ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

# Fire-induced pressure and smoke spreading in mechanically ventilated buildings with air-tight envelopes

Simo Hostikka[a,*], Rahul Kallada Janardhan[a], Umar Riaz[a], Topi Sikanen[b]

[a] *Aalto University, Espoo, Finland*
[b] *VTT Technical Research Centre of Finland Ltd., Espoo, Finland*

ARTICLE INFO

*Keywords:*
Pressure
Modelling
CFD
Smoke
Airtightness
Near-zero buildings
High-rise buildings

ABSTRACT

Fire-induced pressures have not been considered dangerous in building fires, but the situation may be changing as building envelopes become increasingly air-tight. In this study, we investigate whether this can change the fire development and pose new risks for structural and evacuation safety. We used experiments to validate the numerical models, and models for simulating the fire development in buildings with different air-tightness levels. The simulations considered air permeability values typical for traditional, modern and Near-Zero buildings. Three different smoke damper configurations were studied, and the fire growth rates were varied from medium to ultra-fast. The results showed that transitioning from traditional and modern buildings to Near-Zero buildings can sufficiently increase the peak overpressures from fast-growing fires to cause structural damage. Conditions were identified for avoiding excessively high overpressures, while preventing smoke from spreading through the ventilation system.

## 1. Introduction

Fire-induced pressures have gained increasing attention in fire science mainly their capability to drive flows between compartments. Pressure has been identified as a potential risk for structural damage mainly in industrial scenarios though these have been limited to explosions or gas deflagrations. Adverse effects of pressure on evacuation and structural safety in residential buildings has not been studied. Our understanding of the potential threats to fire compartmentation has been dominated by the thermal impact of a fire and the load-bearing capacity of structures.

Evacuation-related risks is of greater significance in residential fire scenarios. Recently, a group of Finnish firefighters reported that they were unable to open the inward-opening door of a fire apartment during the growth stage of the fire, thereby indicating the overpressure to be well above 100 Pa. This makes it impossible for the occupants to use the door for escape. If we combine this observation with the rapid shift in construction requirements and practices are rapidly moving towards more air-tight building envelopes, as demanded for the energy efficiency and high-rise constructions, we can expect the pressure-related risks may become more significant, unless the preventive measures can be found and justified.

Various studies have analyzed the effects of pressure on building performance. High-quality measurements of fire-induced pressure in a relatively air-tight compartment were recently conducted in the OECD PRISME programme [1]. The influence of air tightness of enclosures have been investiagted using experiments and theoretical analysis by Prétrel et al. [2,3]. They found that closing the ventilation paths, and particularly exhaust ducts, during the fire significantly increased the pressure. This increased pressure was identified by Forneau et al. [4] as one of the consequences of better energy efficiency, concluding that the high pressure can lead to a reverse flow in the supply ventilation system. However, they did not recognize this pressure rise as posing a risk for escape or structural integrity.

Calculating compartment fire pressure requires knowledge of the gas temperature development and leakage flows [5]. This usually requires numerical integration as the leakage flows depend on pressure. The situation is even more complex if ventilation is mechanically controlled, as is the case in most modern, energy efficient buildings. Pressure calculation has been included in most numerical fire models capable of solving the flows between several compartments. Of these models, the Fire Dynamics Simulator (FDS) [6], has been further developed by Floyd [7] to include a dedicated HVAC module. The current FDS validation database for fire-induced pressures consists of three experimental campaigns, and the peak over-pressures ranging from a few Pa to 1300 Pa [8]. A detailed validation of the of FDS-HVAC module was recently reported by Wahlqvist and van Hees [9].

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.firesaf.2017.04.006
Received 15 February 2017; Received in revised form 27 March 2017; Accepted 3 April 2017

Please cite this article as: Hostikka, S., Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.04.006

**Nomenclature**

*Roman Symbols*

| | |
|---|---|
| $A$ | crossectional area of the duct (m$^2$) |
| $A_L$ | leakage area (m$^2$) |
| $c_p$ | spesific heat capacity (kJ kg$^{-1}$K$^{-1}$) |
| $C_d$ | discharge coefficient (-) |
| $\Delta p$ | pressure difference (Pa) |
| $h$ | enthalpy of fluid (W m$^{-2}$K$^{-1}$) |
| $K$ | loss coefficient (-) |
| $P$ | pressure (Pa) |
| $Q$ | heat release rate (HRR) (kW) |
| $t_g$ | growth time (s) |
| $q_{50}$ | leakage flow at $\Delta P$=50 Pa (m$^3$h$^{-1}$m$^{-2}$) |
| $S$ | compartment surface area (m$^2$) |
| $T$ | temperature (K) |
| $u$ | duct flow speed (ms$^{-1}$) |
| $V_{leak}$ | leakage flow (m$^3$s$^{-1}$) |
| $\dot{V}_{50}$ | volumetric leakage flow at $\Delta P$=50 Pa (m$^3$s$^{-1}$) |

