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Influența factorilor de ventilare asupra dezvoltării incendiilor în încăperi și clădiri. Recenzie studii numerice

The influence of ventilation factors on the development of fires in rooms and buildings. Review of numerical studies

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Rezumat. *Ventilarea incendiilor reprezintă o procedură activă de intervenție care determină scăderea temperaturilor, concentrațiilor produșilor de ardere și creșterea vizibilității pentru facilitarea intervenției pompierilor în scopul salvării de vieți și de reducere a pagubelor materiale. În acest scop, a fost realizat un studiu bibliografic a cercetărilor experimentale și numerice inițiate în domeniul ventilării incendiilor. În urma consultării studiilor s-a evidențiat eficiența ventilării incendiilor pentru reducerea concentrațiilor produșilor de ardere și a temperaturii maxime și creșterea vizibilității. De altfel, pentru clădirile înalte s-a confirmat că ventilarea incendiului este puternic influențată de efectul de coș apărut din cauza diferențelor mari de nivel.*

Cuvinte cheie: ventilare, incendiu, temperatura, modelare numerică

Abstract. *Fire ventilation is an active intervention procedure that lowers temperatures, concentrations of combustion products and increases visibility to facilitate the intervention of firefighters for saving lives and reduce material damage. For this purpose, a bibliographic study of the experimental and numerical researches initiated in the field of fire ventilation was carried out. After consulting the studies, the efficiency of fire ventilation was highlighted for reducing the concentrations of combustion products and the maximum temperature and increasing visibility. Moreover, for high-rise buildings, it was confirmed that fire ventilation is strongly influenced by the stack effect caused by big level differences.*

Key words: ventilation, fire, temperature, numerical modelling

1. Introduction

In 2018 alone, fires incidents in the United States caused more than 2,700 deaths and 11,000 fire related injuries [1], meaning that one fire incident occurs among 906 people with a death rate per million of 8.19, the probability of that fire to cause injuries and/or deaths being approximately 3% and 0.7% respectively, and from the point of view, for the year 2018 as well, material losses were evaluated at more than 8 billion dollars, which means on average about 22,000 dollars equivalent of the damages produced by each fire. Also, for the United States of America, the mortality rate remained at a high value, both for professional fire-rescue teams, 2.51% of the total annual deaths [2]–[4], as well as for the American civilian population [5]–[7].

In the case of the states of the European Union, although the mortality rate caused by fires was in a continuous decrease after 1988 as a result of the common European fire incidents prevention policy, but its value continues to remain quite high even after the year 2000, many states not providing data on such events [8]. In the UK since 2000 mortality has fallen considerably, falling by at least 50% in 2016 due to increased use of residential smoke detectors [9].

Therefore, to reduce the incidence of deaths caused by fire and to increase the fire safety of buildings, after the year 2000 at the global level, a series of experimental and numerical studies in the field of fire security were started. I have chosen to consult predominantly numerical scientific papers because they can be reinitialized many more times than experimental ones, much easier and with less resource consumption. Hence, through this paper, following the detailed consultation of scientific works in the field of fire ventilation, we proposed the analysis of numerical fire studies, based rooms or buildings models, the study of fire development for different types of combustible materials, the study of the influence of ventilation conditions on the development of fires, studying smoke exhaust and active and passive ventilation systems, their specifications and how to use them for the purpose of the buildings in which they were installed, as well as making a record of the equipment used from the papers consulted, in conjunction with the presentation of new numerical research directions at the present time in the field of fire security.

In the multitude of these different types of research, numerical and experimental, there is a need to conduct a review-type study regarding the main directions of fire security research, fire security equipment in modern buildings and the influence of this equipment on the development of fire incidents and the safety of the population affected by this type of risk.

2. Numerical studies in the field of fire ventilation

Fire ventilation or operational ventilation involves the active and controlled change of conditions in a burning room or building to evacuate smoke and hot gases in order to reduce the temperature and increased concentrations of combustion products, facilitating the evacuation of occupants and the intervention of firefighters (Fig. 1).

