Preliminary Numerical Study of Fire-Induced Pressure Rise in a Passive House Compartment

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ABSTRACT

Passive houses are becoming more and more popular due to energy efficiency requirements. An important aspect is their airtightness, i.e., they have a very low leakage. The present paper describes a preliminary numerical study on fire-induced pressure variations in a structure that resembles a passive house compartment. The configuration without ventilation system is considered in this paper. The fire source used in the experiment consists of wood cribs that have been simulated in the Fire Dynamics Simulator (FDS), version 6.5.2, as a cube with a prescribed heat release rate (HRR) curve (based on experimental measurements). The grid sensitivity study is conducted by using different mesh cell size and comparing the results of pressure variation. A cell size of 0.1 m is considered sufficient in this preliminary study. The maximum over-pressure obtained without ventilation reached up to 870 Pa in the experiment. Such high over-pressure will definitely hinder the escape of occupants. The structural integrity may also be affected by the over-pressure. Using a constant leakage area, which is the default option, the pressure difference without ventilation rises up to 2027 Pa in the simulation. A good agreement with the experimental data can only be achieved if the simulated leakage area is not kept constant when the room pressure rises. Tuning the leakage pressure exponent in FDS significantly reduces the deviation between the simulation and experimental results. The default setting of reference pressure difference in FDS is used to examine the influence of this parameter on the pressure prediction. When applying the default reference pressure difference, a smaller leakage pressure exponent is needed to reproduce experimental results. Therefore, the reference pressure difference has a certain influence on leakage area and should be set according to the pressure used in determining the reference leakage area during experiments. The overall pressure evolutions are qualitatively well captured in the FDS simulations, as these strongly depend on the fire heat release rate evolution, which was prescribed to match the experimental profile. However, in order to improve the current level of accuracy and address the general validity of the observations made in the present study, more experimental and numerical work need to be carried out.

KEYWORDS:
fire-induced pressure; leakage; passive house fire; CFD modeling; FDS
1. INTRODUCTION

With the increase of energy-saving and environmental awareness, the development of low-energy buildings continues to grow [1]. A passive house is a relatively new type of low-energy house, which conforms to the highest energy standard for buildings. The passive house ‘label’ is a promise to spare up to 90% of heating (or cooling) energy compared to common buildings [2].

From a fire safety standpoint, the construction requirements of passive houses, in particular the very low leakage, may result in a substantial pressure increase in the event of a fire, due to the release of hot combustion products in a well-confined enclosure.

In experimental campaigns carried out in an air-tight apartment in Finland (study conducted by Aalto University and VTT), pressures of up to 1650 Pa have been reported [3,4]. Besides, in the framework of the OECD PRISME project [5,6], a series of experiments have been conducted in confined and mechanically ventilated compartments and over-pressures of more than 2500 Pa have been reported. These experimental results confirm that pressure variation is an important issue to be considered in a confined compartment fire [5,6]. Chow et al. [7] used the Fire Dynamics Simulator (FDS) to investigate the fire-induced pressure variation in a confined chamber and pointed out that simulation results agree reasonably well with experimental results. Wahlqvist et al [8] examined the influence of building leakages on the ventilation system during a fire. The fire-induced overpressure in a room of tight leakage class was found to be about 1900 Pa [8]. Bonte et al. [9] studied the capability of a zone model (CFAST) and a field model (ISIS) to predict the interaction between the mass loss rate and the total relative room pressure in the case of under-ventilated fire conditions. The over-pressure and under-pressure obtained in their study also reached thousands of Pascals.

Pressures between 100 Pa and 200 Pa would be enough to prevent door opening and evacuation of occupants. Thus, the reported pressure levels clearly indicate a threat to life safety. Moreover, a pressure rises up to 1000 Pa can also pose too strong an attack on the structural integrity. E.g., in one of the tests in [3], a window was shattered. Obviously, this has a significant impact on the ventilation conditions and hence the fire dynamics.

The objective of the present paper is to study the fire-induced high-pressure level due to the airtightness, by comparing novel experimental and numerical results.

2. EXPERIMENTAL AND NUMERICAL SETUP

The CFD package FDS, version 6.5.2, is used with the default settings (unless specified otherwise). Lumped species and infinitely fast reaction model are used in FDS combustion simulation. The reader is referred to [10] for details on the FDS default settings and equations.

2.1 Geometry

The experimental facility considered in this research is in the region of Mons in Belgium and consists of two rooms connected by a door (see Fig. 1). The construction has the same inner dimensions as a 40 foot shipping container [11]. The fire room is 7.6 m long, 2.4 m wide and 2.4 m high and the adjacent room is 4.4 m long, 2.4 m wide and 2.4 m high. During the experiment, the partition door was closed but a small leakage area of 0.9 m \times 0.01 m has been measured below the door. The configuration analyzed in this paper is the case without ventilation system (fresh air supply and gas extract) and the ducts were sealed.

