modeling, one of the important factors that need to be considered is the design fire. The design fire provides the heat of combustion or the amount of heat energy available for a fuel per kilogram. In addition, the design fire shows the HRR of the fuel, which is considered the single most important variable or parameter in fire hazard analysis as it can be used as input on how large the fire would be, how much smoke it could release, how high is the flame, and what will be the upper gas layer temperature which are important in determining sprinkler actuation time. Alternatively, instead of specifying the specific fuel package and type of combustible materials, the HRR can be determined as a function of the occupancy type (e.g., industrial, commercial, or education occupancy) for which the HRR per unit area is used and this value is then presumed for a specified area.

HRR per unit area can be calculated using the steady-state or peak heat release of a fire.

$$Q" = Q / A_{FIRE} \tag{3}$$

Where $Q"$ is the HRR per unit area, kW/m^2; Q is the HRR of the fuel at steady-state, kW; and A_{FIRE} is the footprint of the fuel package.

Researchers who performed studies regarding fire dynamics in an atrium have considered different fire sizes. Hopkin *et al.,* [8] have been observed that many of the HRRs per unit area value in UK fire literature were based on ten industrial fire incidents from 1960 to 1970 (Hopkins, 2019).

Quin *et al.,* [9] used a fire with a combined heat release rate of 5.2 MW inside a 20.0 m high cubic atrium. Based on the result of experimentation and FDS, it shows that the far-field temperature predictions are accurate inside the smoke layer with differences of less than 10%.

Lougheed [10] stated that the size of the fire that should be considered should be based on the expected combustible materials in the atrium, primarily dictated by the occupancy type. The typical size of the fire in an atrium is 5 MW.

Madrzykowski [11] performed a fire test and observed that a furnished, non-sprinklered room with a dry tree inside generated a peak HRR in excess of 5.2 MW. The HRR of dry trees was significantly higher than what was published in NFPA 92 standard.

Theobald *et al.,* [12] performed several fire experiments and studied the growth and development of fires in typical industrial buildings such as factory and workshop facilities. Based on the ten fire incidents and conducted fire tests, it was recommended that industrial occupancies' HRR per unit area ranges from 90 Kw/m^2 to 620 Kw/m^2. The first edition of NFPA 92B recommends that the HRR per unit area used in the industrial occupancy should be 260 Kw/m^2, which was based on

Theobald's work. For shops and mercantile occupancies, it was recommended by Morgan in 1979 to use a 5MW design fire which "has become widely accepted as a minimum fire size for design purposes in view of its low probability of occurring."

The 2018 edition of the United Arab Emirates Fire and Life Safety Code of Practice states that the design fire load for office building atrium and shops shall be 2.1 MW and 5.0 MW, respectively. The 5.0 MW design fire size specified in the UAE fire and life safety code of practice appears to adopt what Morgan and Lougheed have recommended as the design fire in the atrium space.

In this study, the heat release of the fire will be taken from the fire test conducted by the National Fire Research Laboratory of a room that contains a dry pine tree with an upholstered chair and shelf in the room corner which is a typical display material that can be observed in an atrium, especially during last quarter of the year where people are celebrating December holidays. The peak HRR that was recorded using a large-scale calorimeter was 7.362 kW.

The 7.362 MW HRR exceeds the average expected HRR per the UAE Fire and Life Safety Code of Practice requirement, which only requires a 5.0 MW fire size for shops and mercantile. The selected design fire size in this study is relatively larger than the typical fire sizes that were considered by previous researchers who conducted studies of atrium fires.

The HRR per unit area can be calculated using the peak HRR value during the entire fire duration divided by the fire area.

$$\begin{aligned}\text{Heat Release Rate per Unit Area} &= 7362 \text{ kW} / 4 \text{ m}^2 \\ &= 1840 \text{ kW}\end{aligned}$$

2.4 Ambient Temperature

The ambient temperature will be based on the thermal comfort condition for human occupancy in typical office space, which is 23.0 °C per American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) standard 55. This value suggests the optimum temperature condition during summer and winter conditions.

2.5 Response Time Index

The fire sprinkler industry has three broad ranges of sprinkler sensitivity: standard, fast, and special response type sprinklers. The selection of which sprinkler response type primarily depends on the occupancy type. In addition, there are two types of sprinkler heads: fusible link and glass bulb sprinkler heads. Both operate autonomously. When the heat-sensitive components of these fire sprinklers reach a specific temperature, they rupture, enabling the discharge of water. The sprinkler head used in this study is based on the TYCO model SW-24, which is a bulb-type sprinkler. In addition, the pictures in Figure 1 - Figure 4 show a bulb-type sprinkler head, a common type of sprinkler head used in the industry compared to the fusible link type.

Table 1 is the typical response time index for each sprinkler type based on the work done by Madrzkowski [13].

Table 1
Generic sprinkler response time index

Sprinkler type	Response time index (m ½ - s ½)
Standard response (link type sprinkler)	130
Standard response (bulb type sprinkler)	235
Quick response (link type sprinkler)	34
Quick response (bulb type sprinkler)	42

In this study, the standard response, bulb type sprinkler will be used as input to the calculation and fire simulation program, which has a response time index of 235 m ½ - s ½.

2.6 Sprinkler Temperature Rating

In addition to the response time index of a sprinkler, another sprinkler characteristic that is an important factor in the activation time of a sprinkler is the sprinkler's temperature rating. Table 2 shows a wide range of temperature classifications for sprinkler heads. The selection of which temperature rating should be used depends on the room's occupancy type and ambient temperature.

Table 2
Temperature rating and classifications (NFPA 13

Maximum ceiling temperature	Temperature rating	Temperature classification
38 °C	55 °C to 77 °C	Ordinary
66 °C	79 °C to 107 °C	Intermediate
107 °C	121 °C to 149 °C	High

Since the maximum ceiling temperature is less than 38°C, hence an ordinary temperature classification will be considered in the simulation inputs. Per the Tyco data sheet, the temperature rating of the extended coverage sidewall sprinkler is 68.0 °C.

