Fire-induced Pressure in Passive Houses: Experiments and FDS Validation

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ABSTRACT

The need for sustainability and smaller ecological footprint leads to the construction of more airtight building envelopes with better thermal insulation in order to increase the energy efficiency of houses, according to the Energy Performance of Buildings Directive. The specific fire hazards possibly associated with such structures has raised questions amongst the fire community in Belgium. A full-scale experimental facility was built in the region of Mons to study the effects of the airtightness of the building envelope and the mechanical ventilation on fire hazards and especially on fire-induced pressure. Two different ventilation duct configurations were tested: one with mechanical ventilation on, the other one with the ducts closed with an airtight metal cap, the mechanical ventilation being off. Measurements were made for gas pressure, mass loss rate, gas temperature, volumetric flow rate in the ducts and, for some tests, O2, CO2, CO and THC concentrations were also quantified. Pressure peaks from 850 to 2035 Pa were measured without mechanical ventilation (ducts closed), while values from 420 to 750 Pa were observed with the mechanical ventilation on. The mechanical ventilation network is not sufficient to prevent pressure inside the rooms. The occupants may not succeed in escaping during a period of several minutes due to the impossibility to open inward opening doors linked to this fire-induced pressure. This experimental campaign was also used for validating the field model FDS predictive capability. The way to take into account the effective leakage, which depends on the pressure level inside the building, as well as the mechanical ventilation for obtaining satisfactory simulation results are presented in this paper. The use of validated software could be helpful to take into account the fire-induced pressure in confined dwellings in fire safety design.

KEYWORDS: Passive house, fire growth, pressure, modelling, FDS.

INTRODUCTION

The need for sustainability and smaller ecological footprint leads to the construction of more airtight building envelopes with better thermal insulation in order to increase the energy efficiency of houses, according to the Energy Performance of Buildings Directive [1]. The specific fire hazards possibly associated with such structures has raised questions amongst the fire community.

Some fatal accidents during the intervention of fire brigades were reported in the past due to a backdraft phenomenon in airtight and insulated renovated apartment [2-4]. Nowadays, the likelihood of backdraft is well recognised by fire brigades, and new operational procedures have been developed in order to take into account this particular hazard.

The specific fire hazards for the occupants have also raised questions within the fire community in Belgium. In 2010 the Belgian Ministry of Interior funded a study for investigating how much the characteristics of a passive house such as airtightness, ventilation and thermal insulation could affect the fire development [5]. From numerical simulations, a significant pressure rise due to the

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thermal expansion of fumes was calculated due to the airtightness in the passive house. The scientific monitoring committee of the project decided not to communicate this potential problem because of a lack of validation from experimental data at large scale, even though inwards-opening doors could block the occupants during a certain period.

In the meantime, pool fire experiments were already conducted in well-confined and force-ventilated enclosure for practical application in the nuclear industry, and pressure up to 3500 Pa were measured leading to flow inversion in the ventilation network [6]. These results were also used to validate the capability of a field model regarding the pressure and showed that great care should be taken in modeling the leakage area [7]. However, it can be noticed that the air changes per hour fixed for the mechanical ventilation in these buildings are somewhat high for residential buildings and the area leakages are particularly low.

More recently, heptane pool and polyurethane mattress fires were carried out inside a real 150 m^3 apartment [8]. Although an air change per hour of about 2.9 h^{-1} was measured at 50 Pa from a blower door test, pressures from 100 to 1650 Pa for short periods were observed during the fire development. During this period of high pressure, it was not possible to open an inwards-turning door by pulling from inside. This experimental campaign was used for validating the predictive capability of FDS and gave good results even though experimental uncertainties were encountered for the ventilation system configuration, the fan characteristics and the additional leakage due to high pressures.

The objective of this study is to quantify the pressure induced by fires in airtight compartment with air changes per hour close to the ones encountered in passive houses (0.6 h^{-1}). A full-scale experimental facility was built in the region of Mons. All the elements of the setup such as ventilation system configuration, fan characteristics and additional leakages were well characterized to validate the capability of FDS to predict fire-induced pressures [9].