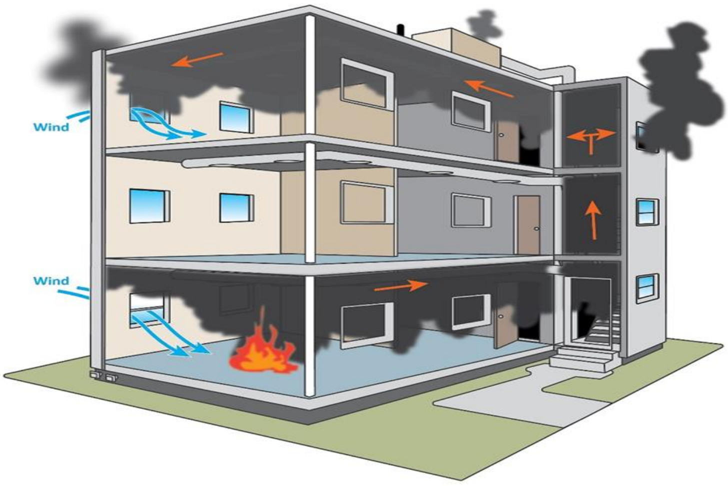


Fig. 1. Natural ventilation [10]

Although in some cases the initiation of operational ventilation can lead to a local increase in temperature, even an incorrectly performed fire ventilation procedure is recommended to the detriment of its absence [11]. This method of extinguishing the fire without using operational ventilation in any way can be found in the specialized literature under the name of anti-ventilation. Fire ventilation can be passive, active or hybrid, and from the point of view of efficiency, both active and hybrid operational ventilation cause an easier intervention for the fire brigades, the fire is located at the level of a single room, the temperature is kept high yet controlled and, thanks to the supply of oxygen brought by ventilation, incomplete combustion is almost non-existent, reducing the concentration of carbon monoxide and other flammable gases [12].

Frederick W. Mowrer through the research he started [13] provided a starting point for understanding the factors that determine and influence the movement of smoke and hot gases. In this study, not only the driving forces that determine the movement of smoke were targeted, but also the smoke detection and exhaust systems that are commonly used to control the movement of smoke within buildings and other spaces. These factors have been addressed individually and conclusions have been drawn for each factor separately, but it is highlighted that for some practical applications it will be necessary to use simulation software that takes into account the combined effects of these factors. A series of design problems of smoke exhaust systems were addressed in a general way, requiring a more detailed analysis,

Following the same research direction from previous years [14]–[16], Lulea et. al. carried out a research by developing a CFD model to create an interdependence between the operation of the sprinkler system and the operation of the ventilation system [17]. A full-scale experiment was conducted and a CFD model was developed. The thermal conductivity of the experimental test stand walls, domain refinement and burner HRR variation were introduced as model inputs so that the resulting time variation of the temperature near the sprinkler location corresponded to the actual measured variation. Two other experiments contributed to the validation of the numerical model. In addition to the air temperature, at a given time, other essential parameters inside the stand were determined such as the ambient air temperature, visibility, oxygen concentration and carbon dioxide concentration. As a result of the research, it was concluded that if the ventilation speed increases, the internal temperatures in the outbreak area decreases, and the sprinkler for that area is activated with a delay or not at all. However, this conclusion is not universally valid for the entirety of the analyzed experimental stand, since the ventilation system, along with the natural air movement, implies a specific air speed and a specific temperature distribution inside the analyzed space.

Starting from a previous experimental research [18], Cai N. and Chow WK performed FDS-type numerical modelling to determine solutions of two existing problems at the time, the feasibility of defined boundary conditions and determining the optimal refinement to obtain the most relevant results [19]. The numerical model created aimed to study the influence upon the height of the ventilation gap (door) in 3 scenarios: the fully open door (SC1), the door open at the lower half (SC2) and the door open at the lower quarter (SC3), and at two domains with different dimensions and refinements (OB1 and OB2), as it can also be seen from Fig. 2.

