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Overpressure induced by fires in airtight buildings

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Overpressure induced by fires in airtight buildings

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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 reduce the pollution and increase the energy efficiency, according to the Energy Performance of Buildings Directive (EPBD 2010/31/EU).
The specific fire hazards possibly associated with such structures raised questions amongst fire community in Belgium. Consequently, in 2010 the Belgian Ministry of Interior funded a study about the fire hazards possibly associated with Passive Houses in comparison to traditional houses. The University of Mons and ISSeP used zone modelling for investigating how much the characteristics of a passive house such as airtightness, ventilation and thermal insulation could affect the fire development. A significant difference in pressure rise (due to thermal expansion of fumes) was observed because of the airtightness in the passive house. However, due to a lack of validation from experimental data at large scale, the scientific monitoring committee of the project decided to not mention the potential problem that the forces of pressure could block the occupants during a certain period due to inwards-opening doors.

It was decided in 2015 to build a full-scale experimental facility in the region of Mons with the support of the KCC centrum and the Régie Provinciale du Hainaut. This facility was designed with the support of the Ghent University. The inner dimensions of the construction are the same as the inner dimensions of a 40-foot shipping container, but the outer shell consists of 20 cm concrete blocks and the inner shell is made of plaster board. The volume is divided into two rooms, which simulate two different rooms of a passive house. In one room air is extracted, while in the other one fresh air is supplied.

In this study, we present the tests carried out in this facility by burning pallets stack and wood cribs. Two different ventilation duct configurations were tested: one with mechanical ventilation on, the other 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 O_2, CO_2, CO and THC concentrations were also quantified. Over 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 overpressure inside the apartment were not sufficient to prevent overpressure inside the rooms. These tests confirm there may be problems of overpressure in very airtight houses such as passive houses in case of fire. Especially, the occupants may not succeed in escaping during a period of several minutes due to the impossibility to open inward opening doors. This experimental study confirms the observations carried out during the reconstruction of the fire which occurred during the night of the 5 February 2013 in an passive apartment in Cologne, the occupant being blocked for about 2 minutes.

This experimental campaign was also used for validating the zone model CFAST predictive capability. The way to take into account the effective leakage which depends on the overpressure inside the building as well as the mechanical ventilation in CFAST for obtaining satisfactory simulation results are briefly presented in this paper. The use of validated software could be helpful to take into account the fire-induced overpressure in confined dwellings in fire safety design.

KEYWORDS

Passive house; compartment fires; fire growth; overpressure; modeling; CFAST

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 reduce the pollution and increase the energy efficiency, according to the Energy Performance of Buildings Directive (EPBD 2010/31/EU) [1]. In such structures, one might wonder if there are specific risks in case of fire.

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]. On March 28, 1994, at 62 Watts Street in Manhattan, New York City, a fire took place in a three-story apartment that had been renovated by installing new windows and doors, minimizing air infiltration and setting up heavy thermal insulation [3]. Upon an emergency call, firefighters arrived and saw smoke coming from the chimney but no other signs of fire, so they decided to open the door of the apartment on the first floor where the fire took place leading to a backdraft and killing the team composed by three firefighters. A similar event occurred on September 14, 2002, in Neuilly-sur-Seine, near Paris, killing a team of five young firefighters [4]. Nowadays, the likelihood of backdraft is well recognised by fire brigades, new operational procedures were develop in order to take into account this particular hazard.

Thanks to the growing interest to build more airtight and insulated buildings, the specific fire hazards for the occupants raised questions amongst fire community in Belgium. In 2010 the Belgian Ministry of Interior funded a study about the fire hazards possibly associated with Passive Houses in comparison to traditional houses. The University of Mons and ISSeP used zone modelling for investigating how much the characteristics of a passive house such as airtightness, ventilation and thermal insulation could affect the fire development [5]. During the growing phase of the fire, similar results are obtained in terms of fumes temperatures and CO and HCN concentrations in the fire room for the same fire scenario and the same interior cladding. However, a significant difference in pressure rise (due to thermal expansion of fumes) was calculated due to the airtightness in the passive house, but the scientific monitoring committee of the project decided to not communicate about 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 conducted in well-confined and force-ventilated enclosure for practical application in the nuclear industry [6]. Overpressure up to 3500Pa were measured leading to the flow inversions in the ventilation network. These results were also used to validate the capability of zone model and field model regarding heat release rate and pressure and showed that great care should be taken about the leakage area [7,8]. It can be noticed that the air change per hour fixed for the mechanical ventilation in these buildings are somewhat high for residential building and the area leakages are particularly low.

