

Smoke Spread in Swedish Office Building Ventilation Systems: A Comparison Between Hand Calculation Models and CFD of Fire-Induced Flows

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Abstract. Modern office buildings are often designed as large fire compartments with balanced mechanical ventilation systems. To limit smoke spread via ventilation, traditional fire protection relies on fire dampers. In performance-based design, alternative strategies such as fans operating during fire are increasingly applied. A key parameter for such solutions is the fire-induced airflow generated during the early stage of a fire due to thermal expansion of gases. This paper evaluates simplified analytical models for fire-induced airflow by comparison with Computational Fluid Dynamics (CFD) simulations using Fire Dynamics Simulator (FDS). Sprinklered and unsprinklered office fire scenarios were analysed for compartment areas between 100 and 1500 m², considering adiabatic, inert, and concrete boundary conditions. The results show good agreement between analytical models and CFD for unsprinklered fires. For sprinklered fires, the analytical models are systematically conservative and increasingly overestimate the fire-induced airflow for larger compartments. CFD results indicate that fire-induced airflow in sprinklered offices plateaus at approximately 500–1000 l/s, depending on boundary conditions. The findings support CFD-based verification and show that normal ventilation airflow is often sufficient to manage fire-induced flows in sprinklered office buildings, allowing fans operating during fire to be applied without the need for backflow dampers or fire dampers.

1 Introduction

Office buildings in Sweden and many other countries are commonly designed as large fire compartments with balanced mechanical ventilation systems, often with heat recovery. Typical design airflows are in the order of 1–1.5 l/(s·m²). To prevent fire and smoke spread through ventilation systems, the traditional solution has been to stop fans and close fire dampers at compartment boundaries (fire cells). While effective, this approach can lead to high installation and maintenance costs. In performance-based fire safety design, alternative strategies have emerged, such as keeping fans in operation during fire, often combined with backflow dampers. The feasibility of such solutions depends on the magnitude of the fire-

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induced airflow that develops during the early, overpressure-dominated phase of a fire. If this airflow can be reliably quantified, simpler and more cost-effective ventilation fire protection strategies can be justified. Simplified analytical models for estimating fire-induced airflow have been used in engineering practice for decades [1], [2], [3]. However, these models are largely based on two-zone models and limited compartment sizes. With the increased use of CFD in fire safety engineering, it is now possible to reassess the validity and limitations of these simplified approaches. The work presented in this paper is based on a comprehensive research and development study on fire-induced airflow in office buildings, where analytical hand-calculation models were systematically compared with CFD simulations for both sprinklered and unsprinklered scenarios [4].

2 Background and Problem Formulation

During the initial stage of a compartment fire, rapid heating of the gas volume leads to thermal expansion and a resulting pressure increase. This expansion-driven flow, often referred to as fire-induced airflow or fire flow, may force gases through leakage paths and ventilation openings. In [3], the fire flow is described as the thermal expansion that occurs during a fire in a room. The average fire flow can be described as:

$$q_b = \frac{(T_2/T_1 - 1) * V}{t_2 - t_1} \quad (1)$$

Where q_b is the fire induced flow (m^3/s), T_i the average temperature (K) in the fire compartment at time t_i (s) and V the volume of the fire compartment (m^3).

This stage typically occurs before significant pressure relief, such as window breakage, and is therefore critical for ventilation fire protection design. In sprinklered compartments, the fire growth is limited once sprinklers activate, in accordance with performance-based design assumptions [5], resulting in lower gas temperatures and shorter duration of the overpressure phase. Analytical models commonly account for this by limiting the fire-induced airflow to conditions at sprinkler activation. However, the applicability of such models for large, modern office compartments remains uncertain. The central question addressed in this study is under what conditions simplified analytical models provide reliable estimates of fire-induced airflow, and when CFD-based evaluation is necessary to support performance-based design decisions.