*Greek*

| | |
|---|---|
| $\rho$ | density (kgm$^{-3}$) |

*subscripts*

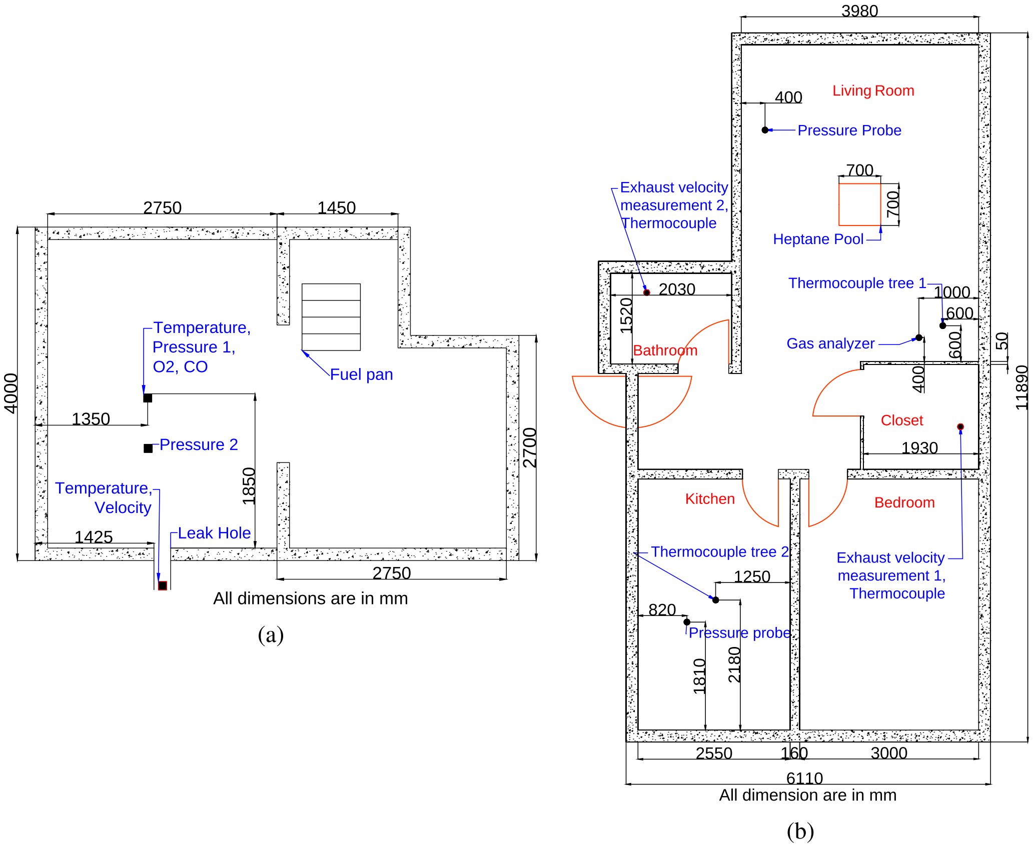
| | |
|---|---|
| $i$, $k$ | nodes |
| $j$ | duct segments |

The aim of the current research was to examine the influence of building envelope air tightness on fire pressure and its consequences in residential buildings. In particular, we intend to determine whether new risks can be expected for structural and evacuation safety and explore the possibility of using the building ventilation network for reducing pressure without increasing the risk of smoke spreading between apartments. First, we use existing [10,11] and new [12] experiments to validate the modelling capability of fire-induced pressures in residential buildings. Next, the validated model is used to perform numerical experiments in hypothetical apartment buildings with different levels of air-tightness. The severity of the predicted conditions is evaluated in light of two model outcomes: pressure inside the apartment and smoke spread to neighbouring apartments through the ventilation network.

## 2. Methods

### 2.1 Numerical method

FDS is a Large Eddy Simulation (LES) based Computational Fluid Dynamics software which solves the low-Mach number combustion equations on a rectilinear grid over time. A dedicated module for modelling Heating, Ventilation and Air-conditioning (HVAC) systems is coupled with the gas phase solver. The ventilation network is described as a series of ducts and nodes. The nodes are placed at points where ducts intersect each other or the CFD computational domain. The ducts represent uninterrupted domains of fluid flow which encompass elbows, expansion/contraction fittings and other fittings. The losses due to friction and duct fittings are assigned as dimensionless loss numbers to the ducts. The node losses are also attached to the



(a)

(b)

**Fig. 1.** Plan drawings and measurements of the FOA (a) and Aalto [12] (b) validation experiments.