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

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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.

KEYWORDS: pressure, modeling, CFD, smoke, airtightness, near-zero buildings, high-rise buildings

NOMENCLATURE

A	crosssectional area of the duct (m^2)	S	compartment surface area (m^2)
A_L	leakage area (m^2)	T	temperature (K)
c_p	specific heat capacity ($kJkg^{-1}K^{-1}$)	u	duct flow speed (ms^{-1})
C_d	discharge coefficient (-)	V_{leak}	leakage flow (m^3s^{-1})
Δp	pressure difference (Pa)	V_{50}	volumetric leakage flow at $\Delta P=50$ Pa (m^3s^{-1})
h	enthalpy of fluid ($Wm^{-2}K^{-1}$)	Greek	
K	loss coefficient (-)	ρ	density (kgm^{-3})
P	pressure (Pa)	subscripts	
Q	heat release rate (HRR) (kW)	i, k	nodes
t_g	growth time (s)	j	duct segments
q_{50}	leakage flow at $\Delta P=50$ Pa ($m^3h^{-1}m^{-2}$)		

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 investigated using experiments and theoretical analysis by Prtrel 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 Fourneau et al. [6] 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 [7]. 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) [8], has been further developed by Floyd [9] 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 [10]. A detailed validation of the of FDS-HVAC module was recently reported by Wahlqvist and van Hees [11].

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 [12,13] and new [14] 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.

METHODS

Numerical method

FDS is a Large Eddy Simulation (LES) based Computational Fluid Dynamics software program 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 ducts as loss terms only appear in the duct equation 3. However, since the module does not presently store any mass, mass flux into a duct is equal to the mass flux out of the duct. The nodal conservation equations for mass, energy and momentum equations are as follows:

$$\sum_j \rho_j u_j A_j = 0 \quad (1)$$

$$\sum_j \rho_j u_j A_j h_j = 0 \quad (2)$$

$$\rho_j L_j \frac{du}{dt} = (P_i - P_k) + (\rho g \Delta z)_j + \Delta P_j + 0.5 K_j \rho_j |u_j| u_j \quad (3)$$

Leakage modelling

Leakage refers to the amount of air flowing through the building envelope due to the pressure difference between the inside and outside. A standardized method for measuring the leakage (e.g. SFS EN: 13829) makes use of a variable-speed fan mounted to a door in the envelope being tested [15]. All the ventilation paths are sealed during the test. The building interior is then pressurized or depressurized using the fan and the leakage flows are determined by monitoring the flow through the fan. Energy efficiency studies, commonly measure leakages at an underpressure of 50 Pa. Overpressures would be more suitable for fire analyses, though both directions can appear. The leakage can be reported as a volumetric flow $\dot{V}_{50}$, air permeability q_{50} or air exchange rate n_{50} .

From the viewpoint of fire CFD, since leakage is a sub grid -scale phenomenon, a leak path boundary condition cannot be directly specified. In FDS simulations, the leaks are modelled as a finite area using vents on the domain boundaries. FDS utilizes the HVAC module to solve the leakage flow

$$\dot{V}_{leak} = A_L \text{sign}(\Delta p) \left(\frac{2\Delta p}{\rho} \right)^{1/2} \quad (4)$$

Validation studies

The FDS validation is performed by simulating two series of compartment fire experiments that were conducted by the Swedish FOA Defence Research Establishment and Aalto University. The FOA experiments were carried out in a room with dimensions of 4.0 m $\times$ 5.5 m $\times$ 2.6 m (height), shown in Fig. 1a. The fire room was divided in two parts with a wall, and the wall had a 1.9 m wide opening from floor to ceiling. The fire source was a heptane pan of 0.73 m $\times$ 1 m. A t^2 -type HRR curve was achieved using a lid that was moved over the pan at a given rate thereby increasing the heptane burning area. Assuming a value of 1600 kW/m² for the HRR per unit area, the movement speed of the lid was adjusted to yield three different growth rates:

