FIRE MODELLING OF ENERGY-EFFICIENT APARTMENT BUILDINGS
Consideration of air-tightness and mechanical ventilation

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Abstract. In this work, we wanted to study how the construction trends aiming at energy efficient and high-rise buildings are changing the fire modelling practices. Through experiments, FDS validation and a simulation case-study, we investigate the reliability and modelling practices of the mechanical ventilation systems and air-tight building envelopes. The simulation results indicate that the new, very air-tight building envelopes can pose a risk for both occupant and structural safety in fires.

1. INTRODUCTION

In the modeling of enclosure fires, it has been common to assume that the buildings that we analyze are not air-tight, with a few exceptions, such as the special industrial facilities like nuclear power plants. Pressure build-up in the simulations has been avoided because (i) it has been deemed sufficient to focus on the hydrostatic pressure driving the flows in the space, (ii) accurate information about the air-tightness has not been generally available, and (iii) the means of calculating the leakage flows have been difficult to integrate with the numerical fire models. For long, it was a common practice to define a 10 by 10 cm leakage hole to the rooms when modeling them with zone or CFD models. With the current trends of energy-efficiency and high-rise buildings, the situation has changed. Both trends pose much more strict requirements for the building envelope's air-tightness than what has been the common practice before. As a result, the development of over- and under-pressures has become an essential feature of building fires and their simulations.

At the same time with building envelopes becoming more air-tight, the ventilation systems are getting more complicated. Meeting the energy-efficiency requirements necessitates the use of mechanical supply and exhaust ventilation with heat recovery. Integration with building services and active fire protection technologies makes the systems complicated and challenging for modeling.

In FDS, the technical capability to simulate HVAC systems and leakages was introduced by the implementation of a dedicated HVAC module [4].

2. FEATURES OF MODERN BUILDINGS

2.1. 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. In modern HVAC systems, there are usually 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 an 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 fire situation, turning off the fan can therefore lead to complete closing of the ventilation system.

In principle, the ventilation system could be modelled starting from the drawing describing the design or 'as built' status. This is possible if we know the exact dimensions and characteristics of the various components of the system. The losses were determined using based on individual pressure loss of each duct fitting and the friction loss of the duct. The volume flow or velocity of flow through the ducts is required to find the loss coefficient K_j appearing in the duct momentum equation

$$\rho_j L_j \frac{du}{dt} = (P_i - P_k) + (\rho g \Delta z)_j + \Delta P_j + 0.5 K_j \rho_j |u_j| u_j \qquad (1)$$

For example, assuming a duct of length 1m and diameter of 0.1m with an expansion fitting which leads to a duct of 0.125m and a damper regulating the flow to 25 L/s. The loss coefficient for this duct is calculated as follows:

- The value of friction loss for a given diameter and volume flow/velocity can be found from a friction loss chart for a duct. In this case, friction loss is about 1.6...1.8 Pa, and $F_{\text{loss}} = 1 \times 1.8 = 1.8$ Pa.
- For an expansion, loss would be calculated using the equation $\Delta P = \frac{\rho V^2}{2}(1 - \frac{A_1}{A_2})^2$ which give us the value of ΔP as 0.85 Pa.
- The loss across the damper is usually the highest. Here we can assume that it causes a loss of 50 Pa.
- The total loss accounts to 52.603 Pa. This value should equal to the last term in Equation (1): $0.5 K_j \rho_j |u_j| u_j = 52.603$ Pa $\Rightarrow K_j = 8.476$.

This kind of process requires a lot of information that can be difficult or impossible to obtain for a fire engineer. Additionally, the process is sensitive to errors.

Practical experiences from the two validation studies and two case studies has shown us that the practical HVAC modelling procedure in the near future will go along the following lines:

1. Gather the basic design information about flow rates, known pressure losses (HVAC valves and fan unit components), and the fan operating characteristics (fan curve).
2. Model the HVAC network in the simplest possible way, maintaining the physical dimensions (diameters, lengths and heights) of the system.
3. Assign some realistic value for the duct roughness to introduce main duct pressure losses.
4. Specify additional losses to the ducts and adjust them to reach the expected flow rates through the system.
5. Verify the pressure levels and flow rates in a normal state by adding measurements for the flows and node pressures.

