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# NUMERICAL EVALUATION OF THERMAL AND SMOKE BEHAVIOUR IN A STACK-VENTILATED ATRIUM WITH DIFFERENT NATURAL VENTILATION OPENING CONFIGURATIONS

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**Abstract:** This study uses numerical simulations to evaluate the effects of architectural variables such as the location of natural ventilation openings and opening status on the temperature distribution and smoke density during a fire in buildings with an atrium. In scenarios modeled in different configurations, the fire starting point is defined at two locations, the ground floor room and the atrium floor, and only the location and open/closed status of the ventilation openings are considered variables. The findings reveal that when the top and side ventilations are open together, the stack effect works more effectively, smoke is concentrated at the upper floor levels, and contributes to the evacuation process. On the other hand, in scenarios with limited openings, smoke accumulation increased throughout the building, and absorption coefficient (κ) values reached levels that would negatively affect visibility. Thermocouple data also support this trend; temperature values increased on all floors when openings were limited, and temperatures remained lower on the lower floors in scenarios where openings were active. In conclusion, this study demonstrates the decisive role of positioning natural ventilation openings on the stack effect and fire safety.

**Keywords:** Atrium, Natural ventilation, Stack effect, Fire simulation, Smoke spread

**Farklı Doğal Havalandırma Açıklığı Konfigürasyonlarına Sahip, Baca Etkisiyle Havalandırılan Bir Atriumda Isıl ve Duman Davranışının Sayısal Olarak Değerlendirilmesi**

**Öz:** Bu çalışma, atrium içeren yapılarda doğal havalandırma açıklıklarının konumu ve açıklık durumu mimari değişkenlerinin, yangın sırasında sıcaklık dağılımı ve duman yoğunluğu üzerindeki etkilerini sayısal simülasyonlarla değerlendirmektedir. Farklı konfigürasyonlarda modellenen senaryolarda, yangın başlangıç noktası zemin kat odası ve atrium zemini olmak üzere iki farklı konumda tanımlanmış; yalnızca havalandırma açıklıklarının konumları ve açık/kapalı olma durumları değişken olarak ele alınmıştır. Elde edilen bulgular, üst ve yan havalandırma açıklıklarının birlikte açık olduğu durumlarda baca etkisinin daha etkin çalıştığını, dumanın üst kat seviyelerinde yoğunlaştığını ve tahliye sürecine katkı sağlandığını; alt katlarda ise görüş mesafesinin büyük ölçüde korunduğunu ortaya koymaktadır. Buna karşılık, açıklıkların sınırlı olduğu senaryolarda duman birikimi tüm yapı boyunca artmış, absorption coefficient (κ) değerleri kritik eşiklerin üzerine çıkarak görüş güvenliği açısından riskli koşullar oluşturmuştur. Termokupl verileri de bu eğilimi desteklemekte; açıklıkların sınırlı olduğu durumlarda sıcaklık değerleri tüm katlarda artarken, açıklıkların aktif olduğu senaryolarda alt katlarda sıcaklıkların daha düşük kaldığı gözlemlenmiştir. Sonuç olarak, bu çalışma doğal havalandırma açıklıklarının konumlandırılmasının baca etkisi ve yangın güvenliği üzerindeki belirleyici rolünü açık biçimde ortaya koymaktadır.

**Anahtar Kelimeler:** Atrium, Doğal havalandırma, Baca etkisi, Yangın simülasyonu, Duman yayılımı

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## 1. INTRODUCTION

Atriums are spatial areas that increase user comfort and provide visual-functional continuity by allowing uninterrupted natural light into the interior spaces of buildings. The natural air and light taken into the atrium from the horizontal and vertical areas where the building envelope establishes a relationship with the external environment increase indoor user comfort and reduce artificial lighting and air conditioning (Sharples and Lash, 2007; Rastegari et al., 2021). These aspects contribute to energy efficiency and become a part of sustainable building design (Saxena and Sharma, 2018).

The stack effect, which allows the warm air to rise naturally in atriums, is an important mechanism that passively supports the air flow inside the building (Kaviani and Zarandi, 2024). The stack effect is a natural convection process caused by the density difference between warm and cold air. When the air inside the atrium is heated by solar radiation or internal heat sources, it expands, decreases in density, and moves upwards. Instead of the warm air rising upwards, cooler and denser air enters from the outdoor openings at the lower levels, creating an indoor air cycle and providing natural ventilation (Heydari et al., 2023; Mijorski and Cammelli, 2016). As a result, atriums, which work with the stack effect, reduce energy consumption and offer sustainable air conditioning solutions by naturally providing air circulation in the building.

In buildings with atria, natural ventilation is primarily driven by wind effects and thermal buoyancy. In this context, cross ventilation occurs through horizontal airflow driven by the pressure difference between opposing openings. In contrast, stack-effect ventilation relies on the principle of expelling rising hot air through upper openings and drawing in fresh air from lower levels, driven by the temperature and density differences between the interior and exterior environments (Moosavi et al., 2014). Atriums, especially due to their vertical void geometries, are structures where the stack effect is pronounced, and natural air movement is supported through upper-level openings (Kaviani and Zarandi, 2024). Additionally, skylights, upper-level openings, wind towers, and architectural solutions that direct airflow at roof level are among the applications aimed at improving natural ventilation performance The effectiveness of these systems varies depending on parameters such as building geometry, atrium height, location and size of openings, balance between inlet and outlet areas, wind conditions, and differences between interior and exterior temperatures (Yetiş and Tuna Kayılı, 2024). Therefore, in atrium fires, natural ventilation should be considered not only as an energy-efficient environmental control strategy but also as a decisive fire safety parameter affecting smoke movement, visibility, and evacuation safety.

In addition to the beneficial components that atriums provide for sustainability, fire development, which is highly affected by natural air movements, should be integrated into the designs. Designed as high and uninterrupted vertical voids, atriums can cause smoke and hot gases to spread rapidly. This situation negatively affects the evacuation and intervention processes in the building in case of fire and poses a risk to life and property safety (Chow and Chow, 2005; Ivanov et al., 2021). The main physical and design parameters affecting the movement of natural air, smoke, and hot gases in atriums include atrium height, position of openings, indoor-outdoor temperature difference, roof slope, building geometry, material properties, and outdoor conditions. Increasing the height of the vertical voids increases the prominence of the stack effect and affects the movement of air and fire elements in the space (Xue et al., 2018; Strege and Ferreira, 2017; Sha and Qi, 2019).

