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Development and Validation of a One-Zone Model for Fire-Induced Pressure Prediction in Airtight Houses

Sylvain Brohez[a]*, Francesco Cabras[b],

[a] University of Mons, Faculty of Engineering, Department of Chemical Enginerring, 20 Place du Parc, 7000 Mons, Belgium.
[b] Università di Bologna, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Via Zamboni, 33 - 40126 Bologna, Italia
sylvain.brohez@umons.ac.be

The need for sustainability and smaller ecological footprint lead to the construction of more airtight building envelopes with better thermal insulation in order to increase the energy efficiency according to the Energy Performance of Buildings Directive (EPBD 2010/31/EU). However, specific fire risks can be encountered by the occupants since they can be blocked for a long period due to the fire-induced pressure and the inward door opening. In 2015 a full-scale fire setting was built in Bauffe (Belgium) by the Régie Provinciale Autonome du Hainaut RPA on its fire brigade training site for studying the effects related to fire development in a building with high air tightness. These experimental results were used for validating the zone model CFAST 7.3.2 predictive capability for fire induced pressure. Thanks to the very low calculation time, using a fire zone model as first step is a practical way to understand the influence of the major physical phenomena before using much more complex software such as computational fluid dynamics. However, serious limitations were observed with CFAST version 7.2.3. For the tests carried out without mechanical ventilation, CFAST does not consider the effect of pressure on the natural leakages area which increases with pressure. This limitation leads to an overprediction of the fire induced pressure by a factor of 4. For the tests carried out with mechanical ventilation, CFAST version 7.2.3 does not consider the reverse flow of fan supplying fresh air into the building when the fire induced pressure is higher than the stall pressure of the fan neither the extra flow of fumes of the fan extracting air from the setup leading also to an overprediction of the fire induced pressure by a factor of 4. This paper presents the development of a one-zone fire model for the calculation of the fire induced pressure in a multiple rooms airtight building taking into account the effects of the fire induced pressure on both the effective leakage area (according to the ASTM E779) and the characteristic curve of the fans. This new code has been validated thanks to the novel experimental results obtained at large scale. Satisfactory results were obtained for parameters such as fumes temperatures, pressures, major species concentrations and flow rates in the mechanical ventilation. This paper focuses on the results obtained without mechanical ventilation, the ducts being tickly closed.

1. Introduction

The need for sustainability and smaller ecological footprint lead 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 (2010). However, specific fire risks can be encountered by the occupants related to the fire-induced pressure and the inward door opening as this was confirmed in a real case during the night of the 5 February 2013 (Brohez et al, 2018a). Learning from fire accidents is essential for preventing as far as possible that accidents of the past being repeated in the future (Hailwood, 2016), relying on research practical results and fire safety regulations.

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-induced pressure (Fourneau, 2012). Bioethanol fire tests were carried out in a 20.7 m^3 room by van den Brink in 2015 to study the effect of the building envelope on the fire and the pressure behavior in well-insulated and airtight

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dwellings. It appeared that pressures in the order of hundreds of Pa can occured within the first 23 seconds after ignition and may prevent the occupants from escaping.

Heptane pool and polyurethane mattress fires were carried out inside a real 150 m^3 apartment in Finland (Hostikka et al, 2017; Kallada Janardhan et al, 2017). Pressure from 100 Pa to 1650 Pa for short periods were observed during the fire development and it was not possible to open an inwards-turning door by pulling from inside.

Based on a design proposed by Vanhaverbeke (2015), a full-scale fire setting was built in 2015 in Bauffe by the Régie Provinciale Autonome du Hainaut RPA on its fire brigade training site for studying the effects related to fire development in a building with high air tightness. Two different ventilation duct configurations were tested during pallets or wood cribs fires tests carried out by University of Mons (Brohez et al, 2018b, 2019): one with mechanical ventilation on, the other one with the ducts being closed with an airtight metal cap (the mechanical ventilation being off). Fire-induced peaks pressures from 870 to 2035 Pa were measured without mechanical ventilation (ducts closed), while values from 420 to 750 Pa were observed with the mechanical ventilation on.

These experimental results were used for validating the zone model CFAST version 7.2.3 predictive capability for fire induced pressure (Brohez et al, 2018b). However, serious limitations were observed with CFAST. For the tests carried out without mechanical ventilation, CFAST does not consider the effect of pressure on the natural leakages area which increases with pressure. This limitation leads to an overprediction of the fire induced pressure by a factor of 4. For the tests carried out with mechanical ventilation, CFAST version 7.2.3 does not consider the reverse flow of fan supplying fresh air into the building when the fire induced pressure is higher than the stall pressure of the fan neither the extra flow of fumes of the fan extracting air from the setup leading also to an overprediction of the fire induced pressure by a factor of 4.