![Fig. 1. Layout of experimental setup.](image)

2.2 Fire load and Heat Release Rate

Experimental tests were carried out in the structure with overlapping wooden slats, see Fig. 2. The slats are 38 cm long and the section of a slat is 27 mm \times 18 mm. There are 15 layers of slats. A stainless-steel cup 9.5 cm in diameter containing 100 ml of heptane is centered below the slats. In the FDS simulations, a 0.4 m \times 0.4 m \times 0.4 m cubic obstruction was set as a fire source.
The heat release rate (HRR) was calculated from the mass loss rate measured using a scale placed underneath the fire source, assuming complete combustion inside the compartment. The HRR obtained from the experiments was prescribed as HRR input in the FDS simulations. Fig. 3 confirms that the HRR as retrieved from the FDS output follows the input very well.

2.3 Mesh resolution

For the setting of mesh resolution, the non-dimensional expression $D^* / \delta x$ is used to calculate the suitable mesh size. $D^*$ is the characteristic length scale associated with the fire HRR and $\delta x$ is the mesh cell size. Equation 1 is used to calculate $D^*$.

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

where $\dot{Q}$ is the heat release rate (kW), $\rho_c$ is the ambient air density (kg/m$^3$), $c_p$ is the specific heat of fluid (kJ/(kg·K)), $T_\infty$ (= 293 K) is the ambient air temperature and $g$ is the gravitational acceleration (m/s$^2$).

The characteristic length scale is 0.5 m in this paper. This value is calculated based on the measured peak HRR value of 280 kW. The recommended ratio of $D^* / \delta x$ is between 4 and 16. According to the recommended ratio, the mesh cell size of 0.1 m, 0.075 m and 0.05 m were chosen to study the grid sensitivity.

2.4 Boundary conditions

The outer walls are made of 0.2 m concrete and finished with plaster on the inside to ensure the airtightness. Behind the plaster board an insulation layer is set with 0.05 m Rockwool. The partition wall is 0.2 m thick and has three layers: two gypsum layers (0.035 m) with Rockwool (0.13 m) in between. The partition door also has three layers: two steel layers (0.004 m) with foam (0.192 m) in between. The outer door was well sealed to meet passive house standards. The thermal properties of each material are listed in Table 1.

| Material name | Density (kg/m$^3$) | Conductivity (W/(m·K)) | Specific heat (kJ/(kg·K)) |
|---------------|-------------------|------------------------|---------------------------|
| Concrete      | 2200              | 0.7                    | 0.75                      |
| Rockwool      | 45                | 0.035                  | 0.84                      |
| Gypsum        | 1440              | 0.3                    | 0.84                      |
| Foam          | 800               | 0.028                  | 1.45                      |
| Steel         | 8050              | 50.2                   | 0.49                      |

2.5 Leakage settings

The leakage area of the experimental facility was determined through a leakage measurement (blower door test) with an imposed differential pressure of 50 Pa. During the test, a fan was used to pull air out of the compartment, creating and maintaining a negative pressure differential (50 Pa) between inside and outside. The air flow rate can be measured and the leakage area can be calculated by using Eq. 2 [12].
\[ A_L = \sqrt{\frac{\rho q^2}{2\Delta P}} \]  

where \( A_L \) is the leakage area (m\(^2\)), \( q \) is the air volume flow rate (m\(^3\)/h), \( \rho \) is the air density (kg/m\(^3\)), and \( \Delta P \) is the pressure differential (Pa).

The leakage area obtained is 0.0026 m\(^2\). The blower door test was conducted before each experiment and the leakage area was found to be constant [12]. This area was set as reference leakage area between the compartment and the ambient in FDS. There are two leakage simulation approaches in FDS: Pressure Zone Leakage (Bulk Leakage) and Localized Leakage [10]. The pressure zone leakage approach is intended to capture the bulk leakage that occurs through walls. The leak flow is uniformly imposed over all surfaces designated as leak path. The localized leakage approach is suitable for simulating small cracks with a known location. In the present study, the air leakage from the compartment to the ambient environment was simulated using the pressure zone leakage approach. The walls and ceiling were set as leak path. Since the partition door was closed during the experiment, two pressure zones (one for each room) were prescribed in FDS, in addition to the ambient pressure zone. The leakage area was evenly distributed over the walls and ceiling surface area and thus the leakage area of the fire room and adjacent room were 0.0016 m\(^2\) and 0.001 m\(^2\) respectively. Furthermore, the leakage between the fire room and the adjacent room under the partition door has been prescribed using the localized leakage approach.

3. RESULTS AND DISCUSSION

3.1 Grid sensitivity study

Finer cell size leads to more accurate simulation results but will also take more computational cost and storage space. The mesh grid sensitivity was studied based on the case in this paper, focusing on the pressure variation in the fire room of the compartment. The pressure curves with cell size of 0.1 m, 0.075 m and 0.05 m are shown in Fig. 4. The data shows a small deviation between the three cell sizes. The peak values for a cell size of 0.1 m, 0.075 m and 0.05 m are 2027 Pa, 2099 Pa and 2131 Pa, respectively. The relative difference between 0.1 m and 0.05 m is 5.1 %. During pressure drop and stationary phase, the three curves almost coincide. Thus, the cell size of 0.1 m is considered sufficient to ensure grid insensitivity of the results for this preliminary study.