In buildings with atria, the movement of smoke and flames, and the temperature distribution during a fire are significantly influenced by architectural and environmental parameters that determine the natural ventilation system (Chow and Chow, 2005). Studies have shown that atrium height, horizontal profile, roof shape, location and size of openings, and the indoor-outdoor temperature difference are decisive in determining the intensity of the stack effect, the formation of the smoke layer, and the vertical-horizontal spread of smoke (Krol, 2016; Sha et al., 2022; Krol and Krol, 2017). In these studies, it was observed that openings located at the upper level are effective in natural smoke extraction. It has been emphasized that the performance of facade or wall openings varies depending on the height of the opening, the opening ratio, and its relationship with other inlet and outlet openings (Chow and Li, 2010; Rafinazari and Hadjisophocleous, 2018; Yuen et al., 2019). Therefore, natural ventilation is considered not only as a passive element supplying air to the interior, but also as a fire safety component that directly affects the direction, stratification, and spread of smoke within the building during a fire (Mo et al., 2010). Furthermore, some studies have shown that the performance of natural air inlet and outlet openings can be better understood when evaluated together with mechanical smoke extraction systems; It is emphasized that factors such as the size of the fire, the buoyancy of the smoke, and the opening configuration directly affect the adequacy of natural systems (Montes et al., 2008; Montes et al., 2009; Wang et al., 2016; Xie et al., 2018).

The arrangement of openings in atriums is evaluated within the framework of the balance between air intake and exhaust openings. In particular, the ratios of the exit and intake areas, along with the compensatory air conditions, directly affect the stability of the smoke layer and visibility (Ding et al., 2004). While the location of fresh air intakes and exhaust openings directly affects air circulation, the level, direction, and distribution of openings in the structure are also decisive in determining the behavior of the smoke layer (Sha et al., 2022; Chow and Chow, 2005). In this context, it is stated that the relationship between the exhaust openings located at the upper level and the air intake openings arranged at the lower and side levels is critical in terms of the stability of the smoke layer and the visibility conditions at lower levels. Studies have shown that symmetrically placed openings provide a more stable smoke extraction performance, while improperly positioned openings can cause reverse flows, disruption of the smoke layer, and reduced extraction efficiency (Doheim et al., 2014, Lei et al., 2024). Similarly, it is reported that arranging the air intake openings at a specific height above the ground or positioning the flame tip at a specific distance contributes to maintaining the boundary between the smoke layer and the lower clean air zone (Ayala et al., 2018; Gutiérrez-Montez et al., 2010). Furthermore, controlling ventilation openings with motorized louvers or smoke dampers enhances the effectiveness of the smoke control strategy by allowing for the management of air inlet-outlet balance during a fire and the regulation of the direction and velocity of air entering the atrium (Yuen et al., 2019; Al-Waked et al., 2021; Rafinazari and Hadjisophocleous, 2018).

Analyses of the dimensional characteristics and mechanical capacity of mechanical smoke exhaust systems and natural air inlet-exit openings in the upper and lower zones of atriums reveal the determining effect of ventilation conditions on fire development. These studies examined how natural air openings affect the distribution of smoke in the structure and the evacuation process through vertical voids; they also evaluated the performance implications of designing these systems integrated with mechanical smoke exhaust systems. The findings show that natural ventilation systems can be sufficient in large-scale fires, but as the fire scale decreases, the buoyancy of the smoke becomes insufficient and therefore the need for mechanically assisted exhaust systems increases (Chow and Li, 2010; Mo et al, 2010). The smoke extraction efficiency of natural ventilation systems depends on the size of the fire and the opening configuration. Mechanical systems provide safety in small and low-energy fire scenarios more effectively, as they offer more predictable and controlled evacuation. Optimizing ventilation conditions during a fire directly affects the stability of the smoke layer, the maintenance of visibility and the safe evacuation process (Wang et al., 2016; Montes et al., 2008; Montes et al., 2009).

External environmental conditions are among the important factors affecting fire development and natural ventilation performance in atrium structures. Under conditions characterized by a sufficient indoor–outdoor temperature difference, inlet–outlet opening arrangement, and limited adverse wind effects, natural ventilation openings can contribute to reducing fire risks (Fakir et al., 2018; Li et al., 2022; Fan et al., 2023). However, controlling ventilation conditions becomes difficult when wind effects are present. It is noted that wind speeds exceeding 1 m/s can lead to irregular air currents in the vertical voids of the structure, causing smoke and hot gases to spread uncontrollably within the building. Numerical studies on fire safety have also shown that wind effects weaken natural smoke evacuation performance, reducing the predictability of outcomes (Krol, 2016; Meroney, 2011). Conversely, it has been shown that appropriate opening configurations and sufficient atrium height facilitate the redirection of hot smoke to the upper levels, while contributing to the maintenance of more favorable temperature and visibility conditions at the lower levels (Liu et al., 2021; Chen et al., 2010). Recent studies emphasize that natural ventilation offers significant advantages in limiting temperature rise but may not be sufficient on its own to control smoke dispersion in all cases. Therefore, it is stated that performance-based approaches that evaluate natural and mechanical systems together yield more reliable results (Ivanov et al., 2021; Li et al., 2022; Chen et al., 2019). In this context, natural ventilation parameters should be considered not only as an architectural preference but also as design variables that directly determine smoke behavior, evacuation efficiency, and temperature distribution.

The atrium shape (square, triangular, rectangular, etc.), shape, and height of the upper floor of the atrium are other parameters affecting fire development. In general, it has been observed that rectangular atriums with a significant difference between the short side and the long side are most effective in smoke extraction (Doheim et al., 2014; Al-Waked et al., 2021). In addition, the atrium roof design, which is flat and has a height above the building height, prolonged the accumulation time of smoke at the upper level and allowed successful evacuation at low levels (Yildiz and Beyhan, 2023).

