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Pressure Behaviour of Hot Gases and Smoke in Fires of Large Enclosures with Different Ventilation Systems

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Abstract

This study investigates numerically the pressure behavior of hot gases and smoke in fires of large enclosures. It mainly covers the effectiveness of using natural and mechanical ventilation in changing the pressure behaviour of hot gases and smoke inside different structures. Fire Dynamics Simulator (FDS), provided by NIST, has been used to run the simulations for all proposed cases. For the assumed scenarios, the values of hot gas pressure and temperature are extracted at different points, especially in the hot layer close to the ceiling, for further analysis. The effect of changing the location of the fire source has been investigated, too. Final results show noticeable changes in the behavior of pressure, and temperature, in the presence of different ventilation systems, both natural and mechanical. Thus, appropriate ventilation systems can improve the pressure behaviour inside the place, which offers a better environment and higher safety level, in case of fire, in such large enclosures, open plan offices,

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Introduction

Changing pressure behaviour in fires of open-plane offices and large enclosures can control the temperature behaviour in such large and closed places. An appropriate pressure profile helps get rid of hot gases and smoke inside the building, which are replaced by cool air instead. Introducing cool air offers a higher level of safety and a better environment for civilians and firefighters in such places in case of fire. Both natural and forced ventilation can change the pressure profile and, thus, the temperature profile in these buildings. Changing, or hopefully modifying, pressure behaviour is not clear for the proposed ventilated places. This paper introduces the effect of adding different ventilation systems to the building in modifying pressure profile and other related parameters, such as temperature, hot gases and smoke inside open-plane offices and large enclosures in case of fire. Different studies (Hostikka *et al.*, 2017; Pretrel *et al.*, 2012; Rehm and Forney, 1992; Prétrel and Audouin, 2015) investigated the pressure variation in the fire of enclosures. They found that the behaviour of fire inside the enclosures depends on the air tightness of the place. Increased pressure can lead to a reverse flow in the supply ventilation systems for such cases. The effects of ventilation procedures on the pressure profile of the hot gases of fire in enclosures have been investigated, too (Pretrel and Such, 2005).

Fire experiments are often performed inside resized structures, at reduced scale. This can save money and allow for a sufficient number of experiments. For tests of the resized scale, the scaling relations were applicable by keeping the Froude number constant (Lassus *et al.*, 2010; Lassus *et al.*, 2014; Lassus *et al.*, 2016). Relative pressures lower than atmospheric pressure were measured continuously by a pressure sensor with a sensitivity of ±2 Pa (Lassus *et al.,* 2010). In addition to pressure variations, smoke propagation in the reduced scale induces smoke filling and zone layers (Prétrel and Audouin, 2015), and the burning rate and its strong dependence on the environmental conditions, such as low oxygen levels (Utiskul *et al.*, 2005; Beji and Merci, 2016).

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The availability of powerful computers and well-validated numerical programs have led to the significant development of fire simulations in complex geometries under a wide varieties of parameters, conditions and assumptions. Numerical simulations for such fire events have been conducted with encouraging results (Nasr *et al.*, 2011; Vilfayeau *et al.*, 2015; Perez Segovia *et al.*, 2017, Prétrel *et al.*, 2016). Several fire simulators have been developed and used for different case studies. The Consolidated Model of Fire and Smoke Transport (CFAST) (Peacock *et al.*, 2008) is a two-zone fire model simulator that has been used to study fire behaviour and related changes in the hot gas temperature and smoke inside large enclosures. Fire Dynamics Simulator (FDS) (McGrattan *et al.*, 2010) has been widely used for simulation of fire in public compartments and large enclosures, such as supermarkets (Ling and Kan, 2011) and offices (Matheislova *et al.*, 2010). FDS numerically solves a form of the Navier-Stokes equation that can be used for "low-speed, thermally-driven flow." Turbulence is modelled using Large Eddy Simulation (LES). The combustion model uses a single-step, mixing-controlled chemical reaction that uses three lumped species (i.e., air, fuel and products) and radiative heat transfer is solved by using the radiation transport equation for grey gas (McGrattan *et al.*, 2010).

Delaying the growth of fire inside large enclosures, and open plane offices can play a crucial role in saving lives and improving the safety level in such large places. Dealing with fire and the associated hot gases, chemicals and smoke needs careful attention and more complicated safety procedures. A natural ventilation system, on the one hand, produces a buoyancy effect in the burning compartment (also known as the chimney effect), which helps get rid of the hot gases and smoke inside the place and, thus, lets more cool air come into the burning area. Mechanical ventilation, on the other hand, can offer the required driving forces to do the same effect. The ventilation effect keeps the floor area with lower levels of hot gases and smoke and, thus, offers safer exits for the firefighters and civilians inside the burning building.