Type 1: $\dot{Q} = 0.035t^2$ kW (between fast and medium)

Type 2: $\dot{Q} = 0.075t^2$ kW (between ultra-fast and fast)

Type 2: $\dot{Q} = 0.085t^2$ kW (between ultra-fast and fast)

The FOA experimental parameters are summarized in Table 1. Experiments 1-3 [12] did not include an actual ventilation network, but the fire room had a circular opening ($D = 0.2$ m) at height 0.6 m from the floor, connected to a 2.2 m long and 0.2 m diameter tube. Temperature and flow speed were measured at the end of the tube.

FOA experiments 11-33 [13] included three different ventilation configurations. The leakage openings of different diameters were connected to a 0.32 m diameter and 3.2 m long tube connecting to the ambient. The openings were placed at height 0.6 m from the floor. Experiments 21-33 included an exhaust network, and experiments 31-33 a supply network. Schematic diagrams of the ventilation networks, simplified for modelling, are shown in Fig. 2. Test 23 had a slightly different exhaust ventilation network, as explained in [13]. The ventilation networks consisted of a main duct connecting a fan to the fire room, and additional branches connecting the main duct to ambient through a damper. The purpose of the branches was to simulate additional rooms of actual ventilation systems. The dampers were used to limit the flow rate to these virtual rooms.

A detailed description of the Aalto experiments is given in [14], and only a brief summary is presented here. The experiments are summarized in Table 2. They were conducted in a single apartment of a 1970's apartment building. The apartment (see Fig. 1b) included a living room, bedroom, kitchen, bathroom, aisle and a closet, having a total floor area of 58.6 m² and a ceiling height of 2.57 m. It was located on the first floor of the building. The apartment had two exhaust ventilation ducts leading to the roof. Three different ventilation

Table 1. FOA experiment configurations, following the original test numbering in [12,13]. Test 15 had constant pool area of 0.5 m².

Test	Fire type	Opening <i>D</i> (m)	Exhaust Network	Supply Network
FOA series 1				
FOA 1	1	0.2m	-	-
FOA 2	2	0.2m	-	-
FOA 3	3	0.2m	-	-
FOA series 2				
FOA 11	1	0.2	-	-
FOA 12	1	0.15	-	-
FOA 13	2	0.2	-	-
FOA 14	2	0.15	-	-
FOA 15	-	0.2	-	-
FOA 21	2	0.2	Exhaust network 1	-
FOA 22	2	0.15	Exhaust network 1	-
FOA 23	2	0.15	Exhaust network 2	-
FOA 31	1	0.10	Exhaust network 1	Supply network 1
FOA 32	2	0.15	Exhaust network 1	Supply network 1
FOA 33	2	0.2	Exhaust network 1	Supply network 1

Fig. 1. Plan drawings and measurements of the FOA (a) and Aalto [14] (b) validation experiments.

Fig. 2. The ventilation networks of FOA experiments as modelled in FDS. Top: Exhaust network 1. Bottom: Supply network 1

configurations were created by keeping the original dampers (Normal), removing them completely (Open) or closing the ducts tightly (Closed). All the other ventilation paths were closed. Two different fires were used: heptane pools with peak HRR of 800 kW were used in experiments 1-3 and flexible polyurethane foam with peak HRR of about 1 MW in test 4. Experiments 1-3 were repeated several times.

Table 2. Parameters of the Aalto experiments. Different numbering from [14] is used here for simplicity.

Test	Fuel	Ducts	Roof fan
Aalto 1	Heptane 3.0 L	Open	OFF
Aalto 2	Heptane 3.0 L	Normal	ON
Aalto 3	Heptane 3.0 L	Closed	ON
Aalto 4	Polyurethane foam 3.82 kg	Normal	ON

Simulation models

The simulation model of the FOA experiments consists of a single room with a leakage area connected to an additional duct. The main components of the HVAC models, shown in Fig. 2, are nodes, ducts, and a fan. The other components such as dampers and expansion/contraction fittings are accounted for in the loss terms. Multiple ducts have been combined into a single duct with appropriate loss coefficients for further simplification. Dampers do not completely block the smoke flow, they only limit the volume flow to 25 l/s.