EXPERIMENTAL SETUP

Geometry-ventilation measurements

The full-scale facility has the same inner dimensions of a 40-foot shipping container (12 m length, 2.38 m width and 2.44 m height), the wall being composed by three layers (0.26 cm plasterboards, 5 cm insulation and 20 cm concrete blocks). The floor and the ceiling are made of 15 cm concrete slabs; the latter is insulated with 5 cm of mineral wool protected by 13 mm thick plasterboards to reduce the heat losses. All the information about the test setup is given in Vanhaverbeke [10]. The building has no window but only one external door 2.15 m high, 0.9 m wide and 0.04 m thick composed of two layers of galvanized steel covering a stratum of polyurethane foam. The structure is divided into two compartments: the first room is 4 m long, the second one is 8 m (Fig. 1). They are separated by a 0.12 m thick wall composed of a steel stud frame filled with mineral wool covered with plasterboard on both sides. There is also one door between the two rooms which is closed during fire tests. There is a space of about 1 cm height between the floor and the bottom of this door which is useful for air circulation between the two rooms. The ventilation of the building is guaranteed by two fans branded Soler & Palau, type TD-250/100 SILENT, placed in the ducts outside the construction. In particular, the maximum static pressure was about 145 Pa and the maximum volume flow rate corresponding to zero pressure was about 240 m^3.h^{-1} (Fig. 2). For the experiments, it is assumed that the large room (which is the fire room) is dry such as a living room and air is supplied in it, whereas the small one is moist such as a bathroom and air is extracted from it [11]. An adjustable orifice plate (damper DIRU) was used for creating a pressure drop in order to adjust the airflows in the ducts. The installed value in this case is 75 m^3.h^{-1} leading to an air change per hour of about 1 h^{-1}. The damper DIRU with flow meter offers measurements of pressure drop and temperature and thus the airflow rates in the ventilation network.

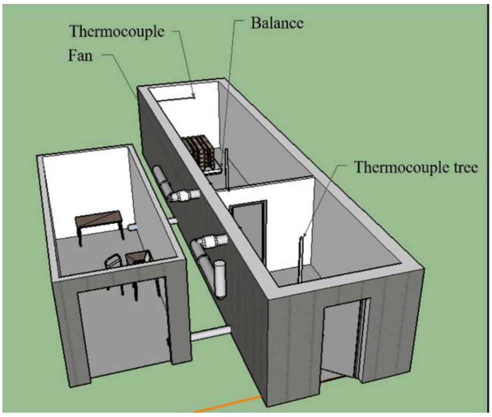


Fig. 1. View of the experimental setup

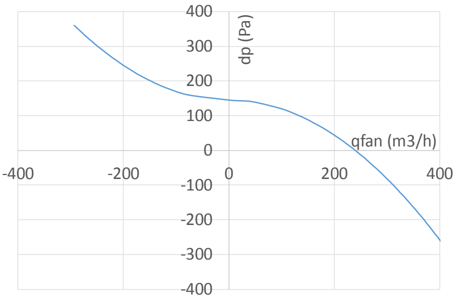


Fig. 2. Quadratic model for fan curve (FDS)

Preliminary tests were carried out in 2016 with stacks of 5 pallets instead of a liquid fuel pan in order to have a more realistic fire scenario. Unfortunately, there were some problems of repeatability for the HRR (Fig. 3c). Consequently, wood cribs of 15 layers of pine slats were used as fuel load in the second part of this study. Two different cribs were used: a layer of 5 pine slats of 380x27x18 mm^3 (small crib) and a layer of 8 pine slats of 594x30x17 mm^3 (large crib). The ignition of the fuel load was carried out with heptane pans. Each fire load was tested with both different ventilation duct configurations. As can be seen in both Fig. 3a and Fig. 3b, good repeatability was obtained for the HRR with the wood cribs.

Measurements were made for gas pressure in the fire room and between the two rooms, gas temperatures in the center of each room by using 1 mm in diameter K-type thermocouples trees with 0.2 m vertical separation, fuel mass from load cell and airflow rate in the ducts (Fig. 1). For pallets fire tests, O_2, CO_2, CO and THC concentrations were also quantified. The mass loss rate was calculated from a smoothing technique and the HRR was then calculated. The heat of combustion was estimated through lab-scale experiments with a cone calorimeter.