This paper presents the development of a fire zone model for the calculation of the fire induced pressure in a multiple rooms airtight building taking into account the effects of the fire induced pressure on both the effective leakage area (according to the ASTM E779-19) and the characteristic curve of the fans.

2. Development of a new fire zone model

2.1 Control volumes of the model – Simplifying assumptions – Input data

The primary assumption of a zone model is that properties such as temperature can be approximated throughout a control volume by a representative average. Fires carried out in an enclosure with forced ventilation and low ventilation flow rate were observed to produce single layer environment in terms of chemical species concentrations [Backovsky et al, 1988; Peatross et al, 1997). Consequently, in this zone model, the gas phase inside a room is assumed to be well stirred. The experimental setup used in this study (Brohez et al, 2019) is divided into two compartments thanks to a partition wall, the larger room being the fire room (Fig.1a). The partition door is closed during the fire experiments, a gap of 0.009 m2 (0.01 m high) being located at the bottom of the door for air circulation (as it is done in airtight houses). A mechanical ventilation network allows to supply fresh air $\dot{m}_S$ into the fire room, while the gas is extracted from the adjacent room $\dot{m}_{EX}$. This paper will focus on the experimental results obtained when the ducts are tightly closed ($\dot{m}_S = \dot{m_{EX}} = 0$).

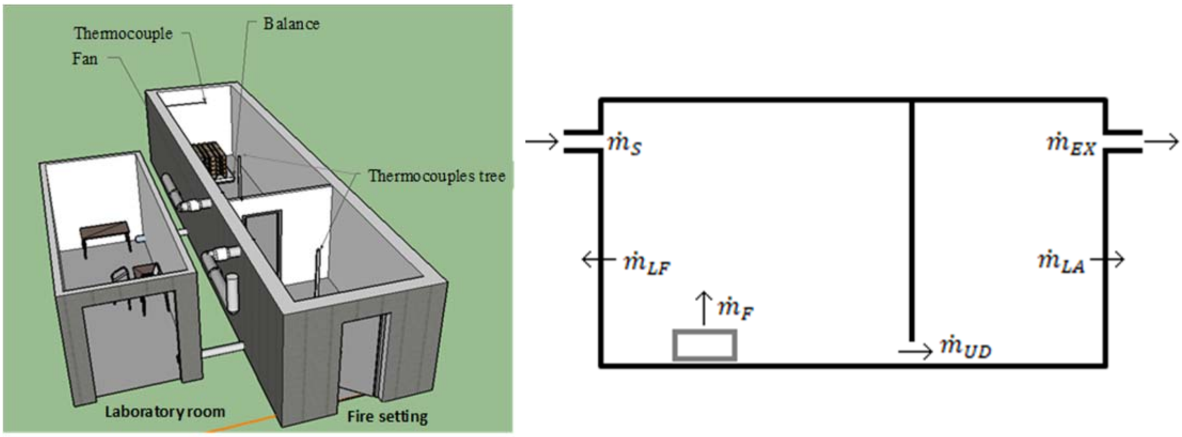


Figure 1: (a) View of the experimental facility. (b) Sketch of the fire zone model (with mass flow rates)

The data required for a simulation are: the dimensions of the compartment (height, width, length), the construction materials of the compartment and their material properties (thermal conductivity, specific heat, density, thickness), the fire properties (heat release rate, heat of combustion).

In case of liquid pool fire, combustion sub-model can be developed to predict the Heat Release Rate HRR of the fire (Brohez et al, 2005; Beji et al, 2016). However, since the validation of this zone model is based on pallets and wood cribs fires, the Heat Release rate HRR ($\dot{Q}_F$) is fixed as input data. The yields of substances Y_i (O_2, CO_2, H_2O, CO) are also given as input data.

In addition, the leakages area of the envelope for each room is defined according to Equation 1 (ASTM E779) considering the effect of pressure on the leakages area:

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

The leakages reference area $A_{L,ref}$ and the *n* exponent are estimated from pressurisation tests.

2.2 Mass and energy conservation equations

The equations used to calculate pressure and fumes temperature in each room are derived from the equations of conservation of mass and energy, as developed by Forney et al (1994). Similarly to CFAST(Peacock, 2017), the ideal gas law is used as an equation of state to relate temperature and density.