1 Materials and Methods

This study investigates changes in the behaviour of pressure of the hot gas and smoke inside two different structures, with and without ventilation systems. Both proposed structures/ cases are:

1.1 First case study: Fire in a large enclosure

Figure 1-b introduces the building of this case study. This building, such as an atrium, has a 20m width, 20m length and 15.5m height (which is the average dimensions of a modern open-office layout). The main inlet door, located at the half of the front building face, has a width of 6m and a height of 3.5m. As a reference case for our calculations, the top vent and the door are replaced with two identical side openings/vents, as shown in Fig. 1-a. Both ones have similar square shapes with an area of 2m x2m. Both are located at half of the same wall; one vent is touching the ceiling of the building and the other one touches the ground floor.

1.2 Second case study: Fire in an open-plan office building

The second case study is a simplified model of a three-story office building with a central atrium (6 m x 6 m) that connects all floor levels into one main door, as shown in Fig. 1-c. The building has 20m width, 20m length and 15.5m height. The main inlet door, located at the half of the front building face, has a width of 6 m, and a height of 3.5 m. In addition to the ground floor, both top ones (first and second floors) are identical in dimensions 20m width, 20m length and 0.5m thickness, and are separated by a distance of 3.5m height from each other. The ceiling, walls and floors are made of gypsum board 1/2in, for all investigated cases.

As a reference case for the calculations of this structure, the top vent and main door are replaced with two identical side openings, as shown in Fig. 1-d. Both have similar square shapes with an area of 2mx2m. Both are located at half of the same wall; one vent touches the ceiling of the building and the other one touches the ground floor.

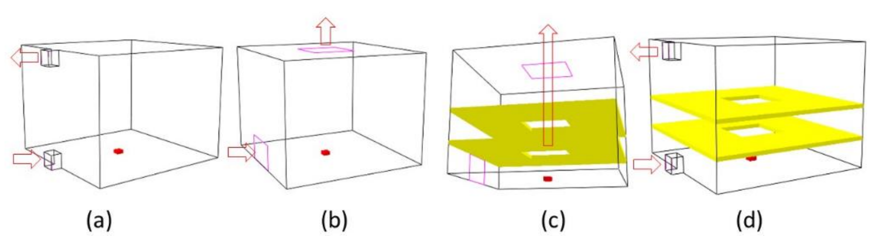

Fig. 1 (a) First case study: An atrium, with a width of 20m, length of 20m, and height of 15.5m. (b) An atrium with two identical side vents/openings, 2mx2m, was used as a reference case for our calculations. (c) Second case study: Three-plan office building with a central atrium with an area of 6mx6m). The building has a width of 20m, length of 20m, and height of 15.5m. (d) An open-plan office building with two identical side openings, 2mx2m, was used as a reference case for our calculations.

The behaviour of the hot gas is numerically investigated, in case of fire in both structures, for two different ventilation systems, natural and mechanical. Only the early fire growth stage, at the first ten minutes from the beginning of the fire, is calculated and analyzed, *i.e.* the simulation time is 600s for all assumed scenarios. The fire source (burning sofa) is assumed for all cases. However, any similar office furniture, with the same equivalent heat release rate, can be used to replace the sofa, too. Fig. 1 shows the sofa in the centre of the ground floor for all proposed cases.

2 Results and Discussion

To improve the safety level inside the proposed structures/ buildings, different scenarios are numerically simulated and introduced for both structures.

2.1 First case study: fire in a large enclosure (Atrium):

Three scenarios are proposed for analyzing this case study:

First scenario; the first proposed scenario is for a fire inside an atrium with two identical side vents of 2mx2m, as shown in **Figure 2**. Natural ventilation takes a place throughout both side vents, only. Second scenario; the second proposed one is for fire inside an atrium with two identical side vents, as shown in Fig. 2. Mechanical ventilation (fan with an area of 2mx2m) has been fixed inside the top side vent. The Fan has a volumetric flow rate capacity of (10 m3/s), to get rid of the hot gases and smoke from the building. the bottom vent is fully opened and nothing inside. Third scenario: the third proposed scenario is for fire inside an atrium with a top vent in the centre of the ceiling 4mx4m, and a door 6mx3.5m, as shown in Fig 1-b.