The exhaust network model consists of 8 nodes, including a room node connecting the main duct to the CFD domain, four ambient nodes, and three internal nodes for connecting the branches to the main duct. The total length of the main duct is 7.5 m. The exhaust fan that drives the flow is placed in the duct connecting the main duct to the ambient. The fan curve was defined by specifying the flow rates (0, 60 and 120 L/s) at three static pressures (310, 190 and 18 Pa), respectively. The layout of the supply network is similar to the exhaust network. The fan is obviously operating in different direction, and it is connected directly to the ambient without any duct segment.

In theory, it would be possible to determine the loss coefficients for all the duct sections from the individual losses of the components and the friction. As all the details cannot be determined at this stage, effective loss coefficients were estimated first by defining a constant roughness of 1 mm for the ducts, and then adjusting the loss of the first duct to match the known volume flow of 25 L/s. The losses from the damper and the 90 degree bend were thus combined into a single loss coefficient. Identical losses are used for forward and reverse flow.

Fig. 3. Measured and simulated gas pressures in FOA experiments 1-3.

For leakages, the bulk leakage method was used over all wall surfaces. A detailed explanation of the simulated model can be found in [14]

For other boundary conditions, the models of both FOA and Aalto experiments included only the interiors of the enclosures, assuming that the exterior sides of the walls are exposed to the ambient. For the concrete boundaries, thermal conductivity, specific heat and density were set to 0.7 W/(m.K), 0.75 kJ/(kg.K) and 2200 kg/m³, respectively. Fire boundary conditions were specified as time dependent heat release rates per unit area (HRRPUA) of the fuel pan surfaces. Technically, they were converted to time dependent mass flux and species concentration boundary condition of the CFD solver.

The simulations were carried out using the FDS version 6.3.2 with a single mesh and 6 OpenMP threads on a personal computer with a 3.2-GHz Intel Xeon processor and 32-GB ram. The CPU time for a single simulation of 300 s was approximately 8 hours.

Table 3. HVAC model inputs [14].

Ventilation configuration	L_1 (m)	L_2 (m)	L_3 (m)	A_1, A_2 (m ²)	A_3 (m ²)	K_1	K_2	K_3
Bathroom duct								
Open	0.4	10	1.0	0.01227	0.049	0	3	1
Normal	0.4	10	1.0	0.01227	0.049	0	38	1
Closet duct								
Open	0.4	10		0.01227		0	2	
Normal	0.4	10		0.01227		0	70	

VALIDATION RESULTS

The experimental and simulated fire room pressures in FOA experiments 1-3 are shown in Fig. 3. The positive pressures during the fire growth stage are reproduced by the simulation model with good accuracy. The negative pressures after the fire suppression, in turn, are not captured as well. The same behaviour was observed in all the validations tests of this work.

Fig. 4. Uncertainty of peak temperature (top figure) and overpressure (bottom figure) predictions. Red solid lines indicate the average over- or underprediction of the model. The dotted lines on either side of the diagonal lines indicate the experimental and model standard deviations.

A summary of the gas temperature and peak overpressure predictions is shown in Fig. 4. Gas temperature comparisons were made for all the individual temperature measurements, not for the averaged layer temperatures as in [10]. The temperatures were overpredicted by 11 % on average. Overall, the temperature uncertainties are satisfactory, and increase our confidence in the accuracy of the estimated model inputs for HRR. The peak overpressures are underpredicted by 7 % in average. The model relative standard deviation is dominated by the combined experimental uncertainty.