According to Figure 1b (with ducts closed), the conservation equations are as follows for the fire room:

- Mass balance : $\frac{dm_F}{dt} = \dot{m}_F - \dot{m}_{LF} - \dot{m}_{UD}$ (2)
- Energy balance : $\frac{V_F}{\gamma-1}\frac{dP_F}{dt} = \dot{Q}_F - cp(\dot{m}_{LF}.T_{LF} + \dot{m}_{UD}.T_{UD}) - \dot{Q}_{WF}$ (3)
- Substance balance: $\frac{V_F\, d(\rho_F\, y_{i,F})}{dt} = Y_i\,.\dot{m}_F - y_{i,LF}\,.\dot{m}_{LF} - y_{i,UD}\,.\,\dot{m}_{UD}$ (4)

Concerning the adjacent room, the conservation equations are as follows:

- Mass balance: $\frac{dm_A}{dt} = \dot{m}_{UD} - \dot{m}_{LA}$ (5)
- Energy balance: $\frac{V_A}{\gamma-1}\frac{dP_A}{dt} = cp(\,\dot{m}_{UD}.T_{UD} - \dot{m}_{LA}.T_{LA}\,) - \dot{Q}_{WA}$ (6)
- Substance balance: $\frac{V_A\, d(\rho_A\, y_{i,A})}{dt} = y_{i,UD}\,.\dot{m}_{UD} - y_{i,LA}\,.\dot{m}_{LA}$ (7)

In case of overpressure inside the setup, the leakages flow rate $\dot{m}_{LF}$, $\dot{m}_{LA}$ are positive (otherwise, they are negative). When the fire room pressure is higher than the adjacent room pressure, the flow the under the door $\dot{m}_{UD}$ is positive (otherwise, it is negative). Obviously, both the temperature and the composition of these fluxes must be consistent with the sign of these fluxes.

The mass flow due to leakages through the boundaries in the fire room can be calculated from the Bernoulli equation. In case of overpressure in the fire room, $\dot{m}_{LF}$ is estimated according to:

$$\dot{m}_{LF} = C_D A_{LF}\sqrt{2|P_F - P_{ATM}|\rho_F} \tag{8}$$

In case of under-pressure, the following equation is used:

$$\dot{m}_{LF} = -C_D A_{LF}\sqrt{2|P_F - P_{ATM}|\rho_{AMB}} \tag{9}$$

Similar equations are used for the mass flow due to leakages through the boundaries in the adjacent room $\dot{m}_{LA}$.

When the pressure in the fire room is higher than the one in the adjacent room, $\dot{m}_{UD}$ is estimated according to:

$$\dot{m}_{UD} = C_D A_{UD}\sqrt{2|P_F - P_A|\rho_F} \tag{10}$$

Otherwise, $\dot{m}_{UD}$ is estimated according to:

$$\dot{m}_{UD} = -\,C_D A_{UD}\sqrt{2|P_F - P_A|\rho_A} \tag{11}$$

For each compartment, the temperature, mass and volume are related to the pressure by the ideal gas law:

$$m_F = \frac{P_F\,.\,V_F}{T_F\,.\,R} \tag{12}$$

$$m_A = \frac{P_A\,.\,V_A}{T_A\,.\,R} \tag{13}$$

with, $\rho_F = \frac{m_F}{V_F}$ and, $\rho_A = \frac{m_A}{V_A}$ (14)

The gas constant *R* (287 J.kg^{-1}.K^{-1}) is the same in Equations 12 and 13, the smoke is assumed to behave as heated air (Peacock et al, 2017). A 1.4 value is taken for the isentropic coefficient γ.

The heat release rate ($\dot{Q}_F$) is related to the combustion flow rate $\dot{m}_F$ through the heat of combustion ΔH_C:

$$\dot{Q}_F = \Delta H_C\, \dot{m}_F \tag{15}$$

2.3 Heat transfer to the boundaries

The ceiling, the floor and the vertical walls of the compartment are assumed to be made in the same material and to have the same behaviour (same thermophysical properties and same surface temperature). The inside surface of the enclosure forms an unique opaque surface assumed to behave as a black body. In this one-zone fire model, the fumes are modelled as an opaque black body, the radiation emitted by the fire is completely absorbed by the fumes. In addition to radiation heat transfer, the convection heat transfer between the fumes and the boundaries has also to be modelled. The net heat flux on the boundaries can be estimated according to the following equations:

$$\dot{Q}_{WF} = A_F\left[\sigma(T_F^4 - T_{WF}^4) + h_o(T_F - T_{WF})\right] \quad (16)$$

$$\dot{Q}_{WA} = A_A\left[\sigma(T_A^4 - T_{WA}^4) + h_0(T_A - T_{WA})\right] \quad (17)$$

In these equations, the temperature of the wall inner surface (T_{WF} and T_{WA}) are unknown. They can be calculated from the one-dimensional heat conduction model applied to each room (Özisik, 1994):

$$\rho c_P \frac{\delta T\ (t,x)}{\delta t} = \lambda \frac{\delta^2 T(t,x)}{\delta x^2} \quad (18)$$

$T(t,x)$= temperature profile in the wall at time *t* with *x* as space coordinate.