2.7 Simulation Process and Conditions

In the research study, the simulation time will be set to 94 seconds. This duration is chosen based on the observation that the peak HRR occurs at 29 seconds from the fire test result of NIST. After reaching the peak, the fire's HRR begins to decay, and the chances of sprinkler activation become less likely if it has not been activated by that point.

Setting the simulation time to 94 seconds ensures that there is sufficient time to observe the fire dynamics and determine if the sidewall sprinklers will activate. Additionally, it ensures that there will be no significant increase in ambient temperature that could affect the evaluation of sprinkler activation.

For the environmental conditions, a humidity level of 50% will be selected based on the average thermal occupancy comfort per ASHRAE standards. The exterior temperature will be set at 47.6 °C, which represents the maximum expected extreme annual design temperature in Abu Dhabi, considering a 10-year return period value of extreme dry bulb temperature as specified in the ASHRAE Handbook Fundamentals. The exterior pressure will be set to the standard sea level pressure of 101.325 kPa.

2.8 Thermal Properties

The wall material is assumed to be made of concrete. The thermal conductivity, specific heat, density, and thickness has been taken from Cengel *et al.,* [14]. The concrete wall has a thickness of 0.20 meters (7.88 inches), equivalent to a 4-hour fire rating, as per the International Building Code table 721.1 (1) (IBC, 2012). Furthermore, for mall shops classified as mercantile occupancy, IBC table 706.4 specifies a minimum fire resistance rating of 3 hours.

2.9 Compartments

The atrium consists of five floors, with each floor being 5 meters high. The total height of the atrium from the ground floor to the ceiling is 30.0 meters. The width and length of the atrium opening will be set equal to twice the maximum water throw of the extended coverage sidewall sprinkler. This dimension ensures that the opening is sufficient to accommodate the sprinkler's water distribution pattern.

The area-to-height squared ratio of the atrium is set to 2.5, which is based on the findings of the atrium fire experiment conducted by Ayala *et al.,* [2]. This ratio aligns with their research and provides a realistic representation of the atrium's fire behavior.

2.10 Vents

In the research study, natural roof vents will be considered for smoke and hot gas exhaust in the atrium design, as opposed to mechanical vents, to ensure conservatism. Natural roof vents rely on the buoyant force of hot gases and smoke to rise and flow out of the building through the vent openings.

The determination of the vent type to be used, whether manual or mechanical, is influenced by fire codes and requires engineering analysis. However, for the purpose of this study, natural roof vents will be utilized.

According to the UAE Fire and Life Safety Code of Practice, the minimum vent or exhaust size opening area should be 1.5% of the floor area. This requirement ensures an adequate flow of smoke and hot gas out of the building, helping to prevent their migration into adjacent spaces.

Floor area = 59.50 m x 44.50 m
= 2,647.75 m^2 say 2, 650 m^2
Minimum vent size = 0.015 x 2, 650 m^2
= 39.75 m2 say 40.0 m^2

A single 40.0 m^2 vent size is not practicable and may create inefficient smoke control; hence, the vent will be divided into four. According to the UAE Fire and Life Safety Code of Practice, the distance between two vents should not exceed four times the height of the ceiling. Hence, the placement of the four vents will be designed with consideration to maintain an appropriate spacing between them. Figure 6 shows the location and arrangement of the natural vents. The vents were distributed closer to the center of the atrium, where the smoke concentration is expected to accumulate significantly in the first fire scenario.