RESIDENTIAL CASE STUDY DESCRIPTION

Building description

The influence of the envelope air-tightness on the fire-induced pressures and smoke spreading in the ventilation network was studied through the fire simulations in a hypothetical residential building. The simulation geometry for the case study consists of a single floor of a multi storey apartment building. The floor contained 11 apartments with floor areas of either 50 m² or 100 m² and a corridor. The model does not include a

staircase connecting the domain to the other floors of the building, nor will the corridor pressure conditions be studied here. The ceiling height is 2.5m. The room walls and ceiling are made of 15-cm-thick concrete. The fire is assumed to ignite in one of the smaller apartments. Within this apartment, the structures dividing the apartment into rooms are included, but the doors are assumed to be open. Fig. 5 shows the geometry.

Fig. 5. Geometry for the apartment case study

Modern ventilation systems

The traditional ventilation systems in residential buildings have been based on mechanical or buoyancy-driven exhaust, with the supply air provided through the building envelope either as an uncontrolled leakage or through valves. Modern HVAC systems, usually provide separate networks for supply and exhaust air. Both networks are typically equipped with a fan unit to control the flow rate and to implement the heating/cooling, as well as heat recovery and air filtration for indoor air quality control. Single fan unit may serve the entire building or a single floor of a multi-storey apartment building. The coils and filters introduce drag to the flow. As a result, the fan unit will cause pressure losses even when the fans are turned off. For fire compartmentation and smoke control, fire and/or smoke dampers are typically installed to the ducts entering and leaving the apartments. In addition, the modern ventilation fans are often equipped with dampers that automatically close the ambient connection when the fan is turned off. In a fire situation, turning off the fan can, therefore, lead to complete closing of the ventilation system.

Simulation model

Each room in the model has a designated mesh. The discretization is 0.10m for the fire room and 0.50m elsewhere. Each room is considered its own pressure zone with an individual solution for the background pressure. There is no heat transfer through the walls between the rooms and all leakages are to the ambient. The ventilation system consists of independent inlet and exhaust networks, both equipped with a fan with stalling pressure of $P_{max} = 550$ Pa and a zero-pressure flow rate of $V_{max} = 650$ l/s. The fan unit model parameters were tuned to produce 150 Pa pressure loss to the flow. Each network consists of a central duct ($\phi=0.25$ m) and smaller ($\phi=0.125$ m) ducts for each individual apartment. Two inlet and exhaust connections are used for the fire apartment, but only one for all the other apartments. Loss coefficients K for the inlet and exhaust ducts are adjusted in non-fire conditions to achieve a ventilation rate of 40 l/s and slightly negative pressure for the apartment.

In total, 34 simulations were performed, varying the damper configuration, envelope air-tightness level and the fire growth rate. The influence of the fire/smoke dampers installed in the ventilation ducts was studied by analyzing three different compartmentation damper configurations:

- Damper=Off** Both inlet and outlet remain open during the fire.
- Damper=Inlet** The inlet duct of the fire apartment is closed by a damper 10 s after the ignition.
- Damper=Both** Both inlet and outlet are closed by dampers 10 s from the ignition.

Additionally the effect of the dampers located at the inlet and outlet fans was investigated.

Three different levels of the building envelope air-tightness were examined. These levels were defined using the air permeability values q_{50} , listed in Table 4. The class “Traditional” represents an average of the required and reference air-tightness value (for heat loss calculations) described in the current Finnish building code (Part D3: Energy efficiency, 2012, Ministry of Environment). The “Modern”, corresponds to the measured air-tightness in the concrete element multistorey buildings [15] and the “Near-zero” represents the current, technically achievable target level.

The volumetric leakage flow rate $\dot{V}_{50}$ at 50 Pa can be calculated from the air permeability values using equation 5.

$$\dot{V}_{50} = \frac{q_{50}}{3600} S \quad (5)$$

and the air exchange rate as $n_{50} = \dot{V}_{50}/V$, where V is the building volume. The leakage areas A_L , through which these air-tightness levels are specified in the FDS models, are then calculated from the volumetric flow rates as

$$A_L = \frac{\dot{V}_{50}}{C_d \left(\frac{2\Delta p}{\rho_\infty} \right)^{1/2}} \quad (6)$$

In the models, these leakage areas are distributed equally at the locations of doors and windows.