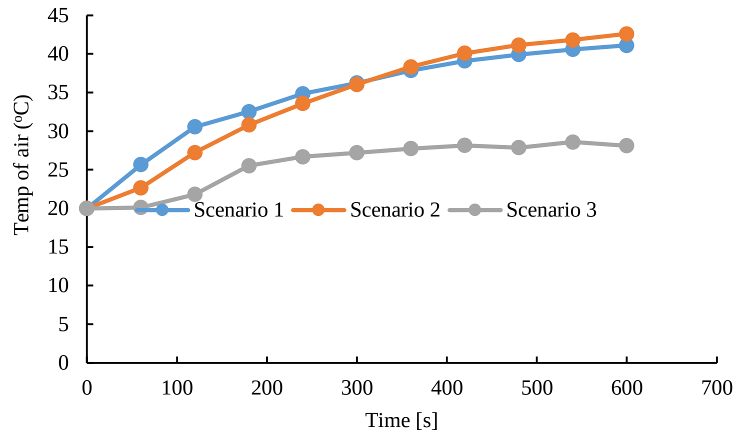

Fig. 2 Average temperature of the hot gas (AT) as a function of time (*t*) inside the hot layer, at a level of (0.5m) below the ceiling, for a burning sofa inside the atrium. Scenario 1 is for a fire inside an atrium with two identical side empty vents (reference case). Both vents have dimensions of (2mx m). For Scenario 2, the top side vent has a fan inside (mechanical ventilation). For Scenario 3, the atrium has a ceiling vent and door (natural ventilation).

The numerical simulations for these proposed scenarios have been conducted and analyzed. Fig 2 shows the average temperature of the hot gas inside the atrium as a function of time (t) for the above-mentioned scenarios (1-3). A side vent with a fan inside the top vent has no significant effect in reducing the average temperature inside the hot layer, 0.5m below the ceiling level. The ceiling vent (natural ventilation) plays a major role in reducing the temperature inside the hot layer by 14 degrees, compared to that of scenario 1 (reference case: side empty vents), (10 minutes) from the beginning of the fire inside the atrium. **Figure 3** shows the average pressure of the hot gas (AP) inside the atrium as a function of the height (m) for both scenarios 1 and 2. For this case, the fan reduces the height of the neutral plane by 2 meters, from 8m to 6m. Here, the level at the neutral plane has a zero pressure (AP=0).

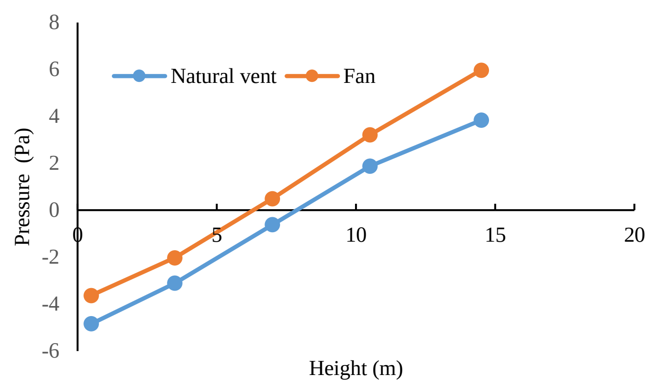

Fig. 3 Average pressure of the hot gas (AP) inside the atrium as a function of the height (m) for both scenarios 1 and 2.

2.2 Second case study: fire in an open-plan office building

Figure 4 shows the average temperature of the hot gas as a function of time (*t*) for scenarios 1-3. The calculated temperature is at a level of 0.5m below the ceiling of the building, which is inside the hot layer. A side vent with a fan inside (mechanical ventilation) has no significant effect in reducing the average temperature inside the hot layer. The ceiling vent (natural ventilation) reduces the temperature of the hot layer by about 5 degrees, compared to that of scenario 1 (reference case), after 10 minutes from the beginning of the fire inside the atrium.

Figure 5 shows the average pressure of the hot gas (AP) inside the building as a function of the height (m) for both scenarios 1 and 2. Here, the fan could not reduce the height of the neutral plane, due to the presence of the two floors inside the building. The hot gas and smoke for this case are shown in **Figure 9-a**. The presence of the two floors improves the safety level on the ground floor in this case.

Figure 7 shows the average pressure of the hot gas (AP) inside the building, at different locations of the fire fuel (burning sofa), as shown in **Figure 6**. Location 1 has the fire on the ground floor at a distance of (3.5 m) from the wall and aligned with the centres of both side vents. Moving the fire upward increases the average temperature inside the hot layer in the fire growth stage. It reaches (53 C) when the fire locates on the second floor. Also, moving the fire upward increases the height of the neutral plane, as shown in **Figure 8**, especially, when the fire is located on the second floor. Figure 9 clarifies well this point. Fire in the upper floors offers a safer environment with lower levels of hot gases and smoke in the lower floors below the fire fuel.