NUMERICAL MODELING WITH FDS

The results obtained from the experimental setup were used to validate the capability of FDS to predict major parameters such as pressure, temperature, volumetric flow rate in the ducts in case of fire in a passive structure. All simulations were done using FDS 6.3.2 [12]. The reader is referred to McGrattan et al. [12] for details on the FDS equations and default settings.

Mesh resolution

A uniform mesh was used with cubic cells of 10x10x10 cm^3. The non-dimensional expression $D^*/\delta x$ was used to calculate the suitable mesh size δx, where the characteristic length is calculated according to:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty\, c_p T_\infty \sqrt{g}}\right)^{2/5}, \qquad (1)$$

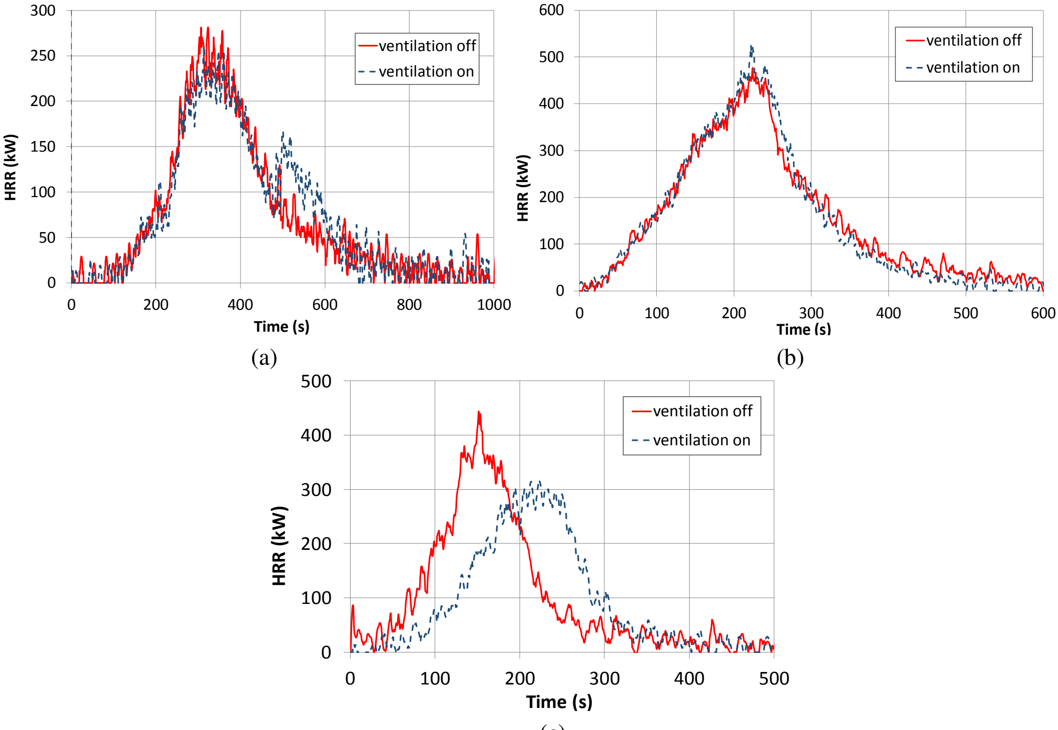
where $\dot{Q}$ is the HRR (kW), ρ_∞ is the ambient air density, c_p is the specific heat of the fluid, T_∞ is the ambient air temperature. A 0.7 m characteristic length was estimated from a peak HRR of 500 kW.

The recommended ratio of $D^*/\delta x$ is between 4 and 16 leading to a mesh cell size respectively of 0.2 and 0.05 m. A 0.1 m mesh cell size was chosen in this study.

In addition to the fire source, all the elements of the setup such as ventilation system configuration, fan characteristics and additional leakages were well characterized in order to use the experimental data for FDS validation.