In 2015, full-scale experiments were carried out by van den Brink to study the effect of the building skin on the fire and the pressure behavior in well-insulated and airtight dwellings [9]. A 20.7 m^3 room was used for the test setup. An air change per hour of about 1 h^{-1} was measured at 50 Pa from a blower door test and bioethanol was used as fuel. From the experiments it appeared that pressures in the order of hundreds of Pa can occur within the first 23 seconds after ignition and may prevent the occupants from escaping.

More recently, a research about fire-induced pressures and smoke spreading in mechanically ventilated buildings with airtight envelopes has been carried out by Kallada Janardhan et al [10]. Heptane pool and polyurethane mattress fires were carried out inside a real 150 m^3 apartment. An air change per hour of about $2.9h^{-1}$ was measured at 50 Pa through a blower door test. The pressure ranges encountered were between 100 Pa to 1650 Pa for short periods and occurred in less than 50 s from the ignition. During this period of high over-pressure, it was not possible to open an inwards-turning door by pulling from inside. This experimental campaign was used for validating FDS predictive capability and gave good results even experimental uncertainties were encountered for the ventilation system configuration, the fan characteristics and the additional leakage due to high over pressures.

In 2015, a full-scale experimental facility was build up in the region of Mons with the support of the KCC centrum and the Régie Provinciale du Hainaut where the firefighters usually do their exercises and trainings. This facility was designed with the support of the Ghent University [11]. The objectives of this study were to quantify the overpressure induced by fires in airtight compartment with air change per hour close to the ones encountered in passive houses. It was decided to burn pallets stack and wood cribs instead of liquid fuel pan in order to have a more realistic fire scenario.

EXPERIMENTAL SETUP

Geometry - ventilation - measurements

The airtight building has the same inner dimensions of a 40-foot shipping container (12 m length, 2.38 m width and 2.44 m height). All the information about the test setup requirements are given in Vanhaverbeke [11]. The wall is composed by three layers of different materials: the inner shell consists of two plasterboards of 13 mm. Behind this layer, there is a 5 cm insulation shell made of a frame of steel studs with mineral wool. The outer shell is made of 20 cm concrete blocks finished with plaster on the inside to ensure the airtightness. The insulation does not need the thickness it should have in a passive house, since the heat front will not travel through this 5 cm insulation layer during the time of interest for the fire tests. 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. The building has no windows 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. They are separated by a 0.12 m thick wall composed by a steel stud frame filled with mineral wool covered with plasterboards on both sides. There is also one door between the two rooms which is closed during fire tests. However, there is a space of about 1 cm height between the floor and the bottom of the door which is useful for air circulation between both 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 volume flow rate corresponding to zero pressure was about 240 $m^3.h^{-1}$. 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. The Belgian government has established precise requirements for the minimal and the maximal flows for every different type of room [12]. An adjustable orifice plate (damper DIRU) was used to adjust the airflow by creating a pressure drop in the ducts. The installed value in this case is 75 m^3/h 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 rate can be obtained.
Measurements were made for gas pressure in fire room and between both 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 (see 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.

Natural leakages

The airtightness of the set-up was measured using a blower door test (with the ducts closed with an airtight metal cap). A value of air exchange rate of $1h^{-1}$ was obtained at 50 Pa overpressure. This test at 50 Pa was made before each fire experiment in order to check the airtightness of the building. Since 2016, the airtightness is constant, so the building has not been damaged by the fires. Moreover, additional leakages due to high overpressure have been also well characterized in the range 0-600 Pa for validation model purpose.
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 zone and field models' validation.