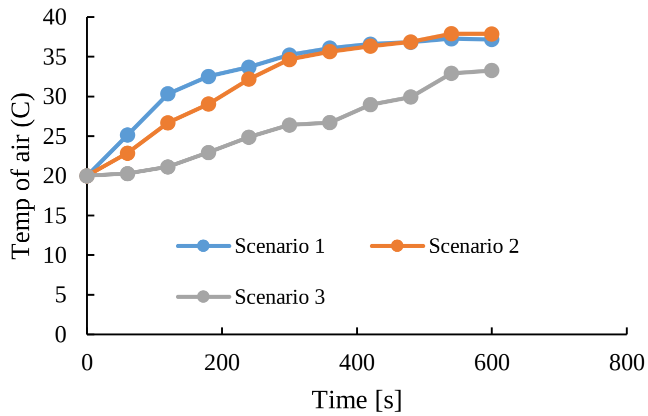

Fig. 4 Average temperature of the hot gas (AT) as a function of time (*t*) at a level of 0.5m below the ceiling, inside the hot layer, for the open-plan office building. Scenario 1 is for a fire inside the building with two identical side empty vents (reference case) with an area of 2mx2m. For Scenario 2, the top side vent has a fan inside (mechanical ventilation). For Scenario 3, the building has a ceiling vent and door (natural ventilation).

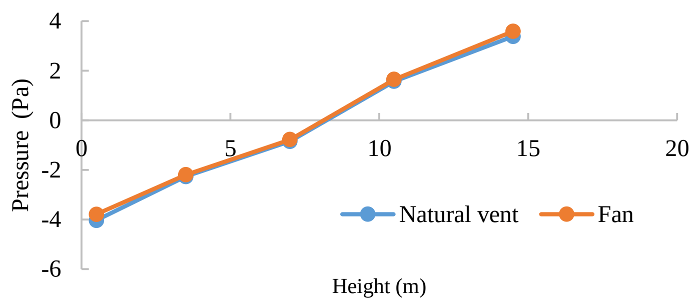

Fig. 5 Average pressure of the hot gas (AP) as a function of the height (m) inside the open-plan office building for both scenarios 1 and 2.

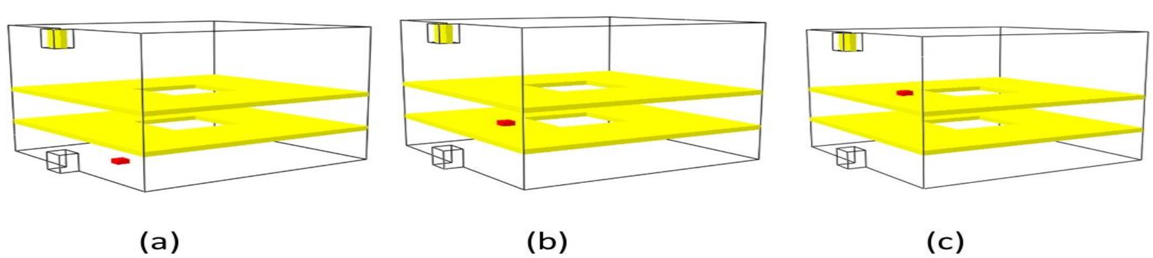

Fig. 6 The effect of changing the location of fire on pressure and temperature is investigated for, (a) fire on the ground floor at a distance of 3.5m, from the wall and aligned with the centers of both side vents, (b) on the same location of point (a), but at the first floor, (c) on the same location of point (a), but at the second floor.

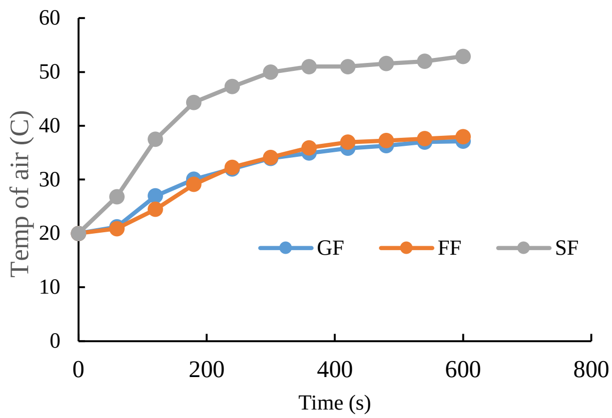

Fig. 7 Average temperature of the hot gas (AT) as a function of time (*t*) at a level of 0.5m, below the ceiling inside the hot layer of the open-plan office building. The location of the fire has been changed, GF is for the fire on the ground floor, FF is for the fire on the first floor and SF is for the fire on the second floor.