Analysing the results of the simulations from a functional point of view, the Euclidean norm (the difference between the lengths of pressure vectors) and the cosine of the angle formed by two vectors (a comparison of curves shapes) are used to compare the numerical results obtained from the FDS model with the experimentally measured data. For a better accuracy of the two curves from experiment and model, the norm is expected to approach 0, and the cosine is expected to approach 1 [20].

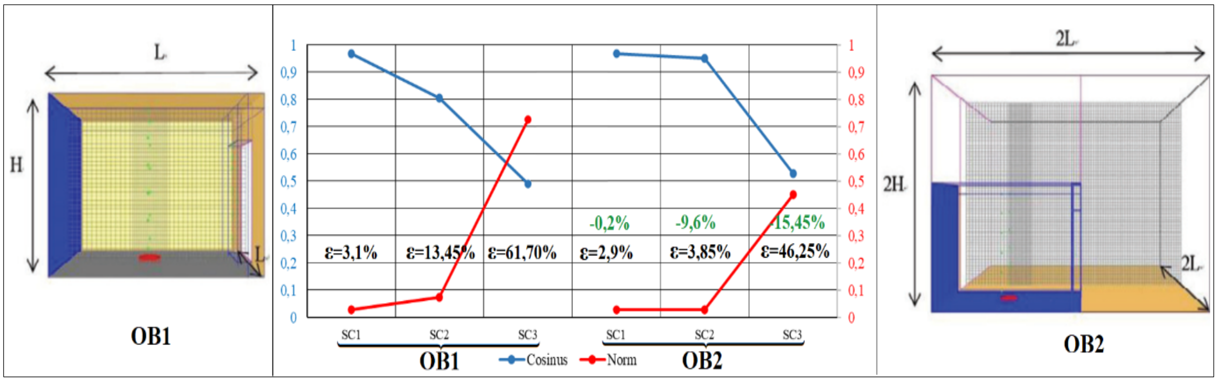


Fig. 2. Analysis of the influence of domain and ventilation conditions on simulation results [19]

It can be seen from Fig. 2 that, with the 8-fold increase in domain size and refinement, the average error between the experimental and numerical model results was reduced by up to -0.2% for SC1, -9.6% for SC2 and -15.45% for SC3, drawing the conclusion that a larger and more refined domain leads to more feasible numerical results independent of the chosen ventilation conditions.

Continuing the research direction started by the previously presented studies [21], [22]**,** Panindre et. al. [23] and Kuti et. al. [24], carried out two simulations to determine the optimal distance of the operational fan from the building’s main entrance and implicitly the dimensions of its reducer, which in the specialized field is used to obstruct part of the surface of the ventilation gap in order to limit the occurrence of multiple-way smoke circulation (Door Open Area Reducer or DOAR). Two scenarios were studied using a DOAR only, or in its absence. The temperature inside the building was monitored in relation to the height between the upper end of the fan and the lower side of the DOAR (k) and the distance from the fan to the entrance of the building (w). These numerical studies developed and highlighted the concept of ventilation by creating a positive pressure (overpressure inside the room) that causes the smoke to be evacuated from the room more quickly. As a result of the two numerical modelling, it was found that the optimal distance for the fan location is between 0.9-1.2 m.

In 2017, following the study of some experiments carried out by NIST [21], [25], Panindre et. al. performed a study based on a computer simulation in FDS [22], in this paper addressing the technical term positive pressure ventilation (PPV) for a fire in an apartment on the 5th floor of a high-rise building. The study demonstrates the efficiency of PPV in reducing temperatures and concentrations of toxic gases in the stairwell and hallway, key locations during the intervention of fire brigades. Six ventilation scenarios were introduced: natural ventilation (NO PPV), ventilation with one fan (PPV) and/or wind control device (WCD+PPV), ventilation with wind control device (WCD), ventilation with two fans located on floors 1 and 3 (2PPV) and ventilation with two fans located in parallel on floor 1 (P2-PPV). Moreover, the wind can also have a significant impact on the evolution of the fire, the influence of wind speed variation was studied at 2.5; 5; 7.5 and 10 m/s for the simulation under natural operational ventilation conditions and 7.5 and 10 m/s for the simulation under forced ventilation conditions by placing one or more operational fans at different levels and/or using a wind control (Fig. 3).