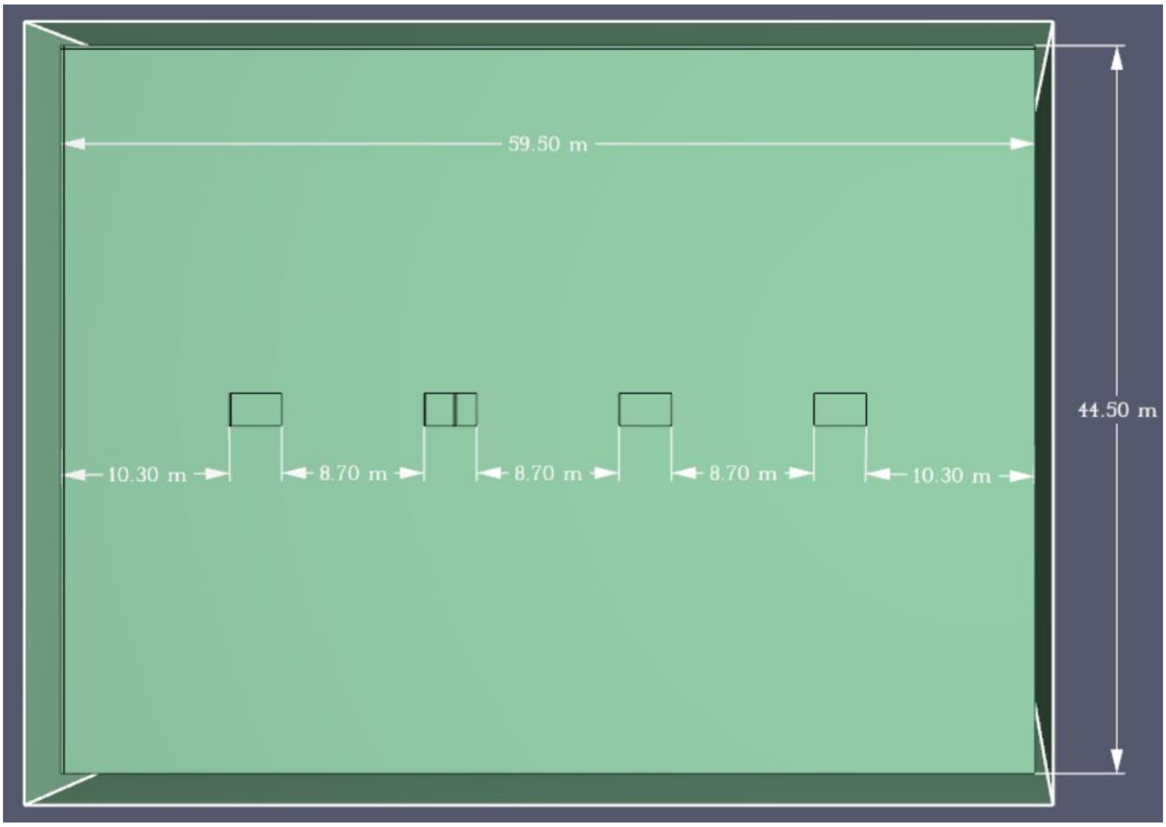

Fig. 6. Vent location and arrangement

In addition to roof vents, wall vents will also be considered in the design input. These vents, along with the doors provided on all four sides of the building, will serve as both ventilation openings and sources of make-up air. Make-up air is essential for the proper functioning of the atrium smoke control system, as it compensates for the air being exhausted from the system.

According to NFPA 92, the recommended make-up air should be between 85% to 95% of the exhaust size, excluding the wall or floor leakage area. In this study, the average value within this range will be considered to determine the appropriate amount of make-up air required for the atrium's smoke control system.

Exhaust vent size	= 40.0 m^2
Inlet vent size	= 0.9 x 40.0 m^2
	= 36.0 m^2
Inlet vent size for each side	= 36.0 m^2 / 4
	= 9.0 m^2
Door size	= 3.0 m x 3.0 m (height x width)

The doors are assumed to be opened during the entire simulation; hence, there will be an uninterrupted combustion process due continuous supply of fresh air to the fire, which will exhaust the entire fuel, commonly known as fuel burnout.

2.11 Input Parameters

Table 3 presents the input values utilized in the simulation. The majority of these values were derived from the default settings embedded within the program.

Table 3
FDS input value parameters

Parameters	Input value
Wall update increment	2-time steps
Smoke quantity	Soot mass fraction
Ambient oxygen mass fraction	0.232378 kg/kg
Ambient carbon dioxide mass fraction	5.95 x 10-4 kg/kg
Smagorinsky constant	0.2 (default value)
The Courant-Friedrichs-Lewy (CFL) constraint	Minimum = 0.8 (default value)
Maximum = 1.0 (default value)	
Von Neumann Constraint	Minimum = 0.8 (default value)
Maximum = 1.0 (default value)	
Simulation type	Very Large Eddy
Schmidt number	0.5 (default value)
Prandtl number	0.5 (default value)
Initial unmixed fraction	1.0 (default value)
Radiation	
Angle increment	5 (default value)
Number of solid angles	100 (default value)
Number of polar angles	15 (default value)
Assumed radiative source temp	900 (default value)
Constant absorption coefficient	0 (default value)
Path length	0.1 m (default value)

2.12 Simulation Type

Very large eddy simulation was selected against Direct Numerical Simulation (DNS) as the domain size of the fire model is relatively large. The use of DNS is computationally very expensive because the scales in a turbulent flow are widely varying, getting worse with the increasing Reynolds number. Hence, instead of resolving all the scales, it is more efficient to calculate only the largest scales, which contain the most information, and the small scales are modeled.

2.13 Mesh Size and Model Grid Size

The accuracy of the CFD solution depends on the model grid size and the complexity of the geometry. The size of the atrium will be the same as in CFAST, but the mesh size will be extended on the sides and top. This allowance above the ceiling will show the exhaust gas temperature coming out of the vent.

A mesh sensitivity analysis will be performed to ensure that the results are independent of the mesh resolution. Simulations will be conducted with multiple mesh resolutions and compare the sprinkler activation time.

Fine meshes with high resolutions require more computational power and longer simulation times. The mesh resolution will be optimized to strike a balance between accuracy and computational efficiency based on the available resources.

The cell size will be uniform in each direction to avoid issues with the pressure solver. It is widely accepted in most literature to have a mesh element size of 0.1 m to 0.3 m for fire studies conducted by Montes *et al.,* [15].

The characteristic fire diameter (D^*) and the cell size (dx) for a specific simulation can be related, i.e., the smaller the characteristic fire diameter, the smaller the cell size need be to sufficiently resolve the fluid flow and fire dynamics.

The characteristics fire diameter is given by the following relationship:

$$D^* = \left(\frac{\dot{Q}}{P_\infty C_\infty T_\infty \sqrt{g}}\right)^{2/5} \tag{4}$$

Where $\dot{Q}$ is the peak HRR, kW; T_∞ is the ambient gas temperature; g is the gravitational constant, 9.81 m/s^2; C_∞ is the heat capacity of air at a constant temperature; and P_∞ is the ambient density of air, 1.2 kg/m3. Substituting the values to the equation will give the characteristic fire diameter, D*, of 2.108.

Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications is a reference in the FDS User Guide. To accurately resolve fires in various settings, NUREG 1824, United States Nuclear Regulatory Commission (USNRC, 2007) employed a D*/dx ratio ranging from 4 to 16. When the FDS mesh resolution (D*/dx) ratio is equal to 4, the suggested course cell size is 0.5270 m (52.6 cm), and for a D*/dx ratio of 8, then the suggested course cell size is 0.2635 m (26.35 cm).

According to the SFPE handbook, the plume becomes increasingly significant in the overall fire scenario as the ratio of H/D* increases. It reveals whether or not the plume entrainment relation is appropriate for empirical and zone models. It provides a non-dimensional measure of how “high” the plume is for computational fluid dynamics.