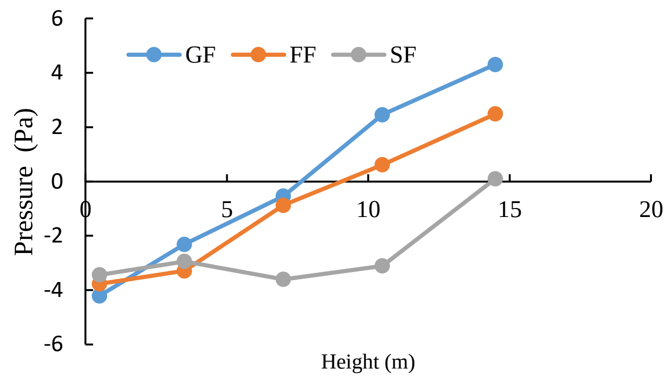

Fig 8 Average pressure of the hot gas (AP) inside the open-plan office building at different locations of fire. Here, GF is for the fire on the ground floor, FF is for the fire on the first floor and SF is for the fire on the second floor.

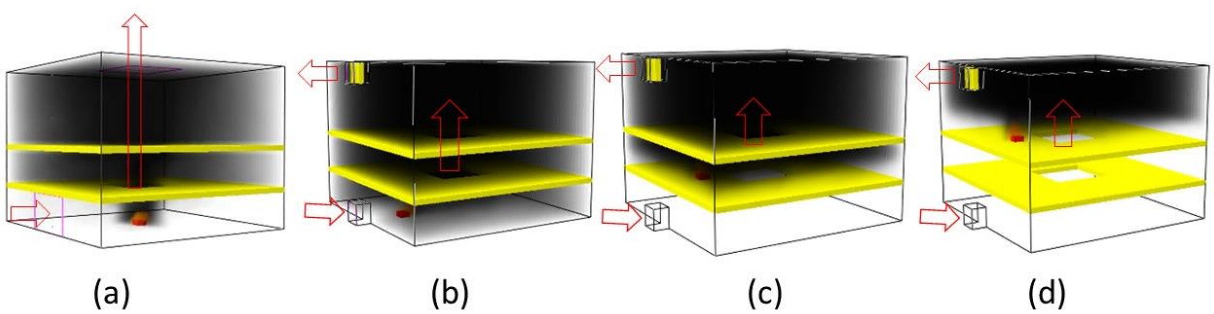

Fig. 9 The hot gases and smoke in the building 10 minutes from the beginning of the fire inside the open-plan office building, (a) the building has a door and ceiling vent only, the fire is in the centre of the ground floor (b) the building has side vents only, fire is on the ground floor at 3.5m, from the wall, aligned with the centres of both side vents, (c) fire is on the same location of b, but at the first floor, (d) fire is on the same location of b, but at the second floor.

Conclusion

This study investigates numerically the behavior of pressure and temperature of the hot gases and smoke in fires of large enclosures and open plane offices for different proposed scenarios and cases. It covers mainly the effectiveness of using natural and mechanical ventilation in changing the behaviour of pressure and temperature of the hot gas inside different structures. Fire Dynamics Simulator (FDS), provided by NIST, has been used to run the simulations for all proposed cases. The proposed atrium in the open-plan office building can help apply natural ventilation efficiently in the building, by creating a venturi effect inside the central gap. For both structures, the atrium and open-plan office buildings, natural ventilation can help reduce the temperature inside the hot layer, similar to that achieved by using mechanical ventilation (fan). Natural ventilation can reduce the temperature, due to the buoyancy effect (i.e. chimney effect) in the burning region. Ventilation systems help reduce pressure in the lower part of the building and create a better vacuum system in place. This will let more cool air come into the smoky area. Thus, it keeps the floor area with lower levels of hot gases and toxic smoke, which will offer safer exits for the firefighters and civilians inside the building. Changing the location of the fire can play a role in improving the behaviour of pressure and temperature inside the building in the fire growth stage, fig 9. The improvement in the behaviour of pressure and temperature in the place will offer less aggressive behaviour of the fire and, thus, hot gases and smoke inside the buildings. Natural ventilation will offer cheaper and cleaner solutions to improve the safety level and environmental conditions inside the building. It will also improve the lighting in the place and go hand-in-hand with the green solutions. Thus, it will reduce the cost of consumed energy in such places.

Nomenclature

AP	=Average pressure	Pa]
AT	=Average temperature	[ºC]
H	=Height	[m]
L	=level	[m]
t	=time	[s

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