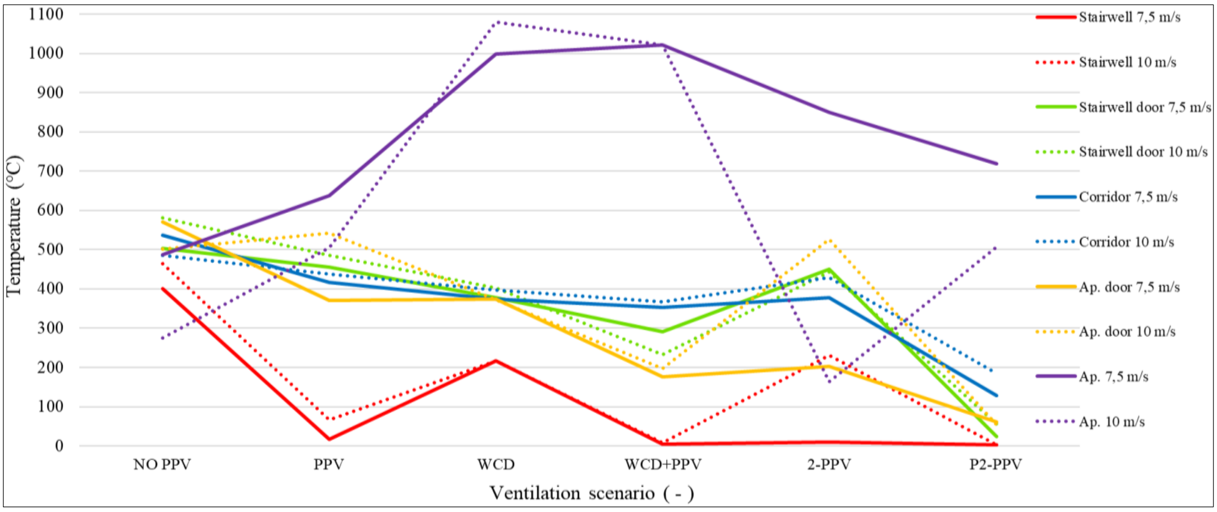


Fig. 3. Analysis of temperature according to ventilation scenarios and wind conditions [22]

In the Fig. 3 the temperature evolution in different locations was depicted depending on the ventilation scenario and the wind speed chosen. The ventilation efficiency is mainly determined by the temperature difference between two landmarks: the stairwell (red) and the burning apartment (purple). If in the case of natural ventilation, the temperature differences between the two benchmarks are around 100 °C, in the case of active ventilation scenarios this value exceeds 600 °C. It can also be seen that in all the active ventilation scenarios a considerably lower temperature is recorded compared to the natural ventilation scenario. Analysing all the ventilation scenarios, we can conclude that the most efficient ventilation method is the one with two fans located in parallel (P2-PPV).

Although the application of a ventilation tactic by creating overpressure inside the building reduces the risk of uncontrolled spread of smoke and flames, in high wind conditions its effectiveness decreases. In these cases where the wind has an important contribution to the fire development, the use of wind control devices (Wind control devices or WCD) simultaneously with the correct application of operational ventilation can significantly increase the pressure recorded inside the building, accelerating the evacuation of gases and reducing the released heat by fire and implicitly the temperatures inside the stairwell and in the hallways, these being the main points of interest during the intervention of the firefighters.