Fire source

The HRR, which is a key parameter for the calculation of the pressure inside the compartment, was calculated from the experimental data and used as input for all the simulations (Fig. 3). The mass loss rate was calculated from a smoothing technique and the HRR was then calculated. The heat of combustion of the pine slats (12 MJ/kg) was estimated through lab-scale experiments with a cone calorimeter.



(a)

(b)

(c)

Fig. 3. Heat release rate. (a) small crib; (b) large crib; (c) pallets.

Natural leakages

The natural leakages are also a key parameter for the calculation of the pressure inside the compartment. The volume flow $\dot{V}_{leak}$ through a leak of area A_L is given by:

$$\dot{V}_{leak} = A_L sign(\Delta p)\sqrt{2\frac{|\Delta p|}{\rho_\infty}}, \qquad (2)$$

where ρ_∞ is the ambient density, Δp is the pressure difference. The discharge coefficient is assumed to be 1 in FDS. The volume flow and thus the airtightness of the set-up was measured using a blower door test (ASTM E 779) both ducts being closed with an airtight metal cap. A value of air exchange rate of 1 h^{-1} was obtained at 50 Pa overpressure. From these measurements, a 19 cm^2 leakage area was calculated according to Eq. (2).

The blower door test at 50 Pa was repeated before each fire experiment in order to check the airtightness of the building. Since 2016, the airtightness has been found to be constant, so the building has not been damaged by the fires.

Modeling of the HVAC system

The solver computes the flows through a duct network as a mapping of duct segments and nodes, where a node is either the joining of two or more ducts or where a duct segment connects to the FDS domain [12]. Instead of writing an HVAC system as each individual fitting or duct with its associated area and loss, an equivalent duct was constructed by using the total length of the duct and a representative area A_{eff}.

The pressure losses associated with all the segments of the duct were collapsed to a single effective loss K_{eff} by summing all of the fitting losses K_{minor} through the duct as follows [12]:

$$K_{eff} = \sum_i (K_{\mathrm{minor}})_i \frac{A_{eff}}{A_i} \qquad (3)$$

where i is a fitting and A_i is the area associated with the fitting loss.

In this case, K_{eff} is calculated for each fire test by considering the duct, the expansion fitting and contacting fitting of the fan, the elbow and the diaphragm (the opening of the diaphragm could be different from one test to another).

The quadratic fan model was used for the modeling of flow rate of the fan:

$$\dot{V}_{fan} = \dot{V}_{max} \;\; sign(\Delta p_{max} - \Delta p)\sqrt{\frac{|\Delta p - \Delta p_{max}|}{\Delta p_{max}}}, \qquad (4)$$

where $\dot{V}_{max}$ is the free volume flow, Δp_{max} is the stall pressure of the fan, Δp is the pressure difference between the downstream compartment and the upstream. In this case, the maximum volume flow rate is 0.067 m^3/s (approximately 240 m^3/h) and the maximum pressure is 145 Pa. This quadratic model leads to a good representation of the fan characteristics given in the technical file of the manufacturer.

RESULTS AND DISCUSSION

Experimental results

For all the tests carried out in the experimental setup, the same behavior is observed for the fire-induced pressure inside the building as the one observed for pool fire in a well-confined and forced-ventilated compartment carried out in the nuclear industry [6]. Before fire ignition, the pressure inside the building is zero, the air flow rate supplied in the dry room is equilibrated with the air flow rate extracted from the wet room. From heptane pool ignition and during the growing phase of the wood crib fire, the pressure increases until a peak is obtained. Then due to a lack of burning fuel (small crib) or to a lack of oxygen (large crib), the HRR decreases, a rapid decrease of the pressure is measured and a negative pressure peak is observed. Then, the pressure increases to return progressively to zero. For the large crib, a stationary oscillatory phenomenon is observed at the end of the test, the combustion regime being under-ventilated.

Pressure peaks from 850 to 2035 Pa were measured without mechanical ventilation (ducts closed), while values from 420 to 750 Pa were observed with the mechanical ventilation on. The mechanical ventilation network succeeded in lowering the pressure by helping the evacuation of the fumes.