![Fig. 4. Pressure variation with different cell size](image)

3.2 Pressure variation

In the configuration without mechanical ventilation, the fire room pressure rises to a high level, see Fig. 5 (left), because the ducts were closed. The peak value of 2027 Pa, obtained in the first FDS simulation (performed with constant leakage area), was much higher than the experimental peak value of 870 Pa. A constant leakage area corresponds to the line \( n = 0.5 \) in Fig. 5, as explained below. Therefore, this over-prediction suggests that the leakage surface area may not be constant during the fire tests. The leakage area may grow as small gaps, cracks and other leakage paths open up when the room pressure increases. In the default settings of FDS, the leakage area is assumed to be constant. In order to simulate the non-constant leakage area, FDS provides a ‘LEAKPRESSION_EXPONENT’ parameter, \( n \), which can be used to reproduce the variation of the leakage area:

\[ A_L = A_{L,\text{ref}} \left( \frac{\Delta P}{\Delta P_{\text{ref}}} \right)^{-0.5} \]  

In the configuration of the fire room and adjacent room, focusing on the pressure variation in the fire room of the compartment.
where $A_L$ is the leakage area (m$^2$), $A_{L,ref}$ is the reference leakage area (m$^2$), $\Delta p$ is the pressure difference (in Pa) between indoor and outdoor, $\Delta p_{ref}$ is the reference pressure difference (in Pa) between indoor and outdoor, and $n$ is the leakage pressure exponent. By default, $n = 0.5$, which means that the leakage area is independent of the pressure rise, and $\Delta p_{ref} = 4$ Pa. However, as the reference leakage area has been determined at a pressure difference of 50 Pa here, $\Delta p_{ref}$ has been set to 50 Pa.

The pressure curves obtained with different exponents are shown in Fig. 5. The leakage pressure exponent does not affect the shape of the pressure evolution graph. This is not surprising, as it is primarily driven by the HRR evolution (Fig. 3). The absolute values reduce with increased values for $n$, due to the increased leakage area as the pressure exceeds $\Delta p_{ref}$, and the deviation between the numerical and experimental values of the pressure is reduced. This indicates that the leakage area measured under the pressure difference of 50 Pa in ‘blower door tests’ is insufficient to characterize the airtightness during fire conditions.

3.3 Influence of reference pressure difference on pressure variation

In order to illustrate the sensitivity of the results on the choice of reference pressure difference, the pressure variation under the reference pressure difference of 4 Pa (FDS default setting) is shown in Fig. 5. When $n=0.5$, the setting of reference pressure difference has no influence on the results, because the exponent ($n=0.5$) = 0, see Eq. 2. When $n$ increased to 0.6 and 0.7, the results become sensitive to the reference pressure difference. The simulation result match the experimental result when $n=0.6$. The reason is that with smaller reference pressure difference, $\Delta p / \Delta p_{ref}$ becomes larger under the same $\Delta p$, so lower value of $n$ is required to be consistent with the experimental results. This means that the setting of reference pressure difference has a certain effect on the simulation results of pressure variation. The reference pressure difference should be set according to the pressure used in determining the reference leakage area.

![Fig. 5. Pressure variation as function of time with $\Delta p_{ref}$ =50 Pa (left) and $\Delta p_{ref}$ =4 Pa (right). The lines correspond to different values of pressure leakage exponent $n$, see Eq. 2.](image)

4. CONCLUSIONS

A numerical study on the fire-induced pressure variation in a structure, resembling a passive house compartment, was conducted using FDS. Configurations without a mechanical ventilation system were considered during the research. The key results and findings of the present work are as follows.

The required mesh cell size is determined by conducting grid sensitivity study on the basis of fire-induced pressure variation. A cell size of 0.1 m is considered sufficient to ensure grid insensitivity of the results for this preliminary study.

Due to the airtightness, a fire occurring in a passive house could cause a high pressure rise, which can have a large impact on the occupant evacuation and fire rescue, of this type of buildings. The maximum over-pressure obtained without ventilation in the simulation is 2027 Pa. This pressure is high enough to impede evacuation and to affect the structural integrity of the compartment.
The leakage area during the course of a fire is not constant and will increase as pressure increases. Tuning the leakage pressure exponent in the FDS simulations strongly improves the level of agreement between simulation and experimental results.

The influence of reference pressure difference on pressure variation has been examined. The results show that with small reference pressure difference, which is 4 Pa in FDS default settings, smaller value for leakage pressure exponent is required to match experimental tests. Thus, the reference pressure difference does have an effect on the simulation results and should be set according to experimental conditions.

This study is a preliminary investigation on passive house fire without ventilation system. Although the simulations can capture the main aspects, the accuracy of results remains to be improved and it remains to be investigated how general the validity of the present conclusions are. More experimental and numerical studies with different conditions (HRR, leakage area, ventilation, et al) should be conducted and analyzed in depth.

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