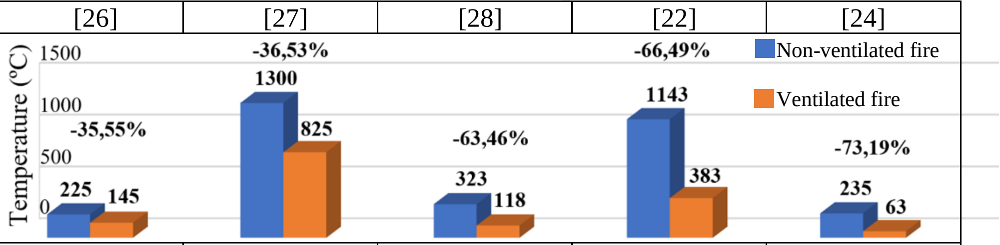
4. Analysis of the influence of ventilation conditions and the stack effect on the fire evolution

The results of the previously studied papers showed a considerable influence of the ventilation conditions on the fire development. Whether we refer to the nature of the ventilation, the environmental conditions or the equipment used, all these have an important impact on the speed of fire spread and the temperatures recorded inside the burning space. Moreover, the stack effect has an important contribution to increasing the speed of fire spread, the influence of this factor increasing exponentially with the height of the burning building.

For studying the influence of ventilation conditions on temperature, the results obtained from 5 studies were compared below. The study of these scientific papers was carried out with the aim of analysing in terms of quality the effectiveness of deliberate ventilation of fires at the expense of faulty ventilation or even its absence, certain input data such as the characteristics of the outbreak, the ventilation conditions, the geometry of the numerical model, the refinement of the domain and the atmospheric conditions do not have close values. It was observed that following the analysis of the 5 numerical studies, the same conclusion can be stated in general, specifically that the ventilation of a fire causes a decrease in the T_{MAX} value by up to 73%, as it can also be seen from the results presented in *Table 1*.

Table 1

Influence of ventilation conditions on temperature

Studies	[26]	[27]	[28]	[22]	[24]
Comparative analysis of T_{MAX} for non-ventilated/ventilated fires					
Ventilation type / ACH	Exhaust Fan $1\ h^{-1}$	Natural Ventilation	Intake Fan (PPV) $45{,}37\ h^{-1}$	Intake Fan (PPV) $12{,}22\ h^{-1}$	Intake Fan (PPV) $24{,}93\ h^{-1}$
T_{MAX} non-ventilated fires	225 ºC	1300 ºC	323 ºC	1143 ºC	235 ºC
T_{MAX} ventilated fires	145 ºC	825 ºC	118 ºC	383 ºC	63 ºC
ΔT_{MAX}	80 ºC **-35,55%**	475 ºC **-36,53%**	205 ºC **-63,46%**	760 ºC **-66,49%**	172 ºC **-73,19%**

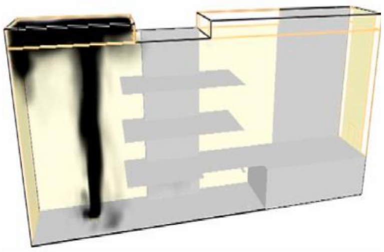
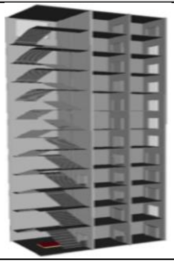
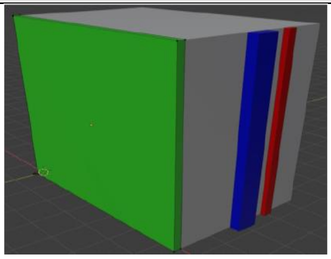
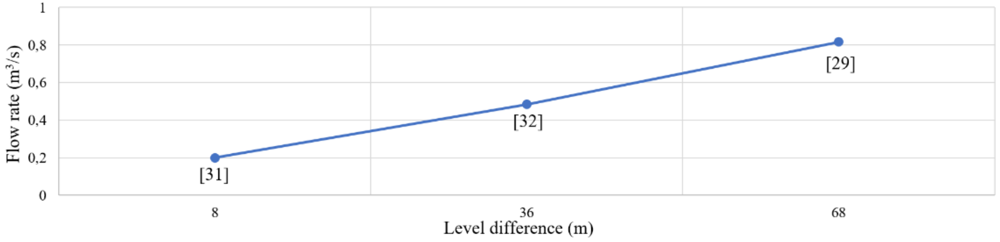
where, ACH represents air change per hour, T_{MAX} represents the maximum temperature measured inside the burning space, and ΔT_{MAX} represents the temperature difference between two compared situations, when the fire is non-ventilated and ventilated.