Before ignition, an air flow rate of 75 m^3/h is set in both ventilation ducts thanks to the dampers. When the HRR increases, the pressure rises as well and pushes the fumes out of the compartment, the flow rate of the extraction duct grows, whereas the flow rate of the incoming air decreases and becomes negative (flow inversion) when the pressure is higher than 145 Pa, the maximum static pressure of the fan (Fig. 2). When the HRR decreases, the pressure decreases consequently, and fresh air can be supplied again in the dry room when the pressure drops below 145 Pa. For some experiments, a flow inversion can also be observed in the exhaust duct at extinction.

It can be noticed that the ventilation network is not sufficient to prevent high pressure. The overpressure of 150 Pa is the threshold value below which most people could open an inward door. It can be observed that in such airtight structures, a period corresponding to a fire-induced pressure higher than this 150 Pa threshold can last 3 minutes. Consequently, the occupants may not succeed in escaping due to the inward door opening for a period that can last 3 minutes in case of fire. These results confirm the observations carried out during the reconstruction of the fire in a passive apartment in Cologne in the night of 5 February 2013, when the occupant was blocked during 2 minutes [13].

Modeling results

Ventilation off (and ducts closed)

Both the HRR and leakage area which are key parameters were fixed as input data in FDS. At first, a constant leakage area of 19 cm^2 was fixed from the results obtained through the blower door test at 50 Pa. Two different approaches were used for modeling the leakages in FDS: the localized leakages and the pressure zone leakages.

For the first model, the 19 cm^2 leakage area was divided by two in order to put one leak area in each room. This leak was located at a height of 1.4 m from the floor. The 9 cm^2 leakage under the partition door between the two rooms was also taken into account in FDS. This approach was not satisfactory for the fire tests because the pressure calculated by FDS was overpredicted by a factor of 4 when the mechanical ventilation was off.

In a typical building, as the pressure increases, the leakage area increases as small gaps, cracks and other leakage paths open up. The leakage areas were measured over a broader pressure range Δp (0-600 Pa) according to the ASTM E779 for improving validation of the model. The leakage areas can be expressed as a function of the pressure according to the following equation:

$$A_L = A_{L,ref}\left(\frac{\Delta \mathrm{p}}{\Delta p_{ref}}\right)^{n-0.5}. \tag{5}$$

From this new blower door test, a value of 0.7 was measured for the leak pressure exponent (n) and a value of 19 cm^2 was obtained for the leak reference area at the leak reference pressure of 58 Pa (Fig. 4).

From Eq. (5), the maximum pressure measured in a fire test was used for calculating the leakage area (for the localized leakage model). For the small crib, 33 cm^2 was obtained for the leakage area (which corresponds to a maximum pressure of about 870 Pa). This leakage area was divided by two and located in each room. This leakage area improves the fire-induced pressure calculated by FDS compared to the measured values but a difference of about 50% is observed in Fig. 5a. In this figure, the fire-induced pressure calculated by CFAST is also plotted as a function of time taking into account the effect of pressure on the leakages area [14]. Similar results are obtained for FDS and CFAST when the localized leakages model is used.

The pressure zone approach instead of the localized leakage model was then used in FDS for modeling the leakages. The walls and the ceiling were set as leak paths. Two pressure zones corresponding to the two rooms were defined in FDS, the partition door being closed during the fire experiments. In the default settings of FDS, the leakage area is constant, the leak pressure exponent in Eq. (5) being 0.5. In this modeling, the leakage area was not considered constant. Equation (5) between the leakage area and the overpressure was used with a value of 0.7 for the leak pressure exponent and 19 cm^2 for the leak area for the leak reference pressure of 58 Pa. This leakage area was divided by two and located in each room. The leakage under the partition door between both rooms was also taken into account (9 cm^2).