Current studies have shown that natural ventilation strategies in atrium-based buildings have significant effects on smoke movement, smoke extraction, and temperature distribution during a fire. Previous research has investigated the effects of the location, opening dimensions and ratios, suction capacity, compensation air conditions, and system typology of natural and mechanical ventilation systems on smoke extraction and temperature distribution. However, studies that consider natural ventilation openings located on the upper surface and side facades of the atrium together with interior openings adjacent to the atrium, and comparatively evaluate scenarios where the fire initiation location varies between the atrium space and the adjacent space, are limited. Based on this gap, this study examines the effects of the location and opening condition variables of natural ventilation openings on temperature distribution, smoke density, and horizontal-vertical smoke spread in fire scenarios on a prototype atrium-based structure through numerical simulations. In this context, openings located on the upper surface and side facades of the atrium, as well as openings in interior spaces adjacent to the atrium, are evaluated under different scenarios; and the cases where the fire starts in the atrium space and in an adjacent interior space are compared. In this study, the atrium geometry and basic building design were kept constant, and the effects of natural ventilation opening strategies were compared in a vertical-void scenario where the stack effect was dominant.

## 2. MATERIALS - METHODS

Computational fluid dynamics (CFD) based computer simulations have become a reliable and widespread method for fire analysis and evaluation of smoke evacuation systems. By enabling the numerical solution of complex flow and heat transfer equations, CFD technology can examine in detail the time variation of smoke movement and temperature distributions, especially in three-dimensional structures. Since atriums are critical regarding smoke propagation, especially in the case of fire due to the stack effect of vertical volumes, the fire safety performance of such spaces is analyzed through FDS (Fire Dynamics Simulator) software (McGrattan et al., 2013).

This study created a prototype building model with an atrium on the side façade, and different ventilation opening scenarios were evaluated on this model. The model considers three main ventilation strategies: upper air outlets on the atrium ceiling, natural ventilation openings on the side façade, and interior ventilation openings in the rooms adjacent to the atrium. Numerical simulations were carried out by defining two different fire starting points: one in the atrium void and the other in a neighboring room on the ground. Within the scope of scenarios, the effects of different ventilation opening configurations on smoke density, temperature distribution, and smoke propagation direction during a fire were comparatively analyzed.

### 2.1. Prototype Building

The prototype building model has plan dimensions of 9.00 m (L) × 4.00 m (W) and a total building height of 12.00 m. Each floor height is 3.00 m, the building has four floors. The atrium is integrated into the side façade of the building and is a rectangular vertical volume with a floor area of 5.00 m (L) × 3.50 m (W). The atrium height is 14.00 m, 2.00 m above the building height. This height was chosen to facilitate the upward transport of smoke by increasing the stack effect (Yildiz and Beyhan, 2023; Yildiz and Beyhan, 2025). There are natural ventilation openings on the upper surface of the atrium and the side façade wall. Each of these openings is 2.00 m (L) and 1.00 m (W) high, and the window-to-wall ratio (WWR) is 15%. Generally, a 2-5% opening area is considered a minimum in smoke exhaust (Ab Ghani and Aripin, 2018). However, when the design is considered without mechanical smoke exhaust systems, the WWR should be increased to increase the effectiveness of the evacuation strategy based only on natural ventilation. This approach is in line with studies that have observed positive effects such as reducing smoke density and improving visibility by increasing the WWR (Wang et al., 2022; Fakir et al., 2018). There is one room on each floor adjacent to the atrium, and there are rectangular window openings of 2.00 m × 1.00 m on the outer walls of these rooms. This proportioning is based on the finding that openings with a significant difference between short and long sides optimise air flow (Yildiz and Beyhan, 2025) (Figure 1).


***Figure1:***
*(a) Prototype building schematic plan (b) schematic section*

The prototype model created in this study is not intended to represent all architectural, climatic, and functional characteristics of a specific real structure. The model is defined as an idealized reference configuration to isolate and compare the effects of variables such as the location and open/closed status of natural ventilation openings on smoke behavior during a fire. Therefore, the prevailing wind direction, local climate data, building use scenario, material variety, and differences in opening height were kept constant at this stage. In this way, changes in smoke density, temperature distribution, and horizontal–vertical smoke dispersion could be monitored directly depending on the opening configuration. The atrium height and the dimensions of the upper and side openings were selected to establish a reference arrangement that supports the stack effect and enables a comparable evaluation of natural smoke evacuation performance. The main reason for selecting a stack-effect-based natural ventilation mechanism in this study is that atriums, as high and uninterrupted vertical spaces, create a flow environment that strongly supports the upward movement of hot smoke. For this reason, the study was not structured as a comparison of different atrium ventilation systems, but as a parametric evaluation of opening configurations under a stack-ventilated reference model in which buoyancy-driven upward flow is dominant.

### 2.2. Computational Model

In performance-based fire safety designs, the T-squared fire model ($t^2$ fire) is often used to describe fire growth. This model assumes that the heat release rate increases proportionally to the square of time during the growth phase of a fire. The T-squared fire model provides a simplified but adequate representation of the fire growth process from an engineering point of view, allowing many parameters such as heat flux, smoke temperature, smoke layer thickness, smoke flow rate and thermal effect on building materials to be predicted by CFD-based analyses (Karlsson and Quintiere, 2000; Hurley et al., 2016). Mathematically, this relationship is expressed by the following equation:

$$Q = a * t^2 \qquad (1)$$

Q: Heat release rate
α: Fire growth coefficient
t: Time

The coefficient α in this equation is the parameter that determines the fire growth rate and is defined according to four different fire growth classes as slow (0.00293 kW/s²), medium (0.01172 kW/s²), fast (0.0469 kW/s²) and ultra-fast (0.1876 kW/s²) (NFPA, 2021; Hurley et al., 2016). According to NFPA 92: Standard for Smoke Control Systems, the reference heat release rate is taken as 1055 kW (NFPA, 2021). The study preferred the fast growth fire model as the design fire scenario. This choice assumes that the fire can develop quickly due to the high load of flammable materials and the stack effect accelerating the spread of smoke and heat in high-volume spaces surrounded by vertical openings, such as an atrium. In the rapid growth scenario, the reference heat release rate is reached in 150 seconds due to the calculation of the fire at the reference heat release rate of 1055 kW and the rapid fire growth coefficient α = 0.0469 kW/s² in Equation 1.