In order to study the stack effect in high-rise buildings, several studies were consulted in which different software were used, FireSTORM [29], COSMO and CONTAM [30] and PyroSim [31], [32], following the main advantages and disadvantages of each. Moreover, in order to understand the stack effect phenomenon, experimental studies started in this regard were also consulted [30], [33]–[36] concluding that a faithful experimental representation of the stack effect cannot be reproduced by a small-scale experiment. If we refer to tall and very tall buildings, the stack effect is much more present due to the considerable height of vertical gaps, stairwells and elevator shafts.

Analysing the influence of this effect on the speed of fire spread and the speed of smoke flow, it was observed that, for tall and very-tall buildings, the increase in the number of floors from 3 to 17 implies amplifying the fire by 4-5 times. For a level difference of 8 m, the measured flow velocities were around 2 m/s most of the time, at an air flow rate of 0.2 m^3/s. The air flow velocity values varied depending on the size of the ventilation gap between 2 and 4 m/s according to Fig. 3 of [31]. The increase in the level difference to 36 m determined an appreciation of the air flow volume up to the value of 0.484 m^3/s. Later, comparing these results with those of the third study, it was observed that the air mass flow rate increased to the value of 1 kg/s (approximately 0.816 m^3/s), causing an increase compared to the first situation by up to 208% (*Table 2*). The data entered in the table resulted from studying the graphs of the *Cold ff1* case according to Fig. 9 (a) of [29], the difference between the maximum and minimum value tended to 1 kg/s.

Table 2

The influence of the stack effect on fire development

Studies	[31]	[32]	[29]
Numerical model			
Evolution of the flow rate depending on the height			
V_{MAX}	2 m/s	2,18 m/s	4,18 m/s
Z	8 m (3 floors)	36 m (12 floors)	68 m (17 floors)
$\dot{V}_{MAX}$, $\Delta\dot{V}_{MAX}$	0,2 m^3/s	0,484 m^3/s, +142%	0,816 m^3/s, +308%

where, V_{MAX} represents air velocity, $\dot{V}_{MAX}$ represents the volume flow of air in the building, and $\Delta\dot{V}_{MAX}$ represents the difference between two compared situations, [31] with [32] and [31] with [29].

5. Conclusions

The fire ventilation procedure, used properly, determines an easier and safer intervention for the firefighters. As presented in the previously mentioned studies, a non-ventilated fire compared to a ventilated one, due to the stratification and stagnation of smoke, generates a higher temperature throughout the building, while the ventilated fire, natural (passive) or forced (active), will cause a high temperature only within the burning compartment, in the rest of the rooms the temperatures being lower by up to 70%. In addition to the temperature, the effectiveness of the application of fire ventilation tactics was also confirmed in reducing the concentrations of combustion products such as monoxide and carbon dioxide and by increasing visibility, both factors being very important in facilitating the self-evacuation of the occupants of the respective space.

Moreover, for tall and very tall buildings, it was proven, through this research, that fire ventilation is strongly influenced by the stack effect caused by large differences in level, therefore research in this direction is feasible on the conditions of increasing the number of this type of buildings worldwide. The stack effect, along with the increase in the level difference, causes an exponential increase in the flow speed of the air currents. The stack effect causes an intake of air to be drawn to the level of the lower floors and thus, the fire started on a higher floor is continuously supplied with oxygen.

The perspective of studying the stack effect and the overpressure ventilation (PPV) technique profiles a need to start numerical studies in this new direction. In the previously mentioned articles, usually only 1-2 parameters were monitored, predominantly temperature and pressure, but there are others that can provide information on the interdependence between the level difference and other parameters associated with the fire.

Only the continuous study of smoke removal and operational ventilation can lead to innovation in the field of fire security of buildings, a very important feature to significantly reduce the loss of human life, material losses generated by fire and pollution in the urban environment.

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