In this study, the grid size used for the simulation starts at 0.5 m and finally at 0.25 m. Considering the relatively large size of the atrium, setting the grid size to 0.25 m results in a high mesh count. Specifically, the total number of meshes reaches 5,919,744.

2.14 Scope and Limitations

The height of the atrium is limited to 30 meters. Considering each floor is 5.0 m high. Selecting 30 meters is to qualify the subject building as a high-rise. A high-rise building, per NFPA 101, has an occupant floor of more than 75 ft (23 meters) above the lowest level of fire brigade truck access. And high-rise building is mandated to be fully protected with sprinkler per NFPA 101. According to NFPA 13, atriums in schools, gymnasiums, hotels, and similar spaces fall under the light hazard occupancy classification. This categorization is based on their low combustibility content and relatively low HRR during fires.

The maximum horizontal dimension between opposite edges is 48.00 feet (14.63 m). This dimension is based on the maximum throw that a sidewall sprinkler can spray. The sprinkler that will be used in this study is the Tyco sidewall sprinkler, extended coverage, model number SW-24, with a k-factor of 11.2 which is a model approved by Underwriters’ Laboratory or commonly known as UL. At the time of the writing, this model is by far the commercially available sprinkler with the longest water coverage of up to 24 feet (7.31 m) based on the research done by the author. A larger atrium dimension will render the sidewall sprinkler ineffective if it activates, as the water will not reach the remotest part of the atrium.

The fire size that will be considered in the simulation is 7.362 MW, equivalent to the maximum HRR of a room with a dry tree, sofa bed, and table, a typical combustible load found in commercial buildings (Madrzykowski, 2008).

This study will only utilize a non-mechanical replacement smoke control system, considered the simplest method of delivering replacement air into the atrium using direct outdoor opening(s). According to NFPA 92, smoke control systems (2015), to ensure the exhaust vent can effectively move the intended amount of air, it is necessary to supply make-up air. The substantial openings leading to the outdoors may include open doors or vents. In this study, the entrance doors at each side of the building will be considered a make-up air source.

This study will not delve into studying the impact of sprinkler spray on the fire itself. Instead, the focus will be solely on investigating whether any of the sidewall sprinklers will activate under the specified fire scenarios. The limitation of this study lies in its exclusion of analyzing the direct effect of sprinkler spray on fire behavior, as the primary objective is to understand sprinkler activation patterns in the given scenarios.

This study does not include the effect of smoke production on visibility and tenability. The analysis will focus solely on sprinkler activation and will not directly investigate how smoke production influences visibility or occupant safety. Furthermore, a conservative assessment of sprinkler activation will be ensured by considering the use of non-mechanical vents in the evaluation.

3. Results and Discussions

3.1 Fire Located at the Center of Atrium

The results obtained from FDS offer a comprehensive understanding of the fire dynamics, including the temperature of the sprinkler, plume, average flame temperature, and the temperature of the plume in close proximity to the flame. Additionally, the study investigates the impact of grid size on the FDS results, recognizing that varying grid sizes can influence the accuracy and reliability of temperature measurements. By considering these factors, the study provides insights into the importance of selecting an appropriate grid size in FDS simulations for the accurate assessment of fire behavior and sprinkler activation in atriums spaces.

Figure 7, and Figure 8 clearly illustrate that the fire plumes do not come into contact with the sprinklers. The absence of contact between the fire plumes and the sprinklers implies that the sprinklers will not be activated by the heat generated by the fire.