The fire load, which is differentiated according to the scenarios and positioned on the atrium floor and ground floor, is modelled as a defined reaction source with dimensions of 100 × 100 cm. For this source, polyurethane GM27, a polymer with a well-defined chemical composition frequently used in literature fire simulations, was selected. The chemical composition of this material is approximately 60% carbon (C), 10% hydrogen (H), 18% oxygen (O), and 12% nitrogen (N). It can produce high amounts of heat and toxic gases during a fire. The smoke production rate for GM27 material was taken as 0.198 g/g, and the carbon monoxide (CO) production rate as 0.042 g/g (Hurley et al., 2016). All thermophysical properties for the design fire are presented in Table 1.

**Table 1. Fire features**

| Feature | Value |
|---|---|
| Fire type | Flaming fire |
| Reaction type | Polyurethane GM27 |
| Fire growth | $t^2$ fire |
| Duman production üretimi | 0.198 g/g |
| CO production | 0.042 g/g |
| Heat release rate | 1055 kW |
| Fire growth coefficient | 0.047 |
| Simulation time | 150 s |

Fire analyses were performed using FDS v6.9.1, a CFD-based open source software. FDS analyses mass, momentum, energy, turbulence, and pressure balances based on the Navier-Stokes equations. Large Eddy Simulation (LES) method is applied in the simulations, which directly analyses large-scale turbulence structures, while modelling minor turbulence and calculating them by assuming equilibrium (McGrattan et al., 2013). This way, variables such as fire development, temperature distribution, smoke movement, and optical density can be modelled in high resolution depending on time and space. Smokeview (SMV) v6.9.1 software was used for three-dimensional visual presentation of FDS outputs. Smokeview allows visual analysis of temperature contours, smoke trails, velocity vectors, and sensor data. Due to the text-based command system of FDS, PyroSim 2023 interface software was used for geometric modelling, defining boundary conditions, and placing measurement devices. PyroSim is fully compatible with FDS and provides easy modelling in geometry creation, zoning, and scenario combination generation processes thanks to its user-friendly graphical interface.

For the properties of the spatial domain to be calculated in the fire model, the mesh dimensions were first determined. In CFD-based fire simulations, the correct determination of the mesh (cell network) size, which determines the limitations for the preparation of the three-dimensional model, is critical in terms of the accuracy of the computation time and the numerical solution. The selection of the appropriate cell size in FDS directly affects the modelling of smoke propagation, temperature distribution, and air movements realistically and stably. For this reason, the characteristic smoke/flame column diameter (D*) was calculated as a basis for mesh optimisation. This size represents the characteristic size of the fire and is calculated by the following relation (McGrattan et al., 2013):

$$D* = [(Q) / (\rho\infty \cdot cp \cdot T\infty \cdot g)]^{2/5} \tag{2}$$

$Q$ = Heat release rate (kW),
$\rho_\infty$= Ambient air density (kg/m³),
$c_p$ = Specific heat of air (kJ/kg·K),
$T_\infty$= Ambient temperature (K),
$g$ = Acceleration of gravity (m/s²)

This study's characteristic plume diameter calculation and other thermodynamic evaluations related to fire modelling are based on an ambient temperature of 10 °C (283 K). The heat release rate was 1055 kW, air density as 1.2 kg/m³, specific heat capacity as 1.0 kJ/kg-K, and gravitational acceleration as 9.81 m/s². These constants are based on standard values widely used in the FDS technical reference and fire engineering literature (McGrattan et al., 2013; Hurley et al., 2016). As a result of the calculation, these values resulted in the characteristic plume diameter being approximately $D*$=0.997 m. This size is an important criterion for evaluating the accuracy of the cell size used in the FDS, and it is recommended that a resolution of at least 10 cells in the plume region be provided. The cell size of 10 cm (0.10 m) edge length used in this study provided the resolution standard due to the calculations.

Within the scope of the simulation, three virtual thermocouple devices were defined in the rooms adjacent to the atrium to monitor temperature distribution during fire development. The measuring bead diameter was defined as 1.0 mm, emissivity value as 0.85, density as 8908 kg/m³, and specific heat capacity as 0.44 kJ/(kg-K). In order to monitor and analyze the fire development during the simulation, three planar slices were defined in the FDS environment. These slices provide visualization of the gas phase variables in a given plane, allowing the temperature distribution and smoke movement to be monitored over time (Figure 2).

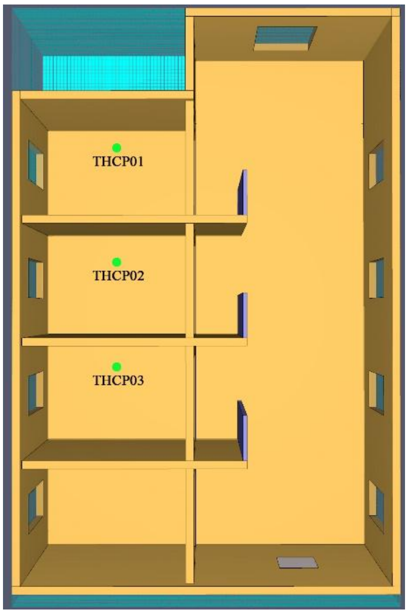



***Figure 2:***
*Numerical model spatial domain*

Within the scope of the study, a total of 8 scenarios were created by considering two different fire starting points and three different ventilation opening combinations to evaluate fire development, smoke movement and temperature distribution (Table 2). These scenarios were designed to analyze the effect of the presence of natural ventilation openings in the atrium ceiling and side façade and in the rooms adjacent to the atrium, and the effect of two different fire starting points, the atrium floor and the ground floor room, on fire dynamics. Thus, the effect of the location of the fire and the spatial diversity of the openings on the stack effect and smoke propagation in the building with atrium is analyzed. A schematic illustration of the stack-effect-driven airflow mechanism used in the prototype atrium is also presented in Figure 3. The figure shows the direction of incoming cool air through the side and room openings, the upward buoyancy-driven movement of heated smoke within the atrium void, and its exhaust through the upper opening. The atrium shape, building dimensions, floor heights, and opening sizes were kept constant, creating a reference configuration in which the stack effect dominates the vertical space. Only the opening configurations defining the natural ventilation strategy and the location of the fire's initiation were considered as variables on this reference model. In this context, openings on the upper surface of the atrium, side-facade openings, and interior openings adjacent to the atrium were simulated in different combinations, and the cases of fire initiation in the atrium and in an adjacent volume were compared. Thus, the study aimed to evaluate the effects of different ventilation strategies on smoke density, smoke spread, and temperature distribution in isolation under the same atrium geometry.