Table 4. Envelope specifications

Envelope Type	q_{50} ($\text{m}^3\text{m}^{-2}\text{h}^{-1}$)	$\dot{V}_{50}$ (m^3/s)	n_{50} (h^{-1})	A_L (m^2)
Traditional	3	0.146	4.2	0.02690
Modern	1.5	0.073	2.1	0.01345
Near-zero	0.75	0.036	1.05	0.006725

Three different fire scenarios were used in the simulations. Two of them were defined as typical t^2 fires with prescribed maximum HRR, and the third one was based on the experimental heptane pool burning rate in the Aalto experiments.

Medium: $\dot{Q} = Q_0(t/t_g)^2$, $t_g = 300$ s, $\dot{Q}_{\max} = 4$ MW

Fast: $\dot{Q} = Q_0(t/t_g)^2$, $t_g = 150$ s, $\dot{Q}_{\max} = 4$ MW

Ultra-fast: $\dot{Q}$ experimental, $t_g \approx 70$ s, $\dot{Q}_{\max} = 1$ MW

In the equations above, $Q_0 = 1$ MW. The targeted peak HRR of the t^2 fires was set to 4 MW which was considered as a realistic value for apartment fires [16]. This is also sufficiently high to consume the O_2 in the compartment and hence yield a physically relevant duration of fire and yield of combustion products.

RESIDENTIAL CASE STUDY RESULTS AND DISCUSSION

Pressure in the fire apartment

Figure 6 presents the simulation results for compartment fire pressure in the most severe conditions, i.e. when the building envelope is very air-tight and the dampers are closed on both the supply and exhaust ducts. The

peak overpressure is shown to depend very strongly on the fire growth rate. The pressure in the medium fire remains below 1000 Pa, while the fast and ultra-fast fires reach a pressure of 3000 Pa and 7000 Pa respectively. It is obvious, that the structure would not withstand such high pressures. Although much more modest are, associated with higher uncertainty than that of the overpressures.

Fig. 6. Effect of fire type on pressures

The predicted peak pressures are summarized in Fig. 7. These results were not corrected for the estimated model bias of - 7 %. The trends in the results are clear and consistent. All three parameters - fire growth rate, damper configuration and air-tightness - are found to be important for the expected peak pressure. Interestingly, the sensitivity of the pressure to the parameter values seems to increase when moving towards a scenario with higher pressure. For instance, the damper configuration is not very important in traditional or normal buildings, but can become crucially important in very air-tight buildings. The results in Fig. 7 were found to be independent of the fan operation (on or off) and position of the fan unit damper. Therefore, the leakages through the other apartments can compensate for the fan pressure differences and complete closing of the ventilation system. Of course, this leads to smoke spreading to the other apartments through the network.

The pressure results can be compared against the simulations of Fourneau [6] who assumed a fire with a growth rate between medium and fast, more airtight envelope ($n_{50} \approx 0.6h^{-1}$), and two open paths through the mechanical ventilation system. The peak pressure in their simulation was about 550 Pa, i.e. between our results obtained for the Damper=Off configuration.

In order to evaluate of the occupants' possibility of escaping from the fire apartment, we compare the overpressure against an appropriate threshold. Here, we assume that opening the door would not be possible if the overpressure were above 100 Pa. For design purposes, although the difference in pressure is usually limited to 50 Pa, we choose a less conservative value for the risk analysis. Based on the predicted peak pressures, it should be possible to open the door in traditional buildings at a medium fire growth rate. For more air-tight buildings and faster fires, opening the door would be challenging. However, it is important to note that these correspond to momentary peak pressures, and reveal little about the time duration of the peak pressure.