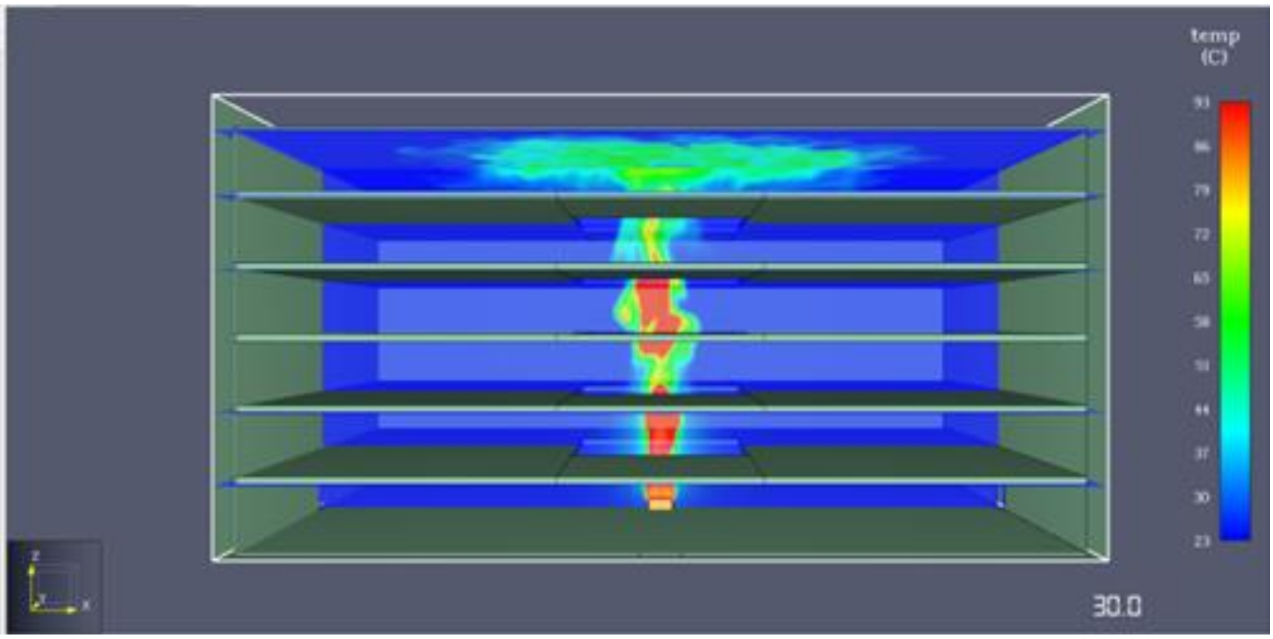

Fig. 7. 2D temperature slice view of fire at 30 seconds

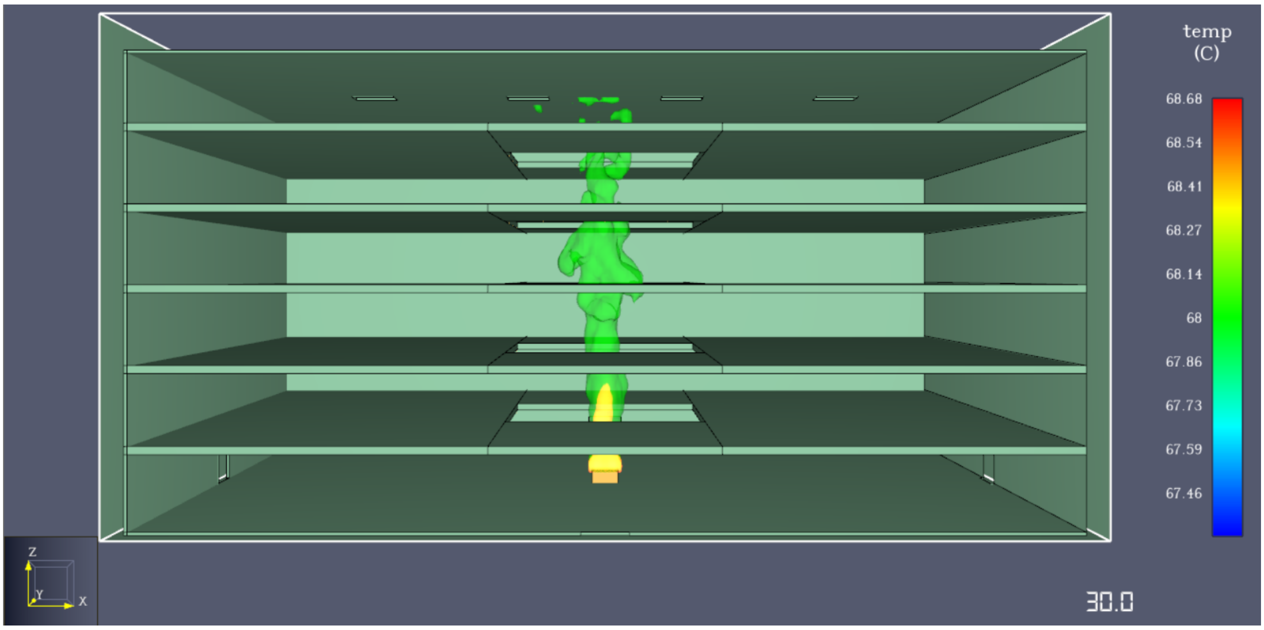

Fig. 8. Isosurface view of 68°C temperature at 30 seconds

The results presented in Table 4 provide valuable insights that none of the sprinklers in the simulated atrium reach a temperature significantly higher than the ambient temperature. This implies that the sprinklers are not activated during the fire event, as their temperature rating is set at 68.33 °C.

Table 4
FDS grid resolution comparison (fire at the center)

Grid size	Sprinkler S1 (Level 5)	Sprinkler S2 (Level 5)	Sprinkler S3 (Level 5)
0.3 m grid size	23.22 °C	23.36 °C	23.12 °C
0.4 m grid size	23.61 °C	23.67 °C	23.68 °C
0.5 m grid size	23.85 °C	23.80 °C	23.82 °C

Furthermore, it can be observed that as the grid resolution increases, meaning that the grid becomes finer and more detailed, the maximum temperature reached by the sprinkler decreases. This behavior can be attributed to FDS adopting an implicit filter that relates to the grid size.

The results also show that the vent location and arrangement will not significantly impact sprinkler activation, as the maximum temperature achieved is less than 1 degree Celsius from time zero. Even if the vents were located away from the fire plume, the increase in temperature would not have a significant effect unless the initial result shows a significant increase in temperature, especially if it is relatively close to the sprinkler activation temperature.

3.2 Edge of the Fire Base Is Located 1.0 Meter from the Sprinkler

Based on Figure 9, it appears that the fire plume in the simulated atrium has made contact with the level 3, 4, and 5 west sprinklers, indicating that these sprinklers are exposed to higher temperatures compared to the level 1 and 2 sprinklers. However, despite the increased temperature exposure, the sprinklers' temperatures are still significantly below their activation temperature.

This finding suggests that the fire conditions in the atrium, as simulated in this study, do not generate enough heat to activate the sprinkler system, even when the fire plume directly interacts with certain sprinklers. The temperatures recorded at the sprinklers are far below their activation temperature, indicating that the fire does not pose a sufficient threat to trigger the sprinkler system.