**Table 2. Fire Scenarios**

| Scenario | Ventilation gap | | | |
|---|---|---|---|---|
| | fire location | atria ceiling | side surface of atrium | room |
| S1 | Atria | Opened | Opened | Opened |
| S2 | Atria | Opened | Closed | Opened |
| S3 | Atria | Opened | Closed | Closed |
| S4 | Atria | Opened | Opened | Closed |
| S5 | Room | Opened | Opened | Opened |
| S6 | Room | Opened | Closed | Opened |
| S7 | Room | Opened | Closed | Closed |
| S8 | Room | Opened | Opened | Closed |

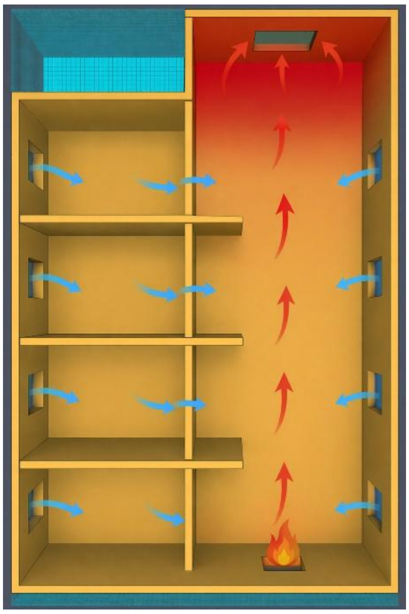


**Figure 3.**
*A schematic illustration of the stack-effect-driven airflow mechanism*

## 3. FINDINGS

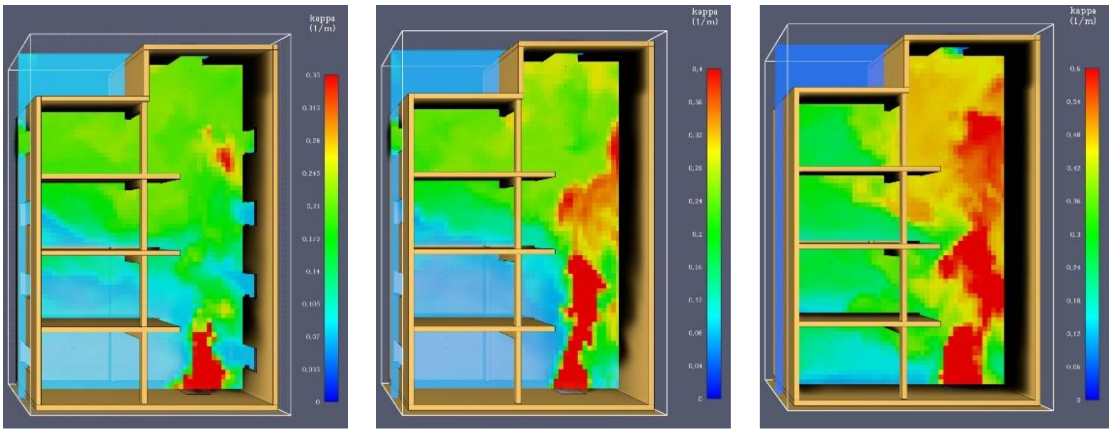
The absorption coefficient (κ) distributions were analyzed in the simulations in order to evaluate the effect of ventilation openings at different locations associated with the atrium on smoke propagation and visibility during a fire. The absorption coefficient (κ) was used as an indicator of smoke density and visibility. In general, higher κ values correspond to poorer visibility and more critical evacuation conditions, whereas lower κ values indicate more tenable visual conditions. This coefficient expresses the extent to which smoke absorbs light and its unit is 1/m. An increase in the value indicates an increase in smoke density and a decrease in visibility. When $\kappa > 0.30$, the smoke level is dense and visibility drops below 5 meters. In contrast, when $\kappa < 0.12$, the air is relatively clean and visibility exceeds 10 meters. Thus, in the simulations, the smoke distribution and visibility can be numerically compared based on the value of κ (Table 3).

**Table 3. Absorption coefficient in relation to smoke density and visibility**

| Value (1/m) | Meaning | Approximate Visibility |
|---|---|---|
| 0.00 – 0.05 | Clear air | > 30 meters |
| 0.10 – 0.15 | Light smoke | 10–20 meters |
| 0.20 – 0.30 | Moderate smoke | 5–10 meters |
| > 0.30 | Heavy smoke (danger) | < 3–5 meters (critical visibility) |

When the absorption coefficient distributions obtained from the eight scenarios in Figure 4 are analyzed, the highest κ value was recorded in scenario S7 with 0.95, and the lowest was recorded in scenario S1 with 0.35. In the first four scenarios where the fire starting point was the atrium floor, dense smoke accumulation and low visibility were detected in this area. In the S1 scenario, the κ ranges in the rooms were between 0.05-0.10 on the lower floors and 0.14-0.20 on the upper floors, and this scenario was generally below the risky levels. In the S2 scenario, the κ value was 0.16-0.24 on the third floor, and medium density smoke was observed. In the S3 scenario, κ values exceeded 0.30, especially on the upper floors, and reached a high risk level. In the S4 scenario, the smoke intensity decreased from the ground floor to the upper floor, and a low risk level was determined with light smoke (κ = 0.12-0.20) in the third-floor room.

In scenarios S5-S8, where the fire started on the ground floor, dense smoke (κ > 0.30) and low visibility (< 5 m) were observed in the ground floor room. In the S5 scenario, the κ value increased as the upper floors increased, and medium-density smoke was observed on the third floor. In scenario S6, the atrium floor has a high risk with κ = 0.20-0.45, and the values increase on the upper floors. In scenario S7, one of the most critical scenarios, the κ value reached up to 0.95, and medium density smoke (κ = 0.15-0.30) was detected on the upper floors. In the S8 scenario, κ = 0.05-0.13 at the human height level in the atrium, and a low-risk environment was provided with values of 0.13-0.20 in the rooms.



