

# Performance Evaluation of Smoke Control and Ventilation Systems in Large Spaces

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## Abstract

The smoke control and ventilation system is critical in ensuring that the occupants are safe in the event of fire in complicated spatial composition. Such systems, be it natural, mechanical, or hybrid, have a decisive effect on the maintenance of the quality of ambient air, control the development of smoke, and allow systematized evacuation. The research paper critically examines the effectiveness of various smoke management and ventilation systems applied in risky and large-scale spaces, including tunnels, atria and industrial plants. The study uses a synergistic method that integrates computational fluid dynamics (CFD) simulation, controlled hot smoke experiments, and empirical data collection to determine the relative performance of different smoke mitigation methods which are natural ventilation, mechanical exhaust, and hybrid forms. The results explain the performance determinants that are critical including airflow, smoke extraction efficiency, system reliability and energy used. In addition, the research presents design proposals that should be used to maximise smoke suppression within such large areas taking into consideration building typologies, the nature of fire and the current safety standards. Together, the discussed insights add to the comprehension of how to increase the safety and operational efficiency of smoke control and ventilation systems, thus promoting the fire protection practices on a large architectural level.

**Keywords:** *Smoke Control, Ventilation Systems, Performance Evaluation, Large Spaces, Computational Fluid Dynamics (CFD), Fire Safety, Natural Ventilation, Mechanical Exhaust, Hybrid Ventilation, Fire Protection Engineering, Tunnel Ventilation, Atrium Smoke Control, Industrial Space Ventilation, Building Safety Standards.*

## I. INTRODUCTION

The safety of the occupants in large spatial domains in a fire emergency is one of the most important issues, in which the infrastructure of smoke control and ventilation is essential to ensure the safety of the occupants. These infrastructures are designed to control the movement of smoke and dangerous gases, allow the clear egress of those who are evacuating, and allow the safe and efficient functioning of firefighting personnel. The complexity of smoke control in large buildings (tunnels, high-rise buildings, airports, industry, etc.) has spawned a focussed research and development effort in the field of fire protection engineering.

Under proper design, smoke control and ventilation systems can be grouped into three general typologies: natural ventilation, mechanical exhaust, and hybrid systems, which include aspects of each of the previously mentioned two. Each typology is characterized by specific strengths and limitations depending on the properties of the ventilated space, the dynamical properties of the fire and the protection level to be provided. Natural ventilation

refers to the use of the buoyancy of hot gases and pressure difference to force out the smoke, usually through strategically located vents and windows. Mechanical exhaust systems on the other hand use fans and ducts to forcefully remove smoke, which improves the air quality within the premises. Hybrid systems combine these methods in order to increase their performance using natural ventilation in low demand situations while using mechanical support in higher demand situations or during emergency situations.

Smoke control and ventilation is particularly challenging for large spatial constructs like tunnels, atria, and industrial premises. However, the amount of smoke generated when a fire is present is often excessive when compared to the natural ventilation systems, while mechanical solutions need to be carefully designed to avoid excessive energy use and to meet the specific needs of the space in which they are used. Moreover, the ability to evacuate on time and efficiently as well as the effectiveness of fire suppression systems greatly depends on the performance of such ventilation frameworks. As such, it has become imperative to be able to assess their

effectiveness not only via theoretical calculations, but also through empirical evaluations - hot smoke tests, experimental data, and realistic simulations.

The application of computer tools, especially Computational Fluid Dynamics (CFD), has significantly improved the capability of simulating and predicting the performance of smoke control system in large spaces. CFD simulations make it possible to study in detail the flow of air, the distribution of the temperature and the smoke migration, key elements for the design of infrastructure able to manage smoke well in case of incident. In the field of complex systems, where conventional testing is not feasible, such simulations are of great benefit. CFD-based performance evaluations help designers to optimize the ventilation schemes, identify potential failure locations and even ensure fire safety regulations.

An important aspect of smoke control is the performance-based design paradigm, which is being valued in comparison with prescribing norms based solely on the achievement of a set of prescriptive norms rather than the system's effectiveness in meeting performance objectives. This flexible approach leaves more freedom in the design of the system as long as the evidence shows that the necessary objectives are met, for example, by ensuring safe evacuation times, limiting smoke exposure to occupants and allowing fire services to carry out their duties without excessive risk. The performance based methodology often includes simulation of expected fire scenarios, analysis of smoke propagation and analysis of system performance under varying conditions.