3 Analytical Models for Fire-Induced Flow

The analytical models examined in this study are based on two-zone formulations originally developed by Jensen [1] [2]. These models estimate fire-induced airflow as a function of compartment volume, fire growth rate, and resulting gas temperature increase. The calculations were based on a two-zone model and were carried out in Matlab [2]. The simulations were stopped when the smoke layer reached the floor. In the simulations, floor areas between 10 and 200 m^2 were assumed. The ceiling height was varied between 2.4 and 3.6 meters. The growth rate and the ventilation were also included in the simulations. In total, this resulted in 2000 combinations. The following equations are suggested by Jensen:

$$q_b = 0,0081 * \alpha^{0,4231} * A^{0,5009} * h^{1,0394} \quad (\text{m}^3/\text{s}) \quad (2)$$

$$t_b = 92,821 * \alpha^{-0,3328} * A^{0,3508} * h^{0,2799} \quad (\text{K}) \quad (3)$$

$$T_b = 409,33 * \alpha^{0,0695} * A^{0,0054} * h^{-0,0736} \quad (\text{K}) \quad (4)$$

Where q_b is the fire induced flow, α is the heat release rate (kW/s^2), A area (m^2), h is the room height (m), t_b the fire duration (s) and T_b the average temperature in the upper layer (K). Separate formulations are used for sprinklered and unsprinklered scenarios, where sprinklered cases include assumptions regarding time to activation and limiting gas temperature. These equations are still widely used in Swedish engineering practice, particularly during early design phases. However, they were primarily developed for compartment areas up to approximately 200 m^2 , and their behaviour for significantly larger compartments is not well documented.

4 CFD Methodology

CFD simulations were performed using Fire Dynamics Simulator (FDS, version 6.7.9) [6], which solves the low-Mach-number form of the Navier–Stokes equations and applies a Large Eddy Simulation (LES) approach for turbulence modelling. The objective of the simulations was to quantify the fire-induced airflow generated by thermal expansion during the early stage of a compartment fire and to compare these results with established analytical models.

A series of open-plan office compartments with floor areas ranging from 100 to 1500 m^2 were modelled. The ceiling height was kept constant at 2.7 m in the reference cases. To isolate the effects of thermal expansion, the compartments were assumed to be airtight, with pressure relief occurring only through two floor-level openings measuring $2.0 \text{ m} \times 0.2 \text{ m}$ located on opposite walls. The volumetric flow through these openings was used to quantify the fire-induced airflow.

The fire source was represented by a medium-growth t^2 -fire with a growth rate of $\alpha=0.012 \text{ kW/s}^2$ and a maximum heat release rate of 5 MW , corresponding to the design fire recommended for office occupancies in Swedish performance-based fire safety design. Fire growth was implemented using SPREAD_RATE. Fuel properties, heat of combustion and combustion parameters were selected in accordance with Swedish design guidance for office occupancies. The mixture-fraction combustion model and the finite-volume radiation model were applied throughout the study. Extinction Model 1 was applied based on experience from previous studies and validation work [7].

For sprinklered scenarios, sprinkler activation was explicitly modelled in FDS using a link temperature of $68 \text{ }^\circ\text{C}$ and an RTI value of $50 (\text{m}\cdot\text{s})^{1/2}$, representing a fast-response sprinkler. Several sprinkler locations at equal distances from the fire source were evaluated in different directions, and the sprinkler with the latest activation time was used as the basis for the analysis. Fire-induced airflow for sprinklered scenarios was extracted at the time of sprinkler activation, consistent with the assumption in Swedish design practice that compartment temperatures are limited once sprinkler activation occurs [5]. For unsprinklered scenarios, the fire-induced airflow was extracted at the peak pre-underventilated stage, typically close to the time of maximum heat release rate.

Three different boundary conditions were considered for the surrounding constructions: ADIABATIC, INERT and concrete walls with a thickness of 100 mm . These boundary conditions represent a range from negligible heat losses to realistic thermal interaction with the building structure and were included to evaluate the influence of heat transfer on the resulting fire-induced airflow.

A uniform Cartesian mesh with a nominal cell size of 0.10 m was used in the reference simulations. Depending on compartment size, between one and five meshes were employed.

Grid sensitivity analyses were conducted using cell sizes down to 0.025 m for selected cases. The results showed good convergence during the period of interest, i.e. prior to the onset of under-ventilated conditions, confirming that the selected grid resolution was adequate for the present study.

Fire-induced airflow was evaluated using two independent methods: (1) direct measurement of volumetric flow through the openings and (2) calculation based on compartment temperature development and gas expansion. Both methods showed similar overall trends, although the flow-based approach produced less numerical fluctuation and was therefore adopted as the primary result parameter.

Sensitivity analyses were performed for selected parameters, including ceiling height, opening size, and heat release rate per unit area. Ceiling height was found to have the strongest influence on the predicted fire-induced airflow.