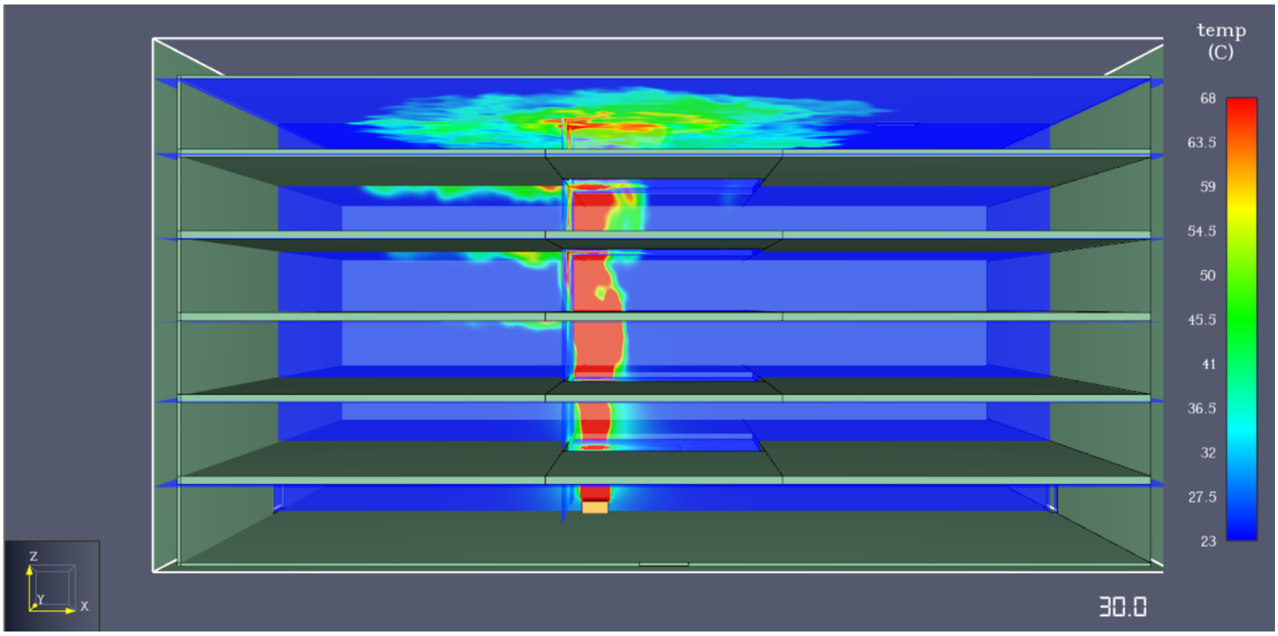

Fig. 9. 2D temperature slice view of fire at 30 seconds (0.3 m grid x 1.0 m distance from sprinkler)

3.3 Edge of the Fire Base Located Below (0 m) the Sprinkler

A series of simulations were performed using four grid sizes to determine the highest temperature the West 2 (W2) sprinkler could achieve and if it could activate at its rated temperature. The simulations included grid sizes of 0.25m, 0.30 m, 0.40 m, and 0.50 m. These values were based on a D*/dx ratio ranging from 4 to 16. The results comparing the sprinkler temperature of each grid are shown in Table 5.

Table 5
FDS grid resolution comparison (fire located below the sprinkler)

Sprinkler location	Maximum sprinkler temperature			
	0.25 m grid size	0.30 m grid size	0.40 m grid size	0.50 m grid size
Sprinkler W2 Level 1	50.44 °C	46.70 °C	57.57 °C	68.33 °C
Sprinkler W2 Level 2	55.70 °C	47.65 °C	49.50 °C	51.58 °C
Sprinkler W2 Level 3	42.05 °C	41.68 °C	44.02 °C	42.30 °C
Sprinkler W2 Level 4	36.51 °C	37.32 °C	37.46 °C	35.44 °C
Sprinkler W2 Level 5	32.03 °C	32.61 °C	33.41 °C	31.65 °C

The simulation was run for the geometry of an atrium with the dimensions 59.50 m × 44.50 m × 30.0 m. There were 4 grid independence tests involved: the elements 0.50 m, 0.40 m, 0.30 m, and 0.25 m. The result for the maximum sprinkler temperature reached within 94 seconds of the simulation was represented in the graph and comparison between grid sizes. Figure 10 shows that there is a trend in the maximum sprinkler temperature as the grid size becomes smaller. Noticeably, all the sprinklers reach below 68 °C except for the 0.50m grid size.

The trend shows that the result is relatively stable at a 0.30m grid size, and the difference between temperatures is smaller compared to a large grid size. Hence, the result at 0.30m or a smaller grid was used to determine whether the sprinkler was activated.

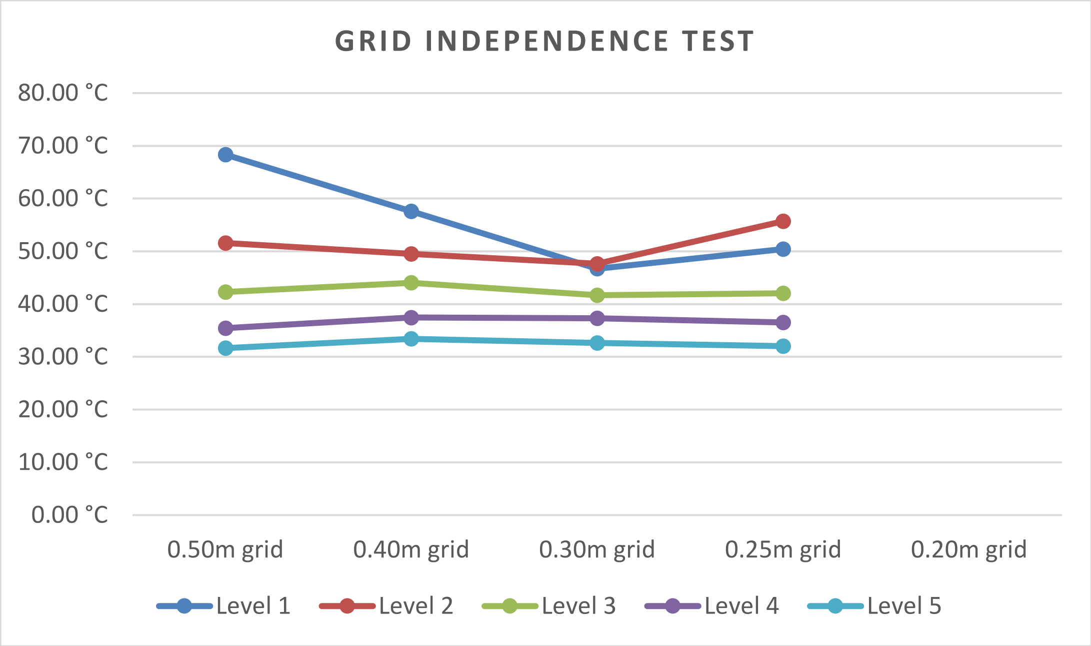

Fig. 10. Maximum sprinkler temperature vs grid size

The results demonstrate a correlation between the sprinkler temperature and the cell size (grid resolution). Specifically, as the grid size increases, the temperature recorded at the sprinkler location also increases.