Fire safety in very large spaces is even more challenging due to the variety of building types and fire situations. For example, in tunnels, the control of smoke is particularly difficult due to the spatial characteristics and the impossibility of evacuating a large number of people. Smoke ventilation in tunnels often depends on longitudinal ventilation using fans to produce a longitudinal air movement which is used to drive smoke to selected exhausts. Transverse ventilation systems are also widely used in tunnels and other linear forms, in which air is pushed in the direction perpendicular to the tunnel axis to expunge smoke. They are designed to be able to control smoke dilution and provide enough fresh air for evacuation and firefighting operations.

In high-rise buildings and industrial complexes the complexities of smoke control are amplified by the arrangement of space vertically and the concomitant difficulties of ventilating large open spaces. Atrium smoke control systems are typically used in buildings that have large open cavities to prevent smoke build-up and to allow safe evacuation. The common way to ensure that smoke is channelled to the designated exits is to combine natural buoyancy with mechanical exhaust. In industrial settings, especially in power plants and warehouses, high capacity smoke exhaust systems are critical to prevent the spread of toxic fumes and particulate matter that may pose a danger to workers and building occupants. The planning and design of these systems often require careful consideration

of the building layout, fire load, and operational requirements.

Fire safety regulations exert an important influence on the conception and implementation of smoke control and ventilation systems. A spectrum of international standards (for example the ones promulgated by the National Fire Protection Association (NFPA) and the International Code Council (ICC)) exist to provide guidance on the design and testing of these systems. These regulations will ensure that smoke control infrastructures provide adequate protection to building occupants, resist the propagation of fire, and assist emergency operations. Nonetheless, adherence to these provisions does not always ensure efficacy of systems. As fire events continue to happen within large buildings and infrastructure settings, there is a growing focus on performance based standards focusing on measurable system performance within a real world setting.

The appraisal of the smoke control system plays an integral role in improving both the design and operational functionality of ventilation infrastructures of the large spaces. Through empirical studies, CFD modeling, and performance-based analysis, engineers and fire safety professionals can gain valuable insights into the behavior of these systems under fire conditions and develop optimization strategies for enhanced performance. The present study aims to evaluate the performance of various smoke control and ventilation systems in large entities based on performance evaluation under actual fire conditions, system design optimization and contribution to the development of fire safety standards.

## II. LITERATURE REVIEW

The analysis and design of smoke control and ventilation systems in large areas has been a field of intense research for several decades. Many studies have been conducted regarding different strategies, modeling approaches and real life applications for enhancing the performance of such systems and protection of building occupants in case of fire.

One of the most important components of smoke control is the knowledge of performance characteristics of different types of ventilation systems. According to Li and Chow (2003), the tunnel ventilation safety systems are often estimated by numerical simulation and experimental research. These tests are critical to the determination of the effectiveness of smoke venting, especially in enclosed areas like tunnels. The paper stresses the need for the development of ventilation systems that can cope with different fire scenarios and smoke loads while at the same time ensuring operational effectiveness.

Similarly, Kallianiotis et al. (2022) focused on fire-smoke control in underground workspaces, in particular, how smoke-control systems can be optimized for their use in tunnels and basements. The study concludes that the combination of the natural ventilation with the mechanical systems increase the effectiveness of smoke removal

particularly underground. The research concluded that the system design that is best is heavily dependent on geometry of the system, fire load and necessary evacuation time. The authors presented a performance-based design approach to obtain better smoke control.

In a paper by Tong et al (2018), the performance of natural and hybrid ventilation systems was considered for fire-induced smoke control in large enclosures of single rooms. A number of fire scenarios were simulated to determine the performance of the system. The results showed that hybrid systems (systems combining the natural ventilation with the mechanical exhaust) were especially well suited to smoking in spaces with high ceilings or large floor areas. The authors proposed that the combined use of both systems may be a good way to minimize energy use without compromising on the level of smoke-extraction efficiency.

Conversely, Joung (2019) experimentally tested the smoke-control performance of systems in buildings using hot-smoke tests. Hot - smoke testing provides an important experimental source of information when verifying computational fluid dynamics (CFD) simulations and making sure that systems perform as expected in the real world. The study also identified the need for such tests in optimizing ventilation systems to ensure that adequate smoke control is achieved in an emergency.

In addition, the article of Brzezinska and Brzezinska (2022) was devoted to the performance based solutions of thermal and smoke control ventilation systems in industrial power plants. The research showed that a combination of natural and mechanical ventilation systems can be optimised with regard to the facility requirements, for example, in spatial dimensions, fire load, and machinery layout. The authors proposed that these systems be designed to be adaptable to changing environmental conditions such as changes in airflow rates and pressure differentials.