To solve the conduction equation, condition must be imposed at the boundary inner and outer surface. A flux boundary condition (Neuman condition) is applied for the inner surface:

$$-\lambda \frac{\partial T}{\partial x} = \dot{q}_0'' \qquad \text{with} \quad \dot{q}_0'' = -\frac{\dot{Q}_{WF}}{A_F} \quad \text{or} \quad \dot{q}_0'' = -\frac{\dot{Q}_{WA}}{A_A} \quad (19)$$

while a convection boundary condition (Fourier condition) is applied for the outer surface:

$$\lambda \frac{\partial T}{\partial x} = h_M(T_{air} - T_M) \quad (20)$$

Values of the convective heat coefficient are set at 10 W/($m^2 \cdot K$) for the inside h_0 and outside boundaries h_M (Beji et al, 2016). Numerical solution of this set of partial differential equations were obtained using an explicit finite difference method, resulting in a set of algebraic equations to be solved. The explicit formulation can be solved directly if the variables are known at the beginning of the time step. The mass of each control volume is estimated from mass balance, the pressure in each room is estimated from energy balance, the temperature of each control volume is estimated from the ideal gas law, the temperature profile in the wall is estimated from the conduction heat transfer equation and the mass fraction of species y_i (CO_2, O_2, CO…) in the fire room and the adjacent room is estimated from the substance balance.

3. Verification and Validation of the fire zone model

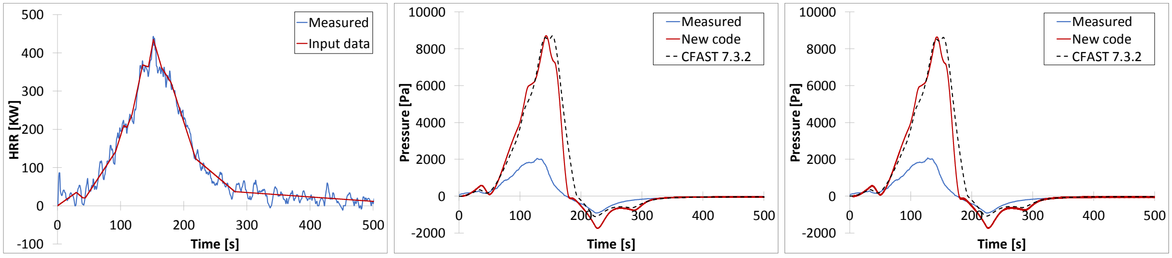
3.1 Experimental facility

An experimental facility was built in Bauffe by the Régie Provinciale Autonome du Hainaut to study the effect of airtightness on fire induced pressure in building such as passive houses (Figure 1a). 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). The walls are composed by three layers of different materials: 26 mm plasterboards, 50 mm insulation layer and 200 mm concrete blocks finished with plaster on the inside to ensure the airtightness. The floor and the ceiling are made of 150 mm concrete slabs; the latter being insulated with 50 mm of mineral wool protected by 130 mm thick plasterboards to reduce the heat losses. The building has no windows but only one external door. 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. A partition door is in this wall, a gap of 0.9 m x 0.01 m being located at the bottom of this door for air circulation. Both doors are closed during the fire tests. The ventilation of the building is guaranteed thanks to mechanical ventilation network. However, for the experiments presented in this paper, the ducts were tightly closed. Pallets and Wood cribs of 15 layers of fir 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.

Measurements were made for gas pressure in fire room and between both rooms, gas temperatures in the center of each room using 1 mm in diameter K-type thermocouples trees with 0.2 m vertical separation, fuel mass from load cell (see Fig.1a). The mass loss rate was calculated from a smoothing technique and the HRR was then calculated. The heat of combustion (12 $MJ.kg^{-1}$) was estimated through lab-scale experiments with a cone calorimeter (Brohez et al, 2020).