5 Results

5.1 Sprinklered Fires

For sprinklered scenarios, CFD results consistently show lower fire-induced airflow than predicted by the analytical models. For compartments larger than approximately 500–750 m², the CFD-predicted airflow plateaus rather than continuing to increase with area. For concrete and inert boundary conditions, the fire-induced airflow stabilizes at approximately 500 l/s. For adiabatic conditions, a higher plateau of approximately 1000 l/s is observed. The analytical models, in contrast, predict a continuous increase with compartment area, leading to increasing conservatism for larger rooms. Only in the smallest compartment (100 m²) with adiabatic boundaries did the CFD results exceed the analytical prediction. The results are shown in Fig. 1 where the plateau effect is clearly seen in the CFD results.

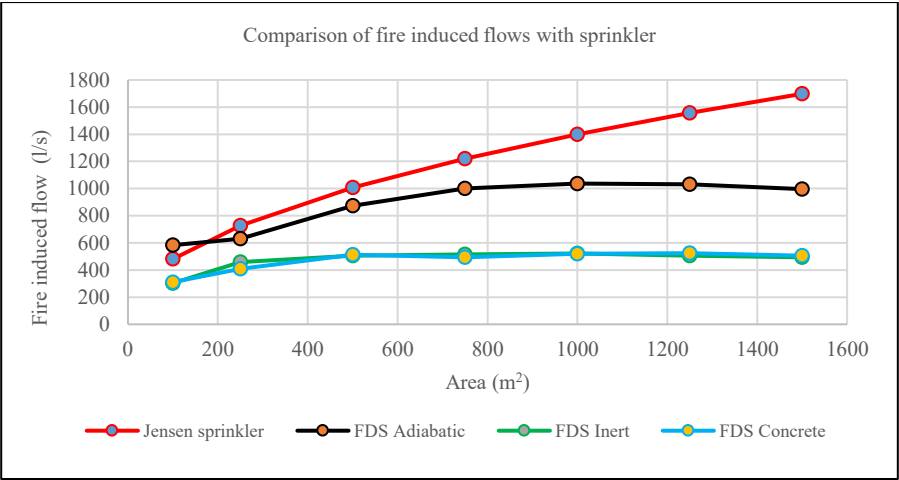


Fig. 1. Comparison of analytical and CFD-predicted fire-induced airflow for sprinklered office compartments.

5.2 Unsprinklered Fires

For unsprinklered scenarios, the agreement between analytical models and CFD results is generally very good. For all studied areas (100–1500 m²), the ratio between CFD and analytical predictions is typically within $\pm 10\%$. The results are shown in Fig 2. The maximum fire-induced airflow usually occurs near the time when the fire reaches its peak heat release rate, before becoming under-ventilated. Both analytical and CFD approaches show similar trends, although some uncertainty remains regarding the exact timing of result extraction.

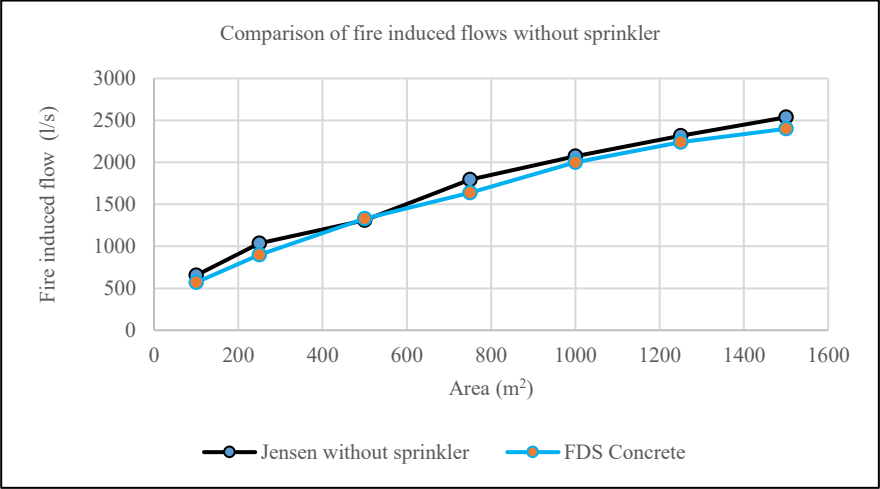


Fig. 2. Comparison of analytical and CFD-predicted fire-induced airflow for unsprinklered office compartments.