S1 S2 S3

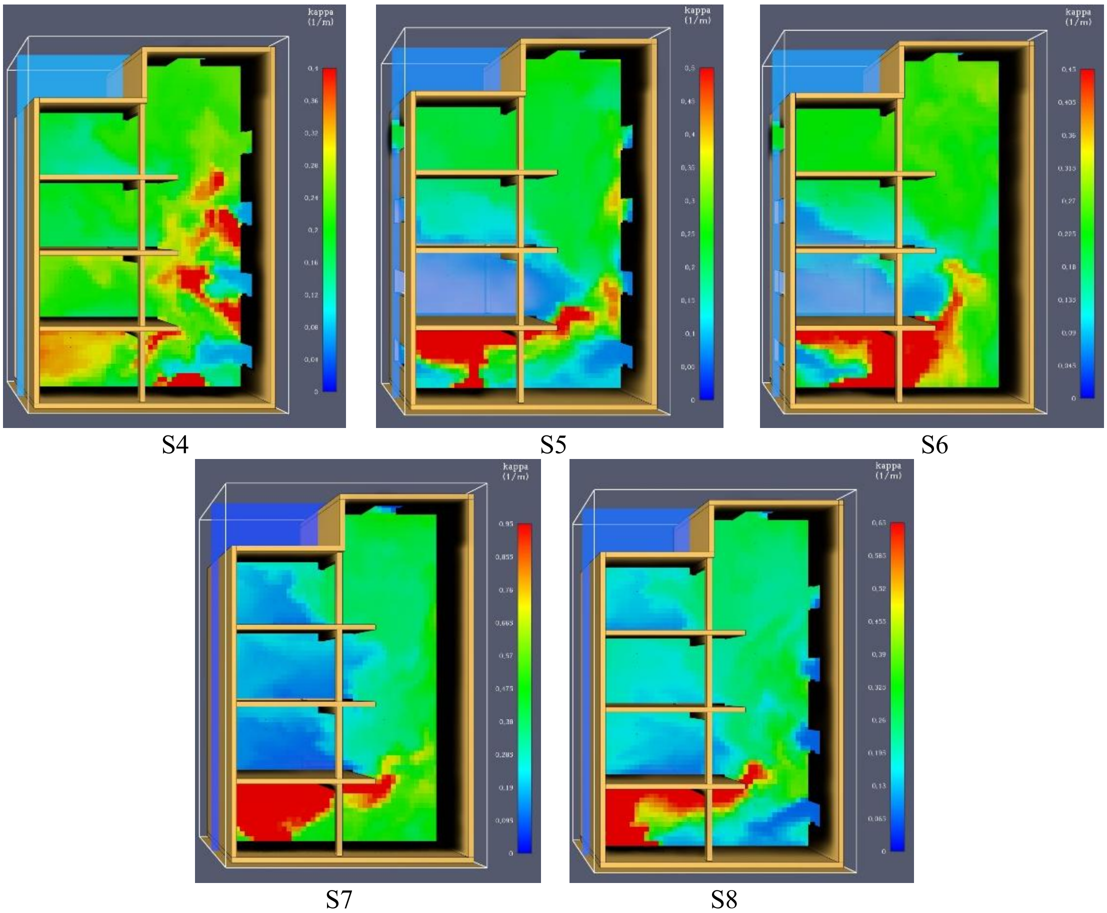



***Figure 4:***
*Absorption coefficient of 150 seconds of simulations*

Temperature data recorded by the virtual thermocouple devices (THCP) defined in the FDS model and located in the rooms on the first, second, and third floors were analysed to evaluate the effect of the stack effect on vertical temperature distribution. The temperature–time history predicted at the third-floor virtual thermocouple (THCP01) for each scenario is presented in Figure 5. According to the analyses, the scenarios in which both the atrium ceiling and the side surface were open (S4 and S8) yielded the lowest temperature levels, regardless of the fire starting point. This result indicates that the simultaneous presence of the upper and side openings promoted a more effective stack-driven upward airflow in the atrium, facilitating the removal of heat and smoke through the upper outlet. On the other hand, in scenario S3, where the fire started in the atrium, and only the ventilation on the atrium ceiling was open, the maximum temperature was recorded as 39.40 °C, and the highest temperature value was reached among all scenarios. This suggests that restricting lateral air exchange weakened overall smoke exhaust performance and caused hot smoke to remain longer in the atrium, thereby increasing heat accumulation on the upper floor. However, in the S7 scenario, where the fire starting point was the ground-floor room and had the same ventilation openings as S3, the temperature only increased to 23.43 °C, and the atrium's stack effect was again demonstrated.