Challenges for the structural integrity can be expected in fast or ultra-fast fires. If the criterion of failure is chosen based on our own experimental observation (1500 Pa), the fast fires could pose a risk when the dampers are closed and the envelope is very airtight. This could occur in near-zero or high-rise buildings. In rapidly developing fires, problems could be expected in all modern buildings using dampers. In near-zero buildings, the capacity of the ventilation network is insufficient to relieve the pressure even without dampers. In such a scenario, alternate means for relieving pressure should be investigated.

Fig. 7. Simulations Peak Pressures Bar Plots

Smoke spreading through the ventilation network

The above pressure results indicate that open ventilation ducts could be used as a potential path for pressure relief, at least in the buildings constructed according to current air-tightness norms, as well as in near-zero constructions. The possibility of smoke spreading to the other apartments and the resulting loss of compartmentation becomes an issue when evacuation safety is undermined. Figure 8 visualizes the smoke concentration in the neighbouring apartments 170 s from the ignition. If no dampers are used, the smoke spreads to the neighbours regardless of fan operation. The third figure corresponds to a scenario in which the damper is used only on the inlet side and the exhaust ventilation fan is kept running. Interestingly, the smoke does not spread to other apartments in this case. Obviously, the cases with both dampers operating can be expected to be safe in this respect.

A more quantitative presentation of the same results is given in Fig. 9 showing the minimum visibility over the entire fire duration in the different damper-fan combinations. The red horizontal bars denote the median values from all the neighbouring apartments, and the boxes indicate a “typical range”. In all the cases without any dampers, the visibility values get down decrease to a few meters whereas closing the fan reduces the visibility to about two meters. Making the building more air-tight increases the amount of soot in the neighbouring apartments, thus reducing the visibility. In the simulations with fan operating and damper only on the inlet side, smoke is not observed in the neighbouring apartments. If the inlet side is open, then operating the fan worsens the situation as the fan pressure head prevents smoke from escaping through the inlet branch.

CONCLUSIONS

We used previously published experimental results to validate the FDS fire modelling of the pressure development in fires taking place within closed by mechanically ventilated compartments. This included the modelling of HVAC systems and building envelope leakages. The validated model was used to investigate

(a) Fan = Off, Dampers = Off

(b) Fan = On, Dampers = Off

(c) Fan = On, Dampers = Inlet

Fig. 8. Visualization of smoke concentration 170 s after ignition.

Fig. 9. Minimum visibility in neighbouring apartments

the influence of damper configuration, envelope air-tightness and fire growth rate on the overpressures and the spreading of smoke to the neighbouring apartments in a mechanically ventilated building with many apartments. The simulated over-pressures were compared against the two experimentally observed [14] criteria: A 100 Pa over-pressure was found to be sufficient to prevent apartment occupants from opening an inwards-opening door, thus preventing them from escaping. Secondly, the light-weight structures were found to fail at 1450-1600 Pa overpressure.

Numerical simulations of the fire scenarios showed that the peak overpressure is sensitive to damper configuration, envelope air-tightness and fire growth rate, but practically independent of the fan operation. The pressure was found to increase with improving air-tightness (reduced leakage), increased use of fire or smoke dampers, and the increased rate of fire growth. The 100 Pa limit was reached in all the simulations except those made for the traditional buildings with medium fire growth rate. In a Near-Zero building, the limit was reached in less than 20 s for ultra-fast fire and in about 100 s for a medium fire. The duration varied with respect to the fire type, being in between 100 and 200 s. The risk of structural damage was found to exist at fast and ultra-fast fire growth rates.

Simulations of different damper configurations and fan operation modes showed that the spreading of smoke to neighbouring apartments can be avoided if only the inlet ventilation branch is closed with a damper and exhaust fan is operating. This mode of operation was found to be the only combination for preventing smoke spread, while simultaneously maintaining the pressure at an acceptable level.