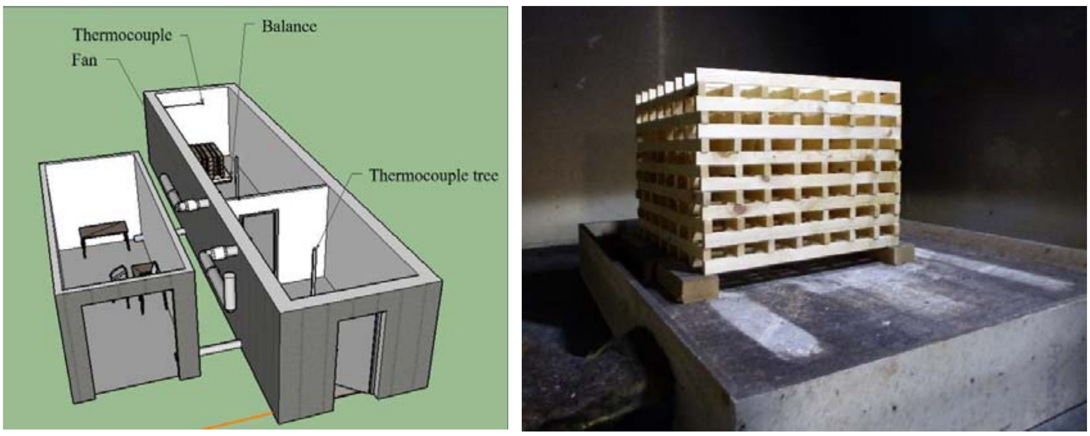

Fig. 1. View of the experimental setup and the (big) wood crib on the load cell.

EXPERIMENTAL RESULTS

In 2016, 4 preliminary tests were carried out with stack of 5 pallets but there were some problems of repeatability for the HRR (Fig.2). Consequently, in 2017 wood cribs of 15 layers of pine slats were used as fuel load. Two different cribs were used: a layer of 5 pine slats of 380x27x18 mm^3 (little crib) and a layer of 8 pine slats of 594x30x17 mm^3 (big crib). The ignition of the fuel load was carried out with heptane pans. Each fire load was tested with the two different ventilation duct configurations.

The measured HRR and overpressure are shown respectively in Fig.2 and 3. As can be seen, there is a good repeatability of the HRR curves for the wood cribs whatever the ventilation (on or off) . Values of about 250 kW (at 300s) and 500 kW (at 230s) are obtained for the HRR peak respectively for the little and the big cribs. As expected, the speed of the growing of the fire is a key parameter for the overpressure measured in an airtight compartment. Over 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 order of magnitude of the pressure measured during the experiment without mechanical ventilation is higher than the one carried out with mechanical ventilation: the mechanical ventilation network succeed in lowering the pressure by helping the fumes going outside. At the beginning, a flow rate of 75 $m^3.h^{-1}$ is given at time zero by both fans. 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 become negative when the overpressure is higher than 145 Pa, the maximum static pressure of the fan (Fig.4). Then due to a lack of oxygen in the fire room the HRR decreases and the pressure decreases consequently. Fresh air can thus be supplied via the fan when the overpressure has decreased below 145 Pa. For the little crib fire, a second peak of HRR is then observed, the wood crib collapsed and restarted to burn for a while leading to a second pressure peak (see Fig.4). For the big wood crib, a pulsating phenomenon can be observed 300 s after ignition of the fuel load for both ventilation configurations when the fire is under ventilated (when the oxygen depletion affect the heat release rate). These oscillations were not observed for the two others fuel loads, perhaps due to the HRR curves which are different. Since 150 Pa is the threshold value below which most people could open an inward door, it is important to notice that the period corresponding to a fire-induced overpressure higher than this threshold can last 3 minutes. These results confirm the observations carried out during the reconstruction of the fire which occurred in the night of the 5 February 2013 in a passive apartment in Cologne, the occupant being blocked during 2 minutes [13].

In Fig.5, one can see the gas temperature measured in the center of the fire room, as well as the CO_2 and O_2 concentration in the upper layer for the test carried out without mechanical ventilation with the pallets as fuel load. The temperature is quite uniform at a height greater than 1.4 meters and there is a strong stratification below this height. Concentration of about 10% and 11% are measured respectively for CO_2 and O_2 concentration 200 s after ignition. O_2 and CO_2 concentrations in the fumes measured when the ventilation was working were not relevant since the inlet flow rate from the fan affected the smoke environment near the gas-sampling probe.