To illustrate the temporal relationship between fire growth and fire-induced airflow, Figure 3 presents the development of heat release rate and the corresponding fire-induced airflow for a 1500 m² office compartment. The figure shows that the maximum fire-induced airflow occurs close to the peak heat release rate. This supports the selected approach for extracting representative fire-induced airflow values. For the unsprinklered cases, result extraction was limited to the period before under-ventilated conditions developed, as significant flow fluctuations were observed thereafter in some cases.

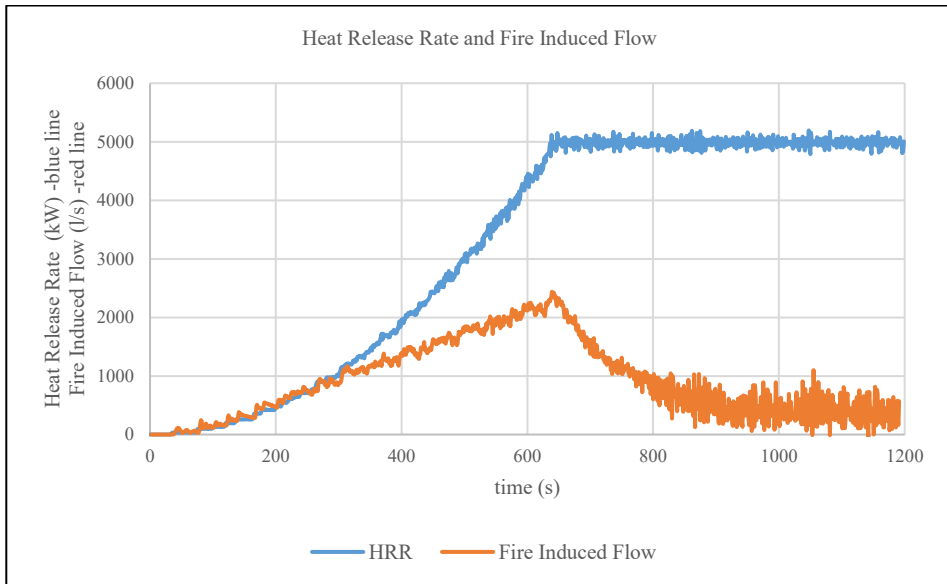


Fig.3. Heat release rate and fire-induced airflow over time for a 1500 m² office compartment.

5.3 Sensitivity Analysis

The sensitivity analysis indicates that variations in heat release rate per unit area and opening size have a limited influence on the predicted fire-induced airflow, typically within $\pm 15\%$ of the reference cases. Ceiling height, however, has a more pronounced effect. Increasing the ceiling height from 2.7 m to 3.4 m results in an increase in fire-induced airflow of approximately 20–25%, particularly for larger and unsprinklered compartments.

6 Discussion

The results confirm that simplified analytical models remain reliable tools for estimating fire-induced airflow in unsprinklered office compartments. For sprinklered scenarios, however, these models are systematically conservative, especially for large compartments. The CFD results demonstrate that, in sprinklered offices, the fire-induced airflow is limited by the early suppression of the fire and the associated cap on gas temperature. The observed plateau behavior is not captured by the analytical models, which continue to scale with compartment area. From a design perspective, this implies that reliance solely on analytical models may lead to unnecessary use of fire dampers or backflow dampers in sprinklered buildings. CFD-based verification provides a more realistic basis for design and supports the implementation of simpler ventilation fire protection strategies.

7 Conclusions

The following conclusions can be drawn:

- For unsprinklered office fires, analytical hand-calculation models correlate well with CFD predictions and remain suitable for design use.
- For sprinklered fires, analytical models are conservative and increasingly overestimate fire-induced airflow as compartment size increases compared to CFD calculations.

- CFD simulations show that fire-induced airflow in large sprinklered offices plateaus at approximately 500–1000 l/s, depending on boundary conditions.
- Normal ventilation airflow in modern offices is often sufficient to handle these fire-induced flows, supporting the use of fans operating during fire without fire dampers och backflow dampers in many sprinklered cases.
- CFD-based evaluation is recommended as a verification tool in performance-based ventilation fire protection design, particularly for large sprinklered compartments.

The results align with the current Swedish performance-based design framework [5] and provide practical guidance for optimizing ventilation fire protection solutions in modern office buildings.

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