According to Yeoh *et al.,* [16], there are three distinct regions of fire which are the persistent flame, a buoyant plume, and an intermittent flame. The varying behavior and characteristics of these fire regions can influence temperature distribution and the heat transfer processes within the computational domain.

With larger grid sizes, it's possible that the modeling of these fire regions becomes less refined, leading to a coarser representation of the heat release and heat transfer mechanisms. This coarser representation may result in higher sprinkler temperatures being predicted compared to simulations with smaller grid sizes, which can capture the detailed dynamics of the fire more accurately [17].

Although the level 1 sprinkler reaches 68.33 °C in 0.5 m grid size, however, it should be noted that the model used in the simulation is a very large eddy which is highly dependent on cell size to accurately solve the eddies and turbulence, especially in the flame region based on the work done by Mc Grattan *et al.,* [18]. Finer grid resolution allows for a better representation of the flame front. Smaller flame features, such as flame wrinkles, flame brush thickness, and flame propagation characteristics, can be captured more accurately. This leads to a more detailed and realistic representation of the flame structure. In addition, Finer grid resolution can capture the interaction between turbulence and the flame more accurately. The resolved small-scale turbulent structures influence the flame behavior, leading to changes in flame shape, wrinkling, and local flame speed. A finer grid size allows for better tracking of these interactions, leading to improved predictions of flame dynamics and flame stability.

Based on Figure 11 to Figure 13, it can be observed that from grid size 0.5 m to 0.3 m, the flame structure depicts a triangular shape pattern. In comparison, in a 0.1 m grid, the flame structure shows a more turbulent flow, and this is one of the main reasons that as the grid size decreases, the calculation is well resolved and depicts a more realistic flame structure.

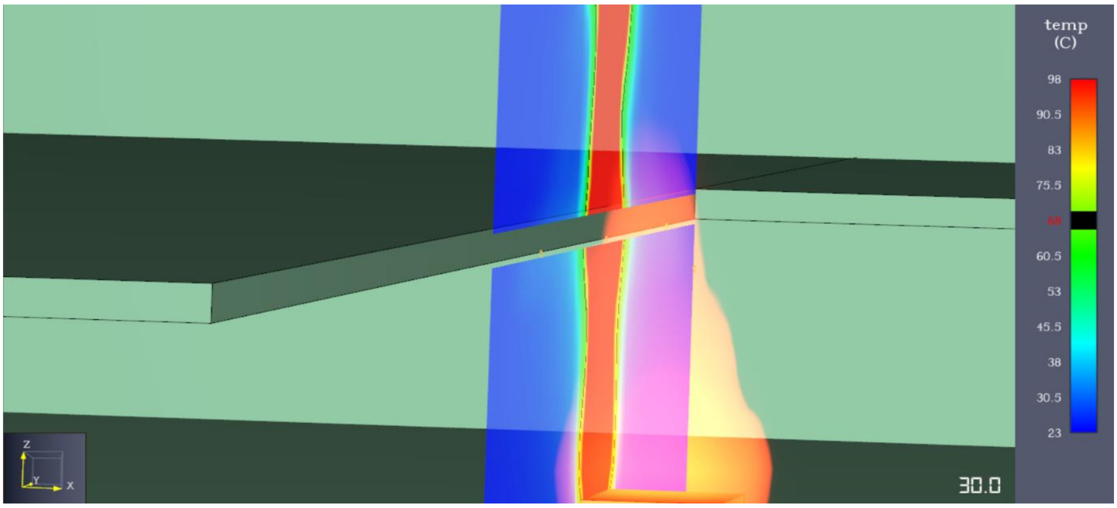

Fig. 11. Visible flame structure at 30.0 seconds (0.5 m grid size)

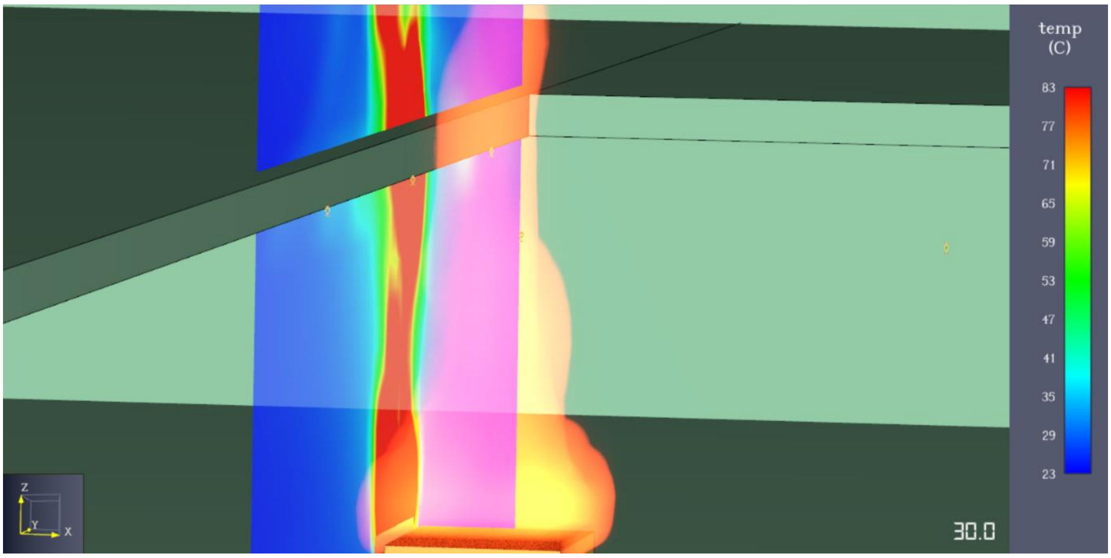

Fig. 12. Visible flame structure at 30.0 seconds (0.3 m grid size)