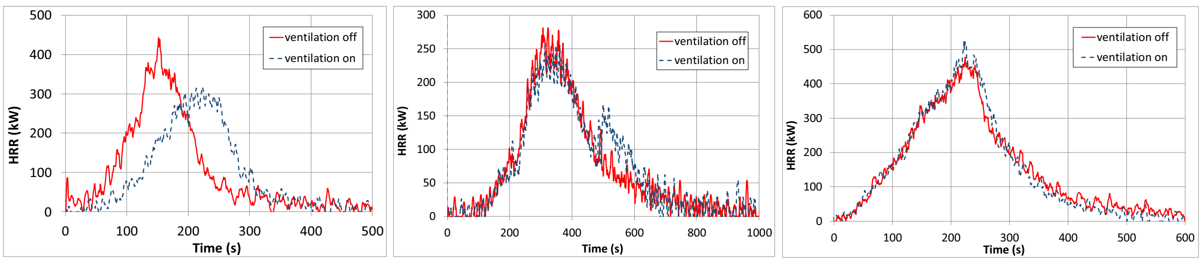

Fig. 2. Heat release rate (from left to right: pallets, little crib, large crib)

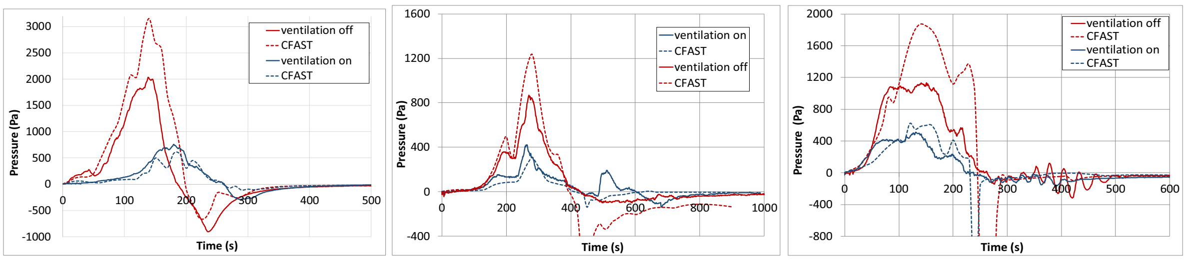

Fig. 3. Overpressure (from left to right: pallets, little crib, large crib)

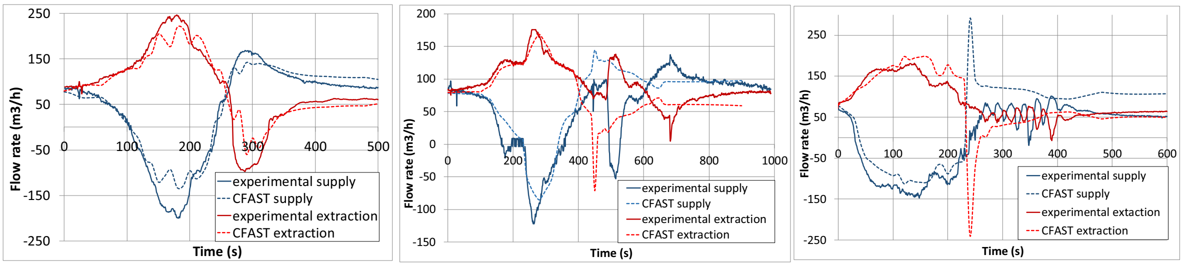

Fig. 4. Flow rate in the ducts when mechanical ventilation is working (from left to right: pallets, little crib, large crib)