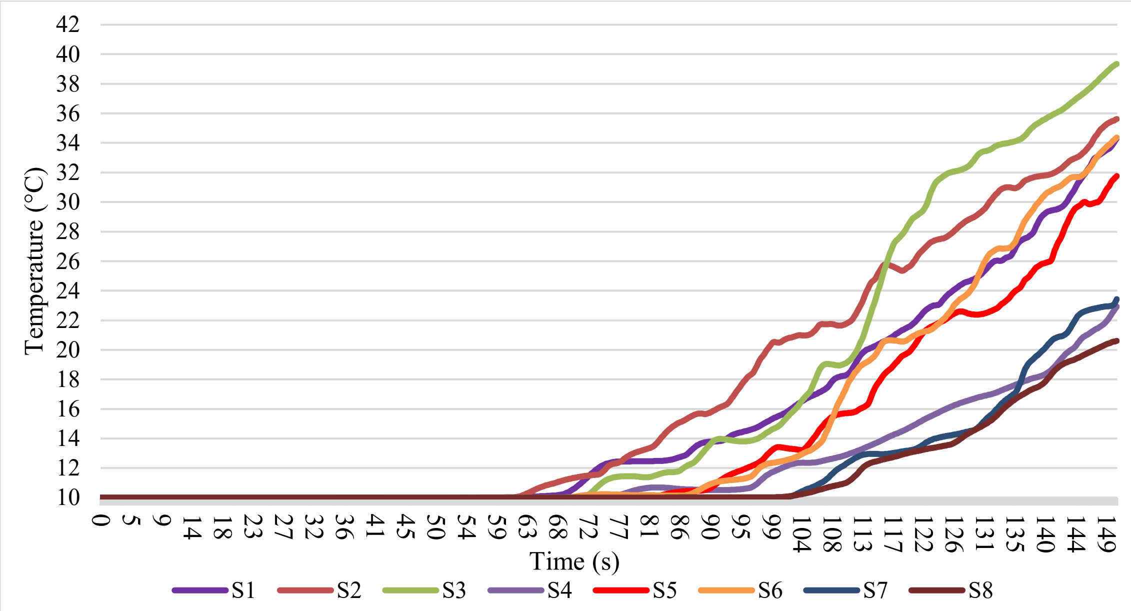



***Figure 5:***
*Temperature-time curves of THCP01 sensor in the third floor room*

The temperature–time histories predicted at the second-floor virtual thermocouple (THCP02), defined in the FDS model, are presented in Figure 6 for each scenario throughout the simulation period. Similar to the results obtained for the third floor, the highest temperature on the second floor was predicted in scenario S3, reaching 41.74 °C. This result indicates that when only the atrium ceiling opening remained active, and both the side façade and room openings were closed, the stack-driven airflow became less effective in removing heat and smoke from the atrium, leading to greater thermal accumulation at the intermediate level. In the remaining scenarios, the temperature-rise curves followed similar trends, and the maximum temperatures remained within the range of 20–26 °C. The relatively lower temperatures observed in these scenarios suggest that opening configurations improved the upward transport of hot smoke and supported more effective smoke exhaust through the upper opening. In addition, in scenario S4, which differs from S3 only in terms of the atrium side-wall opening, the predicted temperature exceeded the ambient temperature of 10 °C earlier, from the 55th second onward, compared with the other scenarios.

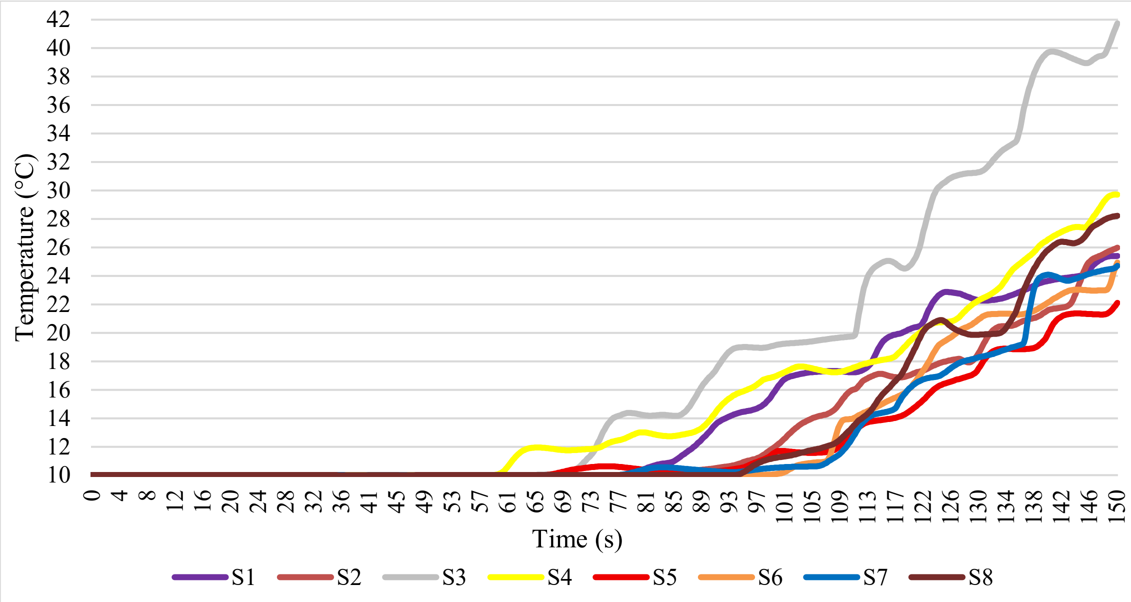



***Figure 6:***
*Temperature-time curves of THCP02 sensor in the second floor room*

The temperature–time histories predicted at the first-floor virtual thermocouple (THCP03), defined in the FDS model, are presented in Figure 7 for each scenario throughout the simulation period. Consistent with the trend observed on the second floor, the highest temperatures on the first floor were predicted in scenarios S3 and S4, reaching 39.03 °C and 37.32 °C, respectively. In contrast, in scenario S5, where the fire originated in the ground-floor room and all ventilation openings were active, the predicted temperature curve remained close to the ambient temperature, indicating the lowest thermal impact on the first floor. This suggests that the fully open configuration promoted a more stable stack-driven airflow path, allowing heat and smoke to move upward more effectively within the atrium and reducing thermal build-up at the lower floor level. A similar trend was observed in scenario S6, in which only the atrium side opening was closed; in this case, the maximum predicted temperature reached 12.01 °C. Unlike the second- and third-floor results, the temperature response at the first-floor virtual thermocouple (THCP03) did not show a fully consistent pattern in relation to the stack effect, except for the clearly lower values observed in S5. This suggests that, given THCP03's location on the lower level and close to the fire source, the thermal response may have been influenced not only by upward flow due to the stack effect but also by local heat accumulation.