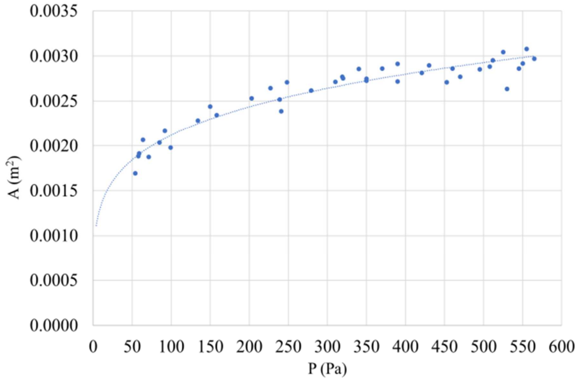
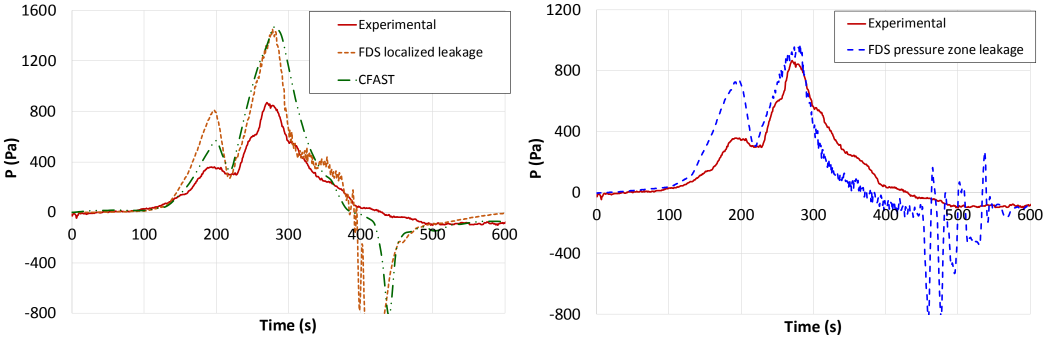


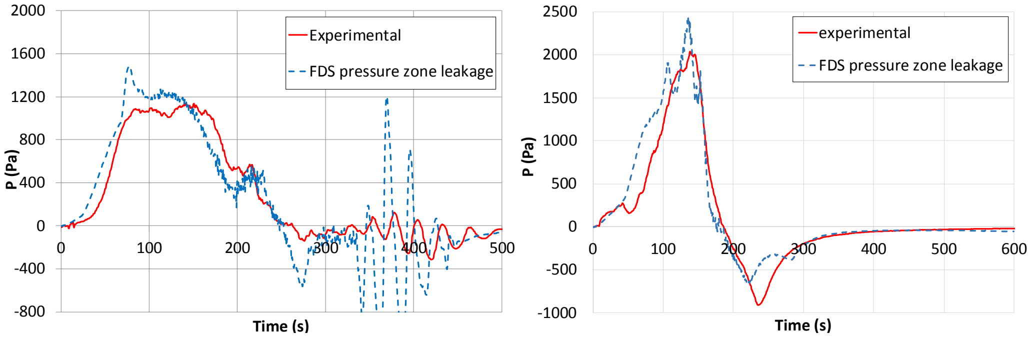
Fig. 4. Relation between leakage area and overpressure



(a) Localized leakage model

(b) Pressure zone leakage model

Fig. 5. Predicted pressure compared to the experimental results for the small crib



(a)

(b)

Fig. 6. Predicted pressure compared to the experimental results for the large crib (a) and the pallets (b).

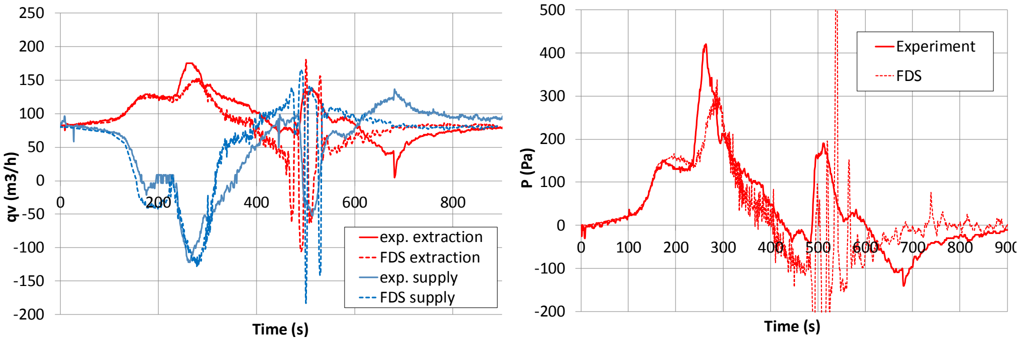
Figure 5b displays the trend of the calculated pressure according to the pressure zone leakage approach compared to the experimental one. As can be seen, good results are obtained with this approach.

Satisfactory results between the pressure calculated from FDS with the use of both pressure zone leakages approach and Eq. (5) and the experimental ones are also obtained for the large crib and the pallets (Fig. 6).

Ventilation on

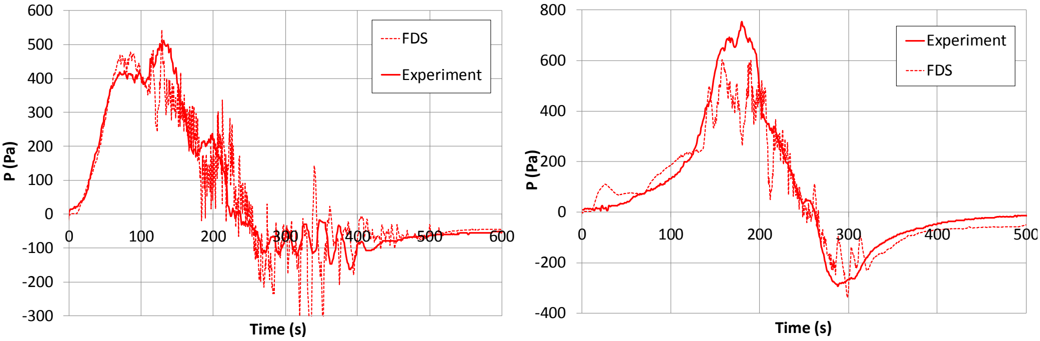
The natural leakages were modeled using the pressure zone leakages approach and the effect of pressure on the leakage area was also taken into account according to Eq. (5) (see section “Ventilation off”). Moreover, for the tests carried out with mechanical ventilation on, both the fan curve and the loss coefficients in the ducts were taken into account in the HVAC system modeling.

Prior to ignition, volumetric flow rates at the inlet and outlet of the compartment are in good agreement with the experimental measurements (75 m^3/h). During the growing phase of the fire, the HVAC model leads to a flow rate in good agreement with the experimental data. The HVAC model takes into account the reverse flow at the inlet of the compartment when the fire-induced pressure is higher than the stall pressure of the fan. The HVAC model takes also into account the extra flow rate at the outlet of the compartment due to the fire-induced pressure (see Fig. 7a for the small crib). During the decreasing phase of the fire, the HVAC model leads to volumetric flow rates which return progressively to 75 m^3/h.



(a) (b)

Fig. 7. Predicted flow rates (a) and pressure (b) compared to the experimental data for the small crib



(a) (b)

Fig. 8. Predicted pressure compared to the experimental data for the large crib (a) and the pallets (b)

The pressure inside the compartment calculated in FDS taking into account the natural leakage and the HVAC system is also in good agreement with the experimental data measured for the small crib (Fig. 7b). FDS leads also to pressures similar to the ones measured in the experimental setup for the tests carried out with the mechanical ventilation for the large crib and the pallets (Fig. 8).

CONCLUSIONS

Full-scale experiments were carried out in an airtight building similar to the passive house concept in order to measure pressure induced by fires. Pressure peaks from 850 to 2035 Pa were measured without mechanical ventilation (ducts closed), while values from 420 to 750 Pa were observed with the mechanical ventilation on. Both the reverse flow of the fan supplying fresh air and the extra flow rate of fumes in the extraction duct due to the high pressure inside the setup were not sufficient to prevent high pressure inside the rooms. All these experiments highlight the fact that there may be problems of pressure in very airtight houses in case of fire. Especially, the occupants may not succeed in escaping due to the inward door opening for period that can last 3 minutes. The experiments were also used for validating the field model FDS predictive capability in terms of fire-induced pressure and ventilation system. The use of validated software could be helpful to take into account the fire-induced overpressure in confined dwellings in fire safety design.

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