3.2 Verification of the one-zone model

A verification of the one-zone model has been performed by comparing the simulation results with the one obtained from CFAST version 7.2.3. For the sake of this comparison, the one-zone model instead of the two-zones model has been chosen in the CFAST software. The same leakages area was fixed in both model: 30 cm^2 (with Cd=0.7) from a blower door test carried out at 58 Pa over-pressure (for this verification, in the new code, the exponent n is equal to 0.5 in Equation 1). The HRR input data were taken from the burning of the pallets (Figure 2a). Yield value of -1,32, 1,72 and 0,6 ($g.g^{-1}$ of fuel) were calculated respectively for O_2, CO_2 and H_2O according to fir composition $CH_{1.7}O_{0.74}$ (Tewarson, 2002). In order to improve the comparison, a value of 0% was fixed for the radiative fraction of the fire in CFAST leading to a total heat transfer to the fumes (which is consistent with the opaque black body assumption taken in the development of the present one-zone model). As can be seen, similar results are obtained between the new code and CFAST 7.3.2. for the pressure in the fire room and the adjacent room in Figure 2b and Figure 2c respectively. A peak pressure difference of about 100 Pa is observed between both rooms. In a second step it can be pointed out that the two-zones model was also selected in CFAST 7.3.2 showing that the interface between the hot upper layer and cold lower layer was at 50 cm from the floor after 1 minute. The one-zone model is thus a good assumption for the simulation.



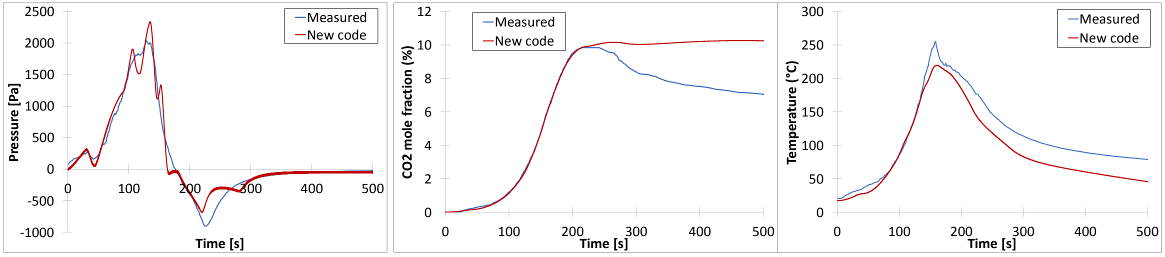
(a) (b) (c)

Figure 2: Verification of the new code (comparison with CFAST 7.3.2) – Fuel = pallets; (a)= Input Heat Release Rate, (b)= Pressure in fire room, (c)= Pressure in adjacent room

However, the simulated pressure is overestimated by a factor of 4 compared to the measured one and is attributed to the leakages area which increases with the room pressure as small gaps, cracks and other leakage open up. This phenomenon has to be considered in the simulation (Brohez et al, 2018b).

3.3 Validation of the one-zone model

Pressurization tests were carried out in the 0-600Pa pressure range for taking in account the influence of the pressure on the leakages area (Brohez et al, 2020). A value of 0.7 was measured for the leakage pressure exponent (*n*) and a value of 30 cm^2 was obtained for the leakages reference area at the reference pressure of 58 Pa (with Cd=0.7), see Equation 1. While the leakages area is constant in CFAST version 7.3.2 (parameter n is fixed to 0.5), Equation 1 introduced in the new code considers the effect of the pressure on the leakages area. As can be seen in Figure 3a, the simulated pressure is now similar to the measured one in the fire room. Moreover, the capability of the one-zone model to predict the temperature and CO_2 concentration in the fire room is presented in Figure 3b and 3c respectively.



(a) (b) (c)

Figure 3: Validation of the new code – Fuel= pallets, (a=) Pressure, (b)= Temperature, (c)= CO_2 concentration in the fire room.

4. Conclusions

This paper presents the development of a one-zone fire model for the calculation of the fire induced pressure in a multiple rooms airtight building taking into account the effects of the fire induced pressure on the effective leakage area. This paper focuses on results obtained without mechanical ventilation, the ducts of the rooms being tickly closed.The model enables also to simulate the temperature and species concentrations (O_2, CO_2, H_2O, CO) in each room. First at all, this new code has been verified by comparisons with results obtained from CFAST 7.3.2, confirming the correctness of the model for a fixed leakages area. Then, the new model has been validated thanks to experimental results obtained at large scale. The effect of pressure on leakages area has to be taken into account in order to obtain satisfactory results for the fire induced pressure. Satisfactory results were also obtained for the temperature and major species concentrations in the fire room. This one-zone model could be helpful in fire safety design to consider the fire-induced pressure in airthigh houses.

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