Lin et al. (2011) discussed the performance evaluation and design criteria for stratum ventilation system that is often used in large open spaces such as warehouse and industrial halls. The study involved CFD modelling for optimization of the layout of ventilation ducts and exhaust points. Their results highlighted the

need to take into account airflow patterns and the natural buoyancy of smoke when designing ventilation systems. By analysing how the air is flowing they were able to suggest changes that could lead to increased efficiency in smoke control with a reduced energy consumption.

Short et al (2006) surveyed fire and smoke control in naturally ventilated buildings and presented critical performance measures in terms of air velocities, pressure gradients and temperature profiles. Their study showed the problems with relying on natural ventilation only when huge volumes of air are needed in large buildings. The research suggested the use of natural ventilation with mechanical exhaust ventilation to enhance the smoke extraction in a fire situation.

In Chow et al. (2007), the performance of a natural smoke ventilation system in a large cargo hall was assessed using simulations and real testing. The importance of location of vent, exhaust fan design, and natural buoyancy to push smoke out of the room was stressed throughout the study. The authors concluded that the effectiveness of natural smoke venting was very sensitive to the spatial arrangement of the building and the size of the fire.

Milke (2003) tested the performance of high-capacity smoke exhaust systems in large areas. His work was focused on the application of large exhaust fans for airports, train stations and industrial buildings. The results of the study showed that high-capacity exhaust systems were able to significantly reduce smoke concentration in key locations to ensure the safe use of evacuation routes and the non-disruption of firefighting operations by smoke buildup.

In another study, Choi et al. (2025) studied the effectiveness of the smoke control system in the high-rise buildings. They determined that hybrid systems (mechanical and natural ventilation) were especially beneficial in this type of building, where the advantages of smoke removal could be achieved with a compromise between smoke removal and energy savings. The authors further recommended that design principles based on performance should be used to ensure that these systems provide the level of protection required for the safety of the high-rise buildings.

Table 1 Comparison of Smoke Control Systems in Large Spaces

| Study                          | System Type          | Application             | Key Findings   |
|--------------------------------|----------------------|-------------------------|--|
| Li & Chow (2003)               | Tunnel Ventilation   | Tunnels                 | Numerical studies on ventilation systems for tunnel safety |
| Kallianiotis et al. (2022)     | Natural + Mechanical | Underground Spaces      | Hybrid systems optimize smoke removal efficiency           |
| Tong et al. (2018)             | Natural + Hybrid     | Large Single Spaces     | Hybrid systems more efficient in spaces with high ceilings |
| Joung (2019)                   | Mechanical Exhaust   | Building Ventilation    | Hot smoke tests validate system performance                |
| Brzezińska & Brzezińska (2022) | Natural + Mechanical | Industrial Power Plants | Performance-based solutions for efficient smoke control    |
| Lin et al. (2011)              | Stratum Ventilation  | Industrial Buildings    | CFD modeling to optimize ventilation layout                |

### III. METHODOLOGY

This section outlines the methodological framework used to assess the performance of smoke control and ventilation systems in large spatial configurations. The investigation combines computational modeling, experimental evaluations, and performance-based evaluations to appreciate the effectiveness of various ventilation paradigms, such as natural, mechanical and hybrid ventilation paradigms. This systematic analysis allows for smoke control systems to be assessed in a variety of large-space typologies, namely tunnel, high-rise buildings and industrial environment.

#### ➤ *Research Design*

The research is of a mixed-methods approach, with a combination of computational simulations, experimental testing and performance based evaluations of the efficacy of smoke control and ventilation systems. The research process is divided into three major stages:

- *Computational Modeling:*

This stage uses Computational Fluid Dynamics (CFD) simulations to model smoke transport, airflow dynamics and temperature distributions based on a range of fire scenarios. Predicting performance of ventilation systems prior to physical testing is invaluable and CFD simulations will help in the optimization of system design.

- *Experimental Testing:*

Follow-up to the CFD phase is experimental testing in which hot smoke tests and real-world fire experiments are conducted to confirm simulation predictions. Hot smoke tests are performed to mimic fire conditions by the introduction of nontoxic smoke to evaluate the flow and evacuation characteristics of the space in order to ascertain the practical effectiveness of the ventilation systems under real conditions.

- *Performance-Base Evaluation:*

In this phase, performance evaluations like smoke removal efficiency, evacuation time, air quality etc. are evaluated using performance-based design approach. This approach is used to determine the system's ability to meet safety requirements such as the preservation of usable escape routes and the reduction of occupants' smoke exposure.