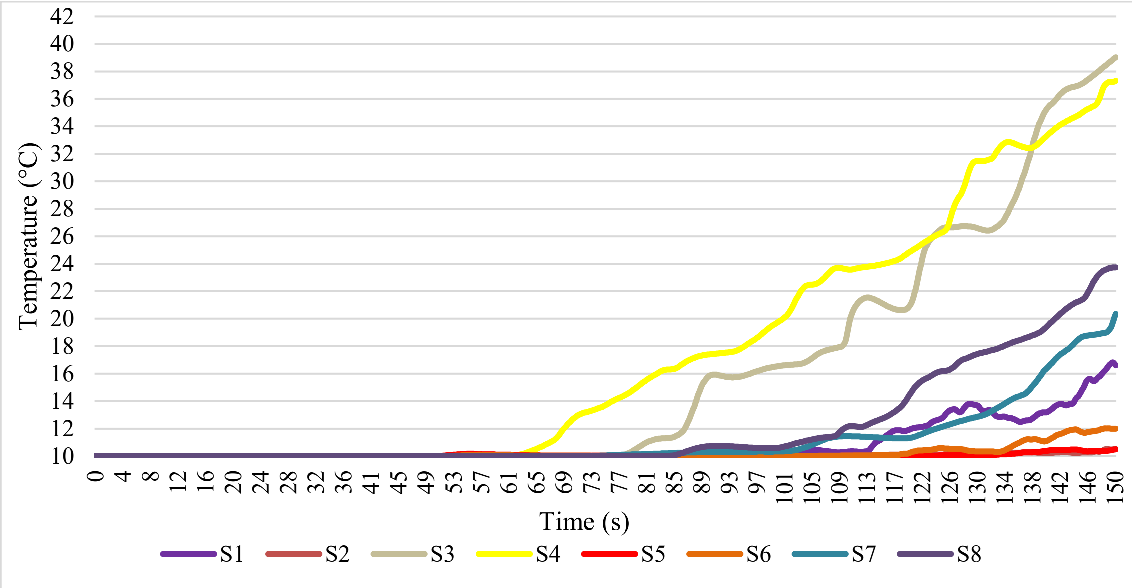



***Figure 7:***
*Temperature-time curves of THCP03 sensor in the first floor room*

## 4. CONCLUSION

This study was carried out to determine the effects of the location and opening status of natural ventilation openings, on smoke propagation and temperature distribution during a fire in buildings with atriums. The fire starting point was fixed to be at ground level only; the openings' location and opening status varied according to the scenarios. The starting location of the fire at different points on the ground floor level affected the severity of the stack effect, temperature profiles on the upper floors and smoke distribution. Analyses based on the absorption coefficient (κ), which is the light absorption coefficient of smoke, quantitatively revealed the visibility and smoke density; it was observed that visibility was significantly reduced in scenarios where κ exceeded 0.30, whereas in scenarios where κ was below 0.12, the environment was at a level that could be considered safe. In particular, κ = 0.95 was reached in scenario S7, which is a strong example of the dangerous consequences of inadequate ventilation openings. In contrast, scenarios S1 and S8 reached the lowest κ levels with configurations where both openings (top and side) were open, confirming the importance of adequate natural ventilation.

Temperature analysis based on thermocouple measurements quantitatively demonstrated how the stack effect varies with the location of the fire start and the arrangement of openings. Scenario S3, which started in the atrium and had limited openings, recorded the highest temperatures on all floors (e.g., 39.40 °C on the third floor). In scenario S7, with the same arrangement of openings but with the fire starting in the room, the temperature reached only 23.43 °C. This shows that the stack effect is activated more strongly when it starts in the atrium space. In scenario S5, where all ventilations were open, the first floor, where the temperature increase was the lowest, was protected by the upward effect of the natural air flow. When the temperature data and absorption coefficient results are analyzed together, it is observed that when the ventilations are open, the smoke rises more controlled and concentrates on the upper floors. In this context, passive ventilation is an effective method in fire safety.

All the findings reveal that natural ventilation openings should be optimized spatially and numerically to ensure fire safety in buildings with atriums. When the parameters of temperature distribution, stack effect, and smoke propagation are evaluated together, it is seen that the openings should not only be numerous but also integrated into strategic surfaces (especially upper ceilings and side facades). Systematic propagation behaviors, which are much more critical than the local effects of fire, have shown in this study how natural ventilation can play a decisive role. However, the contribution of opening proportions and the height of the openings to the stack effect does not show a linear relationship; it varies depending on the geometric and physical conditions of the design. Therefore, combinations of structural form, volume, and openings should be considered together in fire scenario planning.

This study show that the location and combination of natural ventilation openings in atrium are decisive for smoke dispersion and temperature distribution. The more controlled upward movement of smoke in scenarios where upper openings are effective and supported by side openings is consistent with studies highlighting the importance of upper atrium openings for natural smoke extraction (Chow & Li, 2010; Sha et al., 2022). Similarly, in parallel with research showing that opening performance is determined not by the presence of a single opening, but by its height, ratio, and relationship with other openings, this study revealed significant performance differences between scenarios when upper openings, side openings, and room-specific openings were evaluated together (Rafinazari & Hadjisophocleous, 2018; Yuen et al., 2019). The fact that higher temperatures and smoke densities occur on the floors when the fire starts inside the atrium and openings are limited aligns with studies showing that atrium geometry and opening arrangement enhance the stack effect and increase vertical smoke convection (Doheim et al., 2014; Al-Waked et al., 2021; Liu et al., 2021). On the other hand, the fact that natural ventilation is not equally effective in every scenario and that smoke evacuation performance is strongly dependent on the opening design in some cases supports the results of studies suggesting a combined evaluation of natural and mechanical systems (Mo et al., 2011; Wang et al., 2016; Ivanov et al., 2021). In this context, the contribution of this study is that it considers the atrium top opening, the side facade opening, and the openings of rooms adjacent to the atrium together under the same prototype geometry and designs the fire starting location as a variable. Thus, the study demonstrates that natural ventilation parameters should be evaluated alongside the relationships among openings, the location of fire initiation, and the behavior of vertical openings; in this respect, it offers an analytical contribution to performance-based fire safety design.

The findings of this study reveal the effects of the location and configuration of natural ventilation openings on smoke dispersion and temperature distribution through a controlled prototype model. However, parameters affecting real building behavior, such as prevailing wind direction, local environmental conditions, building use type, material properties, interior elements, and varying opening heights, were not included in the model. This choice provides a methodological simplification by isolating the effect of opening configurations, but necessitates evaluating the results as comparative trends within a specific design space. In future studies, considering the effects of varying opening heights, wind conditions, and natural-mechanical hybrid systems together will contribute to the performance-based evaluation of smoke behavior in atrium fires.

## CONFLICT OF INTEREST

The author confirms that there is no known conflict of interest or common interest with any institution/organization or person.

## AUTHOR CONTRIBUTION

Mehmet Akif Yıldız: Literature Review, Conceptualization and Design, Investigation, Writing, Visualization, and Editing.

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