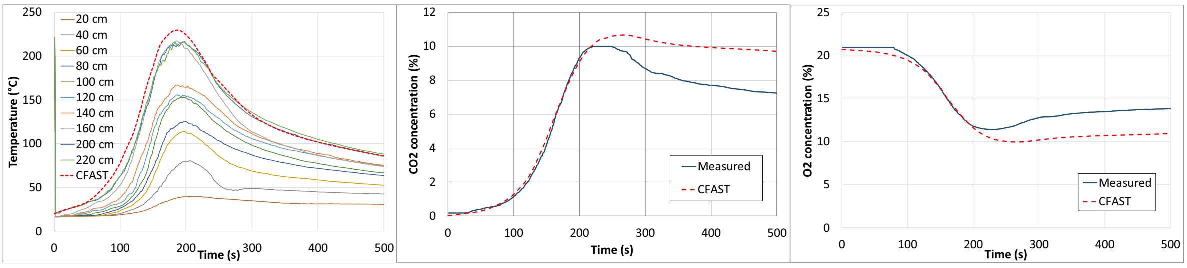

Fig.5. Temperature, CO_2 concentration and O_2 concentration in the fumes. Pallets fire with ventilation off

NUMERICAL SIMULATIONS WITH CFAST

The results obtained in the experimental setup were used to validate the capability of the zone model CFAST to predict major parameters such as pressure, temperature, volumetric flow rate in the ducts in an airtight house configuration. The HRR which is a key parameter was fixed as input data. The leakage modelling is another key parameter for the pressure calculation. At first, a constant leakage area of 26 cm^2 was fixed from the results obtained through the blower door test at 50 Pa. This approach was not satisfactory because the overpressure calculated by CFAST was over predicted by a factor of 4 when the mechanical ventilation was off. However, the overpressures measured during fire tests are an order of magnitude higher than the 50 Pa used during the blower door test. In a typical building, as the overpressure increases, the leakages area increases as small gaps, cracks and other leakage paths open up. The leakage areas were thus measured at a broader range pressure for improving the CFAST simulations. According to the ASTM E 779, overpressure range from 50 to 600 Pa was obtained from blower door test. A value of 0.7 was reached for the leak pressure exponent (n) and 26 cm^2 was obtained for the leak reference area at the leak reference pressure of 50 Pa according to the following correlation:

$$A_L = A_{L,ref}\left(\frac{\Delta p}{\Delta p_{ref}}\right)^{n-0.5} \qquad (1)$$

This equation was used to create in CFAST a table of leakage area varying in function of time by taking into account the evolution of pressure during the fire [14].

For the tests carried out without mechanical ventilation, this time varying leakage improves the overpressure calculated by CFAST compared to the measured values and a difference of about 50% is observed (Fig.3). This error obtained under ventilation off condition is attributed to leakage model which locate the leakages in well-defined positions. Simulations carried with the Fire Dynamics Simulator (FDS) field model using the localized leakages model confirm this statement (in comparison to the pressure zone leakage approach) [14]. It can also be pointed out that the parameter values of equation 1 are validated in the range from 50 to 600 Pa while overpressure up to 2000 Pa are measured during the fire tests. CFAST leads also to fumes temperature, CO_2 and O_2 concentrations which are close to the measured ones (Fig.5).

For the tests carried out with mechanical ventilation, in case of high overpressure, CFAST does not take into account neither the reverse flow of the fan supplying fresh air nor the extra flow rate of the fumes extraction, the overpressure was either over predicted by a factor of 4. In order to overcome these limitations, an extra hole was added to a room connected to the mechanical ventilation when the pressure was higher than the maximum static pressure of the fan (145 Pa). The diameter of this hole was defined by the limiting element related to the pressure drop in the duct, that was the orifice plate. Thanks to this methodology, the sum of the fan flow rate and the volume flow rate through this hole obtained from CFAST is now similar to the measured

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flow rate in the duct (Fig.4). By considering all these improvements, CFAST leads to overpressures similar to the ones measured in the experimental setup for the tests carried out with mechanical ventilation.

The results of this experimental campaign were also used for validating the FSD model [14]. The FDS predictive capability to estimate overpressure induced by fire in airtight houses will be presented in a forthcoming paper.

CONCLUSIONS

Full-scale experiments were carried out in an airtight building in order to measure overpressure induced by fires. Over 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 overpressure inside the apartment were not sufficient to prevent overpressure inside the rooms. All these experiments highlight that there may be problems of overpressure 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 zone model CFAST predictive capability.

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