So, the actual system information is limited to the design flow rates and the fan characteristics,as the fan pressure levels dominate the system's performance.

2.2. Air-tight envelopes

The building envelope air-tightness is important for many building performance aspects, including the energy-efficiency of buildings and for the control of indoor environment and ventilation in high-rise buildings. In energy-efficiency, the goal is to reduce the energy losses by convection through the cracks and gaps of the envelope. The convection is driven by the pressure difference between the interior and exterior, which in small houses can vary from few tens of Pa underpressure to a few Pa overpressure. For the moisture control, it is, at least in Finland, common to maintain the buildings at small negative pressure. In high-rise buildings, the pressure differences can be much higher.

The envelope air-tightness is commonly measured using a blower-door test [1] where a powerful fan is attached to a door leading outside (see Fig. 1), and the other vents of the building are closed tightly. The fan is used to create a pressure difference between the interior and the ambient. The amount of air flow through the fan is measured at several pressure differences. The normal practice in the energy efficiency studies is to report the leakage rate at 50 Pa underpressure in a form of a volumetric flow rate $\dot{V}_{50}$, air permeability $q_{50} = \dot{V}_{50}/A_{\mathrm{env}}$ or air exchange rate $n_{50} = \dot{V}_{50}/V$. Here, A_{env} is the envelope area and V is the building volume.

FDS utilizes the HVAC module to solve the leakage flow

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

Figure 1. Blower-door test (left) and sealed exhaust ventilation duct (right). (Photographs by Mikko Yli-Piipari, Vertia Oy).

The main input for the leakage modelling is therefore the effective leakage area, which can now be determined from the air-tightness measurements as

$$A_{\mathrm{L}} = \frac{\dot{V}_{50}}{C_d \left(\frac{2\times 50}{\rho_\infty}\right)^{1/2}} \ [\mathrm{m}^2] \tag{3}$$

Of course, the area can be calculated using the leakage flow at some other pressure than 50 Pa, if available.

3. VALIDATION

3.1. FOA Test series

The Swedish FOA Defence Research Establishment conducted two sets of experiments in the late 1990’s to investigate the fire pressure and duct flows [2, 3]. The first series [2] consists of three tests with t^2 fires of different growth rates between medium and ultra-fast. The fire room was 4.0 m $\times$ 5.5 m $\times$ 2.6 m (high) and the fire source was a heptane pan of 0.73 m $\times$ 1 m (c.f. Fig. 2). These tests did not include actual ventilation network, but the fire room had a circular opening ($D = 0.2$ m) connected to a 2.2 m long tube. Temperature and flow speed were measured at the end of the tube. The opening was located at 0.6 m from the floor. 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 t^2 behaviour of the HRR was achieved using a lid that was moved over the pan at a given rate thereby increasing the heptane burning area. The quantitative value of HRR was obtained by assuming 1600 kW/m^2 for the HRR per unit area of pool surface.

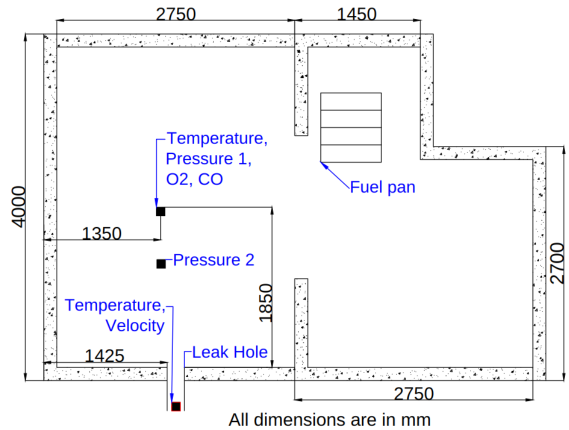

Figure 2. FOA test geometry.

The second series [3] consists of three groups of experiments with the same