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References

- [1] Audouin, L., Rigollet, L., Pretrel, H., Le Saux, W., and Röwekamp, M., (2013) OECD PRISME project: Fires in confined and ventilated nuclear-type multi-compartments - Overview and main experimental results, *Fire Safety Journal* 62 B:80-101.
- [2] Pretrel, H., and Such, J.M., (2005) Effect of ventilation procedures on the behaviour of a fire compartment scenario, *Nuclear Engineering and Design* 235:2155-2169.
- [3] Prétrel, H., Le Saux, W., and Audouin, L., (2012) Pressure variations induced by a pool fire in a well-confined and force-ventilated compartment, *Fire Safety Journal* 52:11-24.
- [4] Audouin, L., Prétrel, H., and Le Saux, W., (2011) "Overview of the OECD PRISME project – main experimental results", in: *21st International Conference on Structural Mechanics in Reactor Technology (SMiRT 21)*.
- [5] Prétrel, H., Koched, A., and Audouin, L., (2016) Doorway Flows Induced by the Combined Effects of Natural and Forced Ventilation in Case of Multi-compartments Large-Scale Fire Experiments, *Fire Technology* 52(2):489-514.
- [6] Forneau, C., Delvosalle, C., Breulet, H., Desmet, S., and Brohez, S., (2012) Comparison of fire hazards in passive and conventional houses, *Chemical engineering Transactions* 26:375-380, <http://dx.doi.org/10.3303/CET1226063>
- [7] Mowrer, F.W. "Enclosure Smoke Filling and Fire-Generated Environmental Conditions," *The SFPE Handbook of Fire Protection Engineering, Fifth ed.*, Hurley, M.J. (ed.), Society of Fire Protection Engineers, 2016. pp. 1066-1101. <http://dx.doi.org/10.1007/978-1-4939-2565-0>
- [8] McGrattan, K.B., McDermott, R., Floyd, J., Hostikka, S., Forney, G. and Baum, H., (2012) Computational fluid dynamics modelling of fire, *International Journal of Computational Fluid Dynamics* 26:6-8, 349-361.
- [9] Floyd, J. "Coupling a Network HVAC Model to a Computational Fluid Dynamics Model Using Large Eddy Simulation." *Fire Safety Science – Proceedings of the Tenth International Symposium*, International Association for Fire Safety Science, 2011, pp. 459-470.

- [10] McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., and Overholt, K., “Fire Dynamics Simulator, Validation Guide, Volume 3: Validation,” National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, November 2015.
- [11] Wahlqvist, J. and van Hees, P., (2013) Validation of FDS for large-scale well-confined mechanically ventilated fire scenarios with emphasis on predicting ventilation system behavior, *Fire Safety Journal* 62 B:102-114.
- [12] Hägglund, B., Nireus, K., and Werling, P., “Pressure rise due to fire growth in a closed room. Description of three full-scale tests,” FOA Defence Research Establishment, FOA-R-96-00347-2.4-SE, 1996. 27 p.
- [13] Hägglund, B., Nireus, K., and Werling, P., “Pressure rise due to fire growth in a closed room. An experimental study of the smoke spread via ventilation ducts,” FOA Defence Research Establishment, FOA-R-98-00870-311-SE, 1998. 97 p.
- [14] Janardhan, R.K. and Hostikka, S. (2016) Experiments and numerical simulations of pressure effects in apartment fires, *Fire Technology* 1-25 <http://dx.doi.org/10.1007/s10694-016-0641-z>
- [15] Vinha, J., Manelius, E., Korpi, M., Salminen, K., Kurnitski, J., Kiviste, M. and Laukkanen, A. (2015) Airtightness of residential buildings in Finland, *Building and Environment* 93:128-140. <http://dx.doi.org/10.1016/j.buildenv.2015.06.011>
- [16] Blomqvist, P., Rosell, L., Simonson, M., “Emissions from Fires Part II: Simulated Room Fires,” SP Swedish National Testing and Research Institute, Borås, Sweden.