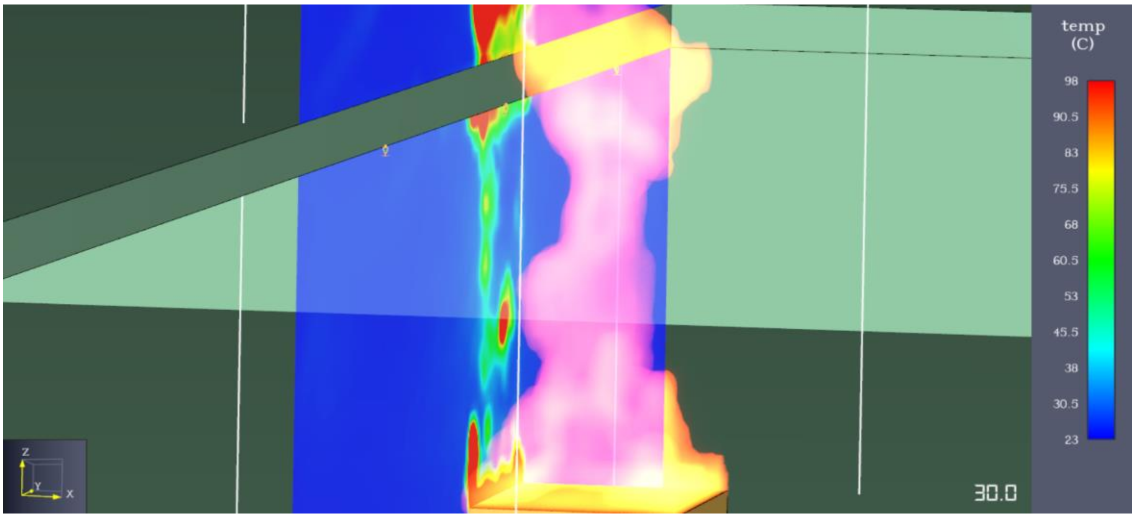

Fig. 13. Visible flame structure at 30.0 seconds (0.1 m grid size)

4. Conclusion

For this study, the researcher was able to determine whether the sidewall sprinkler installed on each level of the balcony in the atrium would activate or not for a given fire size and scenario. The three different fire models conducted for investigating the actuation of sidewall sprinklers in atriums yield valuable insights into the sprinkler activation time. The results obtained from the three different fire models consistently indicate that none of the sprinklers on the top level down to the 1st level will activate if the fire originates at the center of the atrium and the edge of the fire is located 1 meter away from the balcony where the sidewall sprinkler is positioned. This finding suggests that the use of sidewall sprinklers in each balcony level of the atrium could not activate. Hence, suppressing or controlling fires in such a scenario will be compromised.

Upon conducting the FDS analysis with a finer grid size, the results indicate that the temperature surrounding the level 1 W2 sprinkler did not reach its activation temperature rating. This suggests that the sprinkler may not activate as expected in the given fire scenario. These findings highlight the importance of using advanced simulation tools, such as FDS, to accurately assess the sprinkler activation time. It allows for a more detailed and comprehensive analysis of the fire dynamics, heat transfer, and sprinkler behavior within the atrium.

The study highlights the importance of using an FDS mesh resolution (D^*/dx) of 6 or finer when the sprinkler is located in close proximity to the flame or fire plume. This finer grid resolution is necessary to accurately measure the surrounding temperature and the temperature of the sprinkler itself. By employing a mesh resolution (D^*/dx) of 6 or finer, the simulation can capture the small-scale temperature gradients and variations near the sprinkler. This level of detail is crucial for assessing the heat transfer processes between the flame, the surrounding gases, and the sprinkler system. The finer grid resolution enables the simulation to better resolve the flow dynamics, convective heat transfer, and radiation effects near the sprinkler. This, in turn, provides more accurate predictions of the temperature distribution and allows for a more precise evaluation of the sprinkler's thermal response. It is important to note that selecting an appropriate grid size involves a trade-off between computational resources and accuracy.

5. Recommendation

Based on the result of the study, the installation of the sidewall sprinklers on each balcony level should be excluded or disregarded as they are unlikely to actuate even if the fire that was considered in the study is relatively higher than the typical design fire used in other research studies. Fire protection engineers should focus on determining whether ceiling sprinklers are required for atrium space, especially if the ceiling height is relatively low for a higher fire load.

Further investigations through actual fire experiments are recommended to assess the correlation between the results obtained from the fire models used in this study and the outcomes of physical fire experiments, especially in the scenario where the fire edge is located at a distance of 0 meters from the sprinkler. Such experiments would provide valuable validation and verification of the fire models' accuracy and reliability in real-world situations.

It is recommended to set the activation temperature slightly below the expected maximum ceiling temperature to ensure an early response; however, it is essential to consider these recommendations, along with local fire codes, regulations, and the specific characteristics of the atrium under consideration, when designing a sprinkler system.

In the future, a new study could be conducted to evaluate the performance of sidewall sprinklers in atrium spaces once radiation-activated sprinklers are fully developed.

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