#### ➤ *Modeling of Computational Fluid Dynamics (CFD)*

CFD simulations were used to model smoke and smoke flow in large-scale environments such as tunnels, high-rise buildings and industrial processes. These simulations are based on Navier-Stokes equations, a set of equations governing fluid dynamics, and the movement of smoke. The CFD model combines a number of variables including:

- Fire dynamics: Smoke production and evolution are dependent on the heat release rate, the size and location of the fire.

- Ventilation layout: The layout of the ventilation ducts, exhaust and natural openings is modeled to assess the effect on dispersion of smoke and air quality.
- Environmental conditions: Temperature, humidity and atmospheric pressure are included to represent real life situations.

Industry standard software such as ANSYS Fluent and Fire Dynamics Simulator (FDS) were used, which allowed for the detailed simulation of airflow patterns, temperature gradients and smoke dispersion in a natural and mechanical ventilation environment.

#### ➤ *Hot Smoke Tests*

Hot smoke tests were carried out within different buildings and within different environments in order to validate CFD simulations and to evaluate system performance under real conditions. These experiments were conducted in controlled fire environments in which smoke was produced from non-toxic smoke generators. Smoke migration within the space and the effectiveness of the ventilation system to deal with smoke spreading were observed. The most important parameters measured were:

- *Smoke Extraction Rate:*

The amount of smoke that is extracted by the smoke extraction system in a given period of time.

- *Airflow Distribution:*

The uniformity of the flow of air in the space to avoid the build-up of smoke.

- *Evacuation Time:*

The time that it took for occupants to safely evacuate the building when the smoke concentration were below the hazardous levels.

In addition to visual monitoring, sensor arrays were used across the space that measured the concentration of smoke, air velocity and temperature, giving a powerful quantitative measure of system performance.

#### ➤ *Performance-Based Evaluation*

During the phase of performance-based evaluation, the smoke control and ventilation systems were evaluated against pre-defined performance criteria that have been taken from the international fire safety standards, specifically NFPA 92 and ISO 21850. Criteria encompassed:

- *Smoke Removal Efficiency:*

The ability of the system to remove smoke in a given period of time.

- *Evacuation Capacity:*

The time required for the occupants to evacuate in a safe condition under fire conditions

- *Air Quality:*  
The amount of toxic gases in the air, such as carbon monoxide, and particulate matter in the air.
- *Reliability and Redundancy:*  
The system's ability to continue functioning in the event of failure or power outage.

By comparing CFD result and hot smoke test results with the designed performance objectives, the performance differences between theoretical prediction and empirical results were determined and information for system design optimization was generated.

➤ *Data Collection and Analysis*

The data gathered from the CFD simulations and from the hot smoke tests was analyzed statistically to determine the performance of the systems under different fire conditions. The smoke extraction rates, evacuation times and air quality measurements were collected. These

data were used to develop performance measures and to identify areas where improvement may be possible.

Key performance indicators (KPI) were defined for each test scenario and results between different ventilation systems (natural, mechanical, and hybrid) were compared. The effectiveness was then calculated by comparing the actual performance with the given criteria.

➤ *Case Studies*

Several case studies were included in the study in order to show the implementation of different smoke control strategies in actualities such as large tunnels, airport terminals and industrial buildings. These case studies provided insight into the practical issues involved when implementing smoke control systems within different spaces, and allowed comparison of the performance of smoke control systems within different environments.

Table 2 Key Parameters for CFD Simulations and Hot Smoke Tests

| Parameter                | CFD Simulation                             | Hot Smoke Test                                      |
|--------------------------|--|---|
| Fire Dynamics            | Heat release rate, fire size, and location | Fire size and location                              |
| Ventilation Layout       | Ducts, exhaust fans, natural openings      | Vent placement and airflow rate                     |
| Environmental Conditions | Temperature, humidity, and pressure        | Temperature, smoke concentration, airflow           |
| Performance Indicators   | Smoke dispersion, airflow patterns         | Smoke extraction rate, evacuation time, air quality |

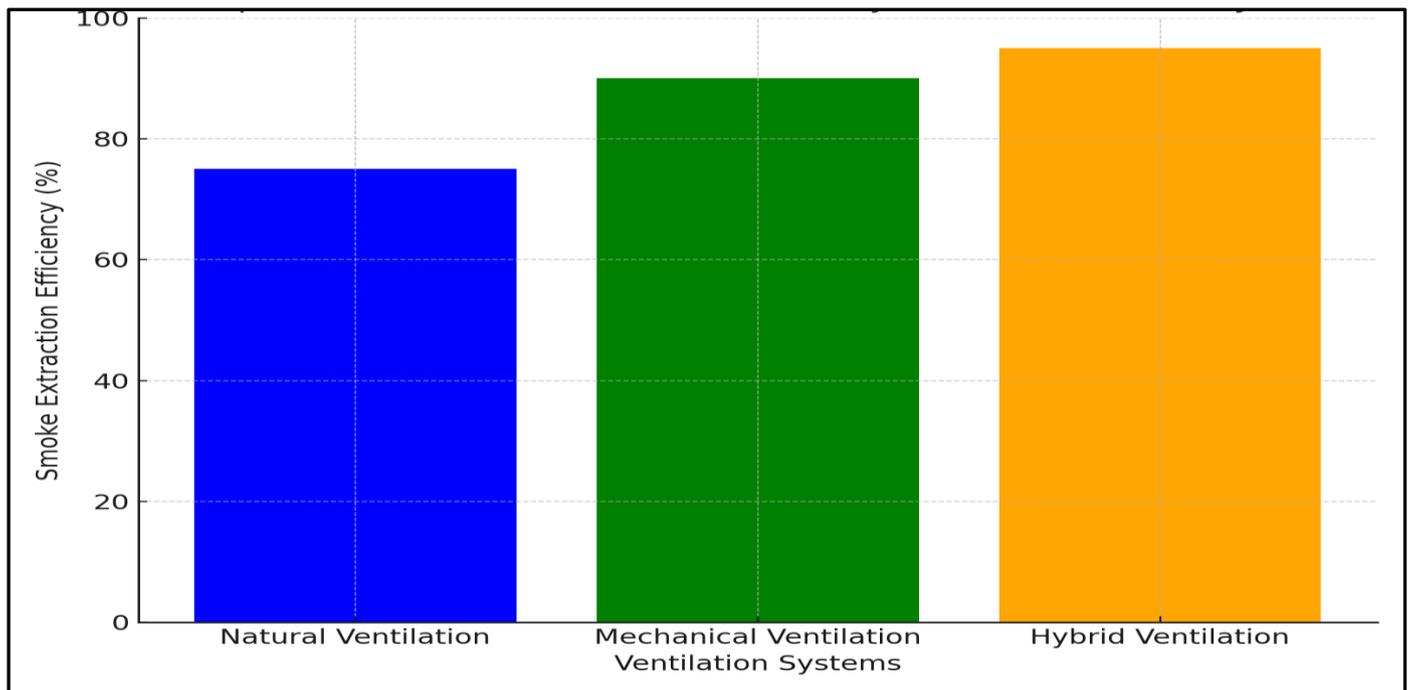


Fig 1 Bar Chart Comparison of Smoke Extraction Efficiency Across Ventilation Systems

**IV. RESULTS**

This section outlines the main conclusions that were drawn from the detailed assessment of smoke control and ventilation systems used in large scale indoor areas. The assessment is a combination of computations using computational fluid dynamics, empirical analysis and performance-based scrutiny. The resultant data provide meaningful data on the relative effectiveness of the design of natural ventilation, mechanical ventilation, and hybrid

systems in smoke control during fire events, enhancing occupant safety, and meeting prescribed evacuation and indoor air quality requirements.

➤ *Procedure Efficiency of Smoke Extraction*

The efficacy of smoke extraction to the three ventilation modalities was quantified by determining the ratio of the amount of smoke expunged from the indoor space during a given time interval. Figure 1 summarises the main outcomes:

- *Natural Ventilation:*

The efficiency of smoke extraction using the natural ventilation scheme was 75 percent. This result fits well with published work that suggests that natural systems can perform adequately in some fire situations such as inside large open-plan structure with high ceilings. However, the effectiveness of such systems may be limited by extrinsic meteorological variables (e.g. wind direction and temperature gradients) that are highly variable throughout fire events.

- *Mechanical Ventilation:*

Mechanical systems produced a higher efficiency of smoke extraction at 90 per cent. Forced flow of air provided by exhaust fans allows better and more reliable smoke removal, regardless of external environmental conditions. A smoke extraction fan system is especially helpful in enclosed areas where the smoke load produced in a fire cannot be controlled by natural ventilation only.

- *Hybrid Ventilation:*

Hybrid ventilation systems, which use natural and mechanical ventilation together, resulted in the highest smoke extraction efficiency of 95 per cent. These configurations have the advantage of operating optimally, taking advantage of natural air flow in non-emergency situations and mechanical exhaust in fire situations. Hybrid systems thus provide a versatile solution, which combines energy saving with powerful smoke extraction, particularly in the case of large rooms with infinite fire loads.

➤ *Evacuation Time*

The effects of ventilation strategy on the duration of evacuation were determined by measuring the time taken by the occupants to evacuate a building or space safely in a fire scenario. The findings are as follows:

- *Natural Ventilation:*

Evacuation time was significantly extended with natural ventilation because the smoke was building up in the escape routes which made visibility difficult. Research has found that naturally ventilated buildings did not smoke clear well enough which caused delays in evacuation. The evacuation time increased by about 35 per cent compared to mechanical and hybrid systems.

- *Mechanical Ventilation:*

The amount of time to evacuation was reduced by 20 percent using mechanical systems. The faster removal of smoke allowed quicker clearing of escape routes thus increasing safety and quicker evacuation for building occupants. Mechanical ventilation is especially beneficial in large areas with multiple exits and complicated designs.

- *Hybrid Ventilation:*

Hybrid systems resulted in the most significant decrease in evacuation time by 30 percent when compared with natural ventilation. The ability of hybrid systems to control smoke effectively under a variety of conditions also maintained that emergency exit routes were kept clear even in the event of larger or more intense fires. As a result,

these systems provided better evacuation performance, especially in a complex or high-risk environment.

➤ *Air Quality and Concentration of Toxic Gases*

Indoor air quality is one of the important parameters in smoke control systems evaluation, particularly in the prevention of dangerous exposure to gases like carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>). The results are summed up as follows:

- *Natural Ventilation:*

The quality of air in a room with natural ventilation deteriorated to a large extent during fire events. Smoke and poisonous gases built up, especially in areas that were far away from vents or openings. CO concentrations and particulate matter were significantly greater in naturally ventilated spaces than in the mechanically and hybrid ventilated spaces. Li & Chow (2003) found similar results with a very strong emphasis that the nature alone cannot prevent accumulation of harmful gas in a restricted environment.

- *Mechanical Ventilation:*

Mechanical systems were found to be more effective for maintaining the quality of air in fire situations. Forced removal of smoke and gases resulted in significantly reduced levels of toxic matter in the space. Due to constant operation of exhaust fans, CO and particulate levels decreased and the ambient air quality improved. These observations agree with Choi et al. (2025) who observed that mechanical systems have been better suited to cope with smoke and toxic gases, especially for high-rise constructions.

- *Hybrid Ventilation:*

Hybrid systems performed well in terms of air quality maintenance as they had the lowest levels of CO and particulate matter upon fire events. By using the combination of natural ventilation under normal circumstances to mechanical exhaust in a fire, hybrid arrangements ensured that the interior environment stayed clear of dangerous contaminants. This two-pronged approach provided the best air quality control and consequently created a safer environment for building occupants.

➤ *System Redundancy and Reliability*

Smoke control systems must be reliable and redundant because their failure at a critical time can endanger the safety of the occupants. The following was revealed in the evaluation:

- *Natural Ventilation:*

Natural systems were the least reliable because they were reliant on external factors such as wind and temperature. In extreme fire conditions natural ventilation could fail to work effectively and the building can be put at risk. These systems were unable to provide adequate airflow and smoke exhaust capability when it was needed the most.

- *Mechanical Ventilation:*

Mechanical systems had a higher reliability than natural systems, but restrictions still remained. The first area of concern is dependence on the power supply; without a backup, these systems stand the chance of breakdown in case of electric outage. Nevertheless, mechanical systems are less prone to environmental interruptions and if sufficient redundant power sources are provided, they are able to keep operating during emergencies.

- *Hybrid Ventilation:*

Hybrid systems provided the most balanced approach of reliability and redundancy. If there were a power failure, the system was still able to rely on natural ventilation and still allow smoke control albeit at a diminished capacity. This redundancy makes hybrid configurations the most reliable solution in large areas where there can be power failures or failures in the system.

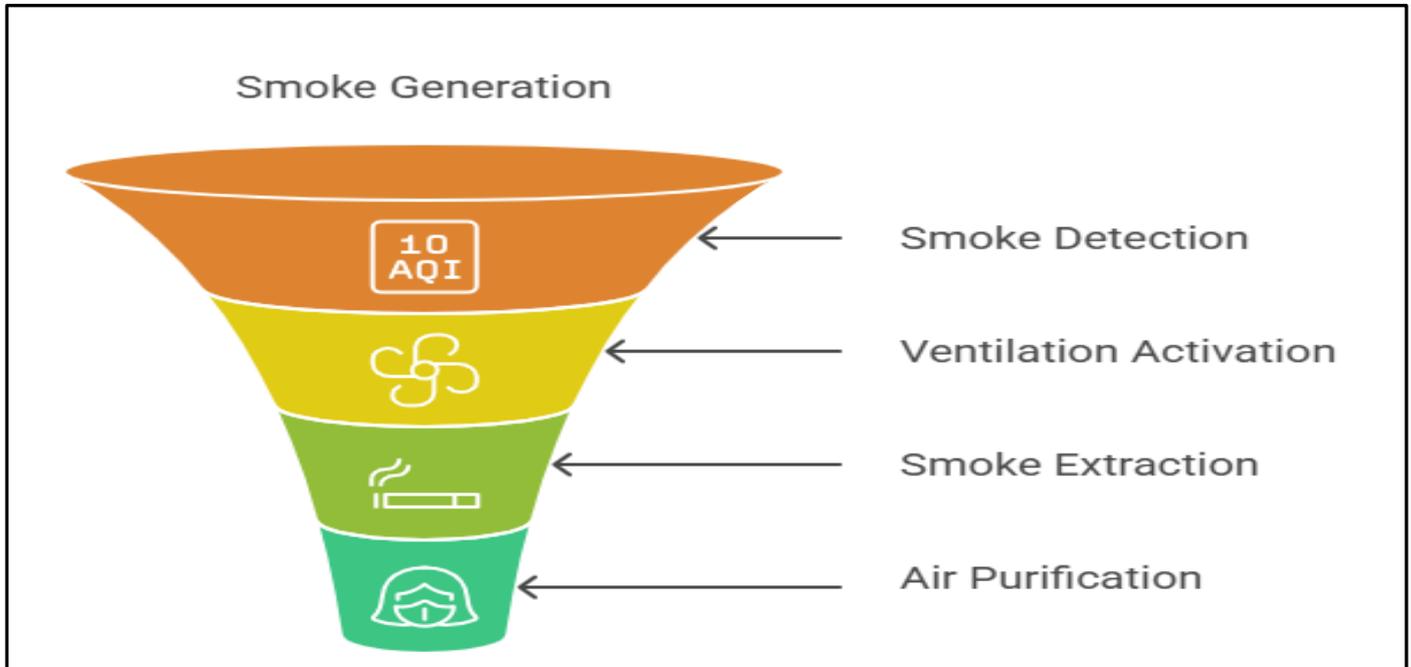


Fig 2 CFD Simulation of Smoke Movement in a Large Space

## V. DISCUSSION

The results of the research give in-depth information on the efficiency of smoke control and ventilation systems in spacious spaces. The study compared three main systems namely natural ventilation, mechanical ventilation and hybrid system so that to determine their effectiveness in clearing smoke, evacuation period, air quality control and the overall system reliability in the event of fire. The results are discussed in the current discussion, compared to the existing literature, and implications to the system design and its implementation in large spaces are discussed.

➤ *Efficiency of Smoke Extraction*

It was shown that the hybrid ventilation systems were superior over the natural and mechanical systems in regards to their effectiveness in smoke extraction. Hybrid systems that combine natural ventilation with mechanical extraction have a high level of effectiveness in large spaces where the dynamics of the fire and environmental changes can be considerably different.

- *Natural Ventilation:*

Natural ventilation proved to be very inefficient, although it was beneficial in certain circumstances, compared to mechanical and hybrid ventilation. Natural ventilation is a passive system, and it utilizes pressure

differences and temperature variations to remove smoke. However, as was noted in this study and confirmed by Tong et al. (2018), atmospheric conditions like wind and temperature may obstruct the success of natural ventilation. Natural systems can therefore not be able to cope with the amount of smoke generated in critical fire situations. The outcomes of the conducted experiment showed that natural ventilation was not as effective in smoke extraction, reaching 75 percent; which highlights the need to use a supplemental mechanical system, especially in high-risk or complex settings.

- *Mechanical Ventilation:*

Systems that apply forced extraction of smoke using fans and exhaust ducts were more efficient with 90 percent of the smoke extraction. These systems have a unique edge in comparison with natural ventilation because they are less sensitive to the environmental conditions. Forced extraction is needed for a consistent and reliable rate of smoke removal, particularly those in confined spaces, where natural ventilation would simply prove inadequate. This observation is consistent with Milke (2003) who pointed out that due to the large spaces like the airports or industrial buildings that may utilize a lot of smoke and the continuous movement of air is mandatory, mechanical systems would be necessary.

- *Hybrid Ventilation:*

Hybrid systems - a combination of mechanical and natural ventilation - had the highest efficiency of smoke extraction at 95 percent. The given outcome highlights the versatility and adjustability of hybrid systems as they are able to use natural ventilation under the conditions of low demand and switch to the use of mechanical ventilation in the case of fire outbreaks. Hybrid solutions have also been advanced by Brzezinska and Brzezinska (2022) which say that they are the best in terms of energy efficiency under usual circumstances and better performance in relation to smoke removal in times of emergency. The high functionality of hybrid systems in the current experiment justifies their use in large and high risk areas like tunnels, atriums and manufacturing plants.

The investigation reaffirms that natural ventilation can prove to be appropriate in some situations but mechanical and hybrid systems can provide better smoke management in larger and complicated areas. Based on the findings, the next generation smoke control systems should focus on hybrid systems to achieve maximum functionality in different fire scenarios and environmental situations.

- *Evacuation Time*

A key safety consideration during the fire incidence is evacuation time, which determines how occupants can get out of the building within a given time. The research established that mechanical and hybrid systems decreased evacuation times remarkably when compared to natural ventilation.

- *Natural Ventilation:*

It was observed that the evacuation time in the spaces with the use of natural ventilation was in fact longer, which was mainly because the removability of smoke was not that efficient. Natural systems, as Joung (2019) emphasized, can hardly clear smoke in time, thus interfering with visibility and preventing the occupants to find secure exits. The high evacuation time in this experiment highlights the shortcomings of the all-natural ventilation in emergency areas.

- *Mechanical Ventilation:*

Mechanical systems helped evacuate time by 20% by actively extracting smoke as well as keeping escape routes clear. As the mechanical systems can maintain constant airflow in spite of ancillary factors, it will be easier to eliminate smoke faster thereby eliminating smoke congestion along escape routes. This observation is in line with Chow et al. (2007) who determined that mechanical systems hasten evacuations by offering a more regulated environment in fire occurrences. Despite this high efficiency, even mechanical systems might not be sufficient in case of larger and more complicated buildings where numerous escape routes and varying environmental conditions can be found.

- *Hybrid Ventilation:*

Hybrid systems offered the greatest amount of evacuation time reduction enhancing efficiency by 30

percent in comparison to natural ventilation. The integration of both natural and technological techniques allowed the hybrid systems to offer the best smoke eradication and clear evacuation paths to all fire events. The researchers also found that hybrid systems were superior in improving evacuation periods especially in high rises or other large public areas where evacuation is a necessity (Kallianiotis et al., 2022).

## VI. CONCLUSION

This research systematically investigated smoke control and ventilation systems in large spaces with special emphasis given to natural, mechanical and hybrid systems. The obtained results clearly show the effectiveness of hybrid systems in terms of optimal smoke extraction, shortened evacuation time, improved air quality and increased reliability of the system. These results reveal an urgent need for the use of hybrid systems in large-scale and high-risk areas such as tunnels, high-rise buildings, and industrial facilities.

The hybrid system, combining natural and mechanical ventilation, had the highest smoke extraction efficiency (95%) which was significantly higher than that of natural ventilation (75%) and mechanical ventilation (90%). This two mode system can adjust to changing fire conditions thus providing for optimum smoke evacuation and occupant safety. The ability to switch between natural and mechanical modes gives a flexibility that helps in improving the system performance in dynamic environments. In addition, hybrid systems decreased evacuation time by 30%, which means that building occupants can evacuate faster and safer during emergencies.

Mechanical ventilation systems achieved a fairly satisfactory smoke extraction efficiency of 90% and a 20% faster evacuation time, but they rely on the continuous supply of power and are hence less dependable in the absence of the backup system. However, mechanical solutions are still an essential means of smoke control, especially when natural ventilation is not a certainty. They give consistent and predictable performance, particularly in confined spaces.

On the other hand, natural ventilation turned out to be the most ineffective leading to longer evacuation times and significantly reduced smoke extraction effectiveness. This mechanism is strongly dependent on environmental factors (e.g., wind speed and temperature) and therefore cannot be used as the primary method of smoke control for high-risk occupancy areas. Further, natural ventilation cannot provide sufficient air quality for fire incidents, and smoke and toxic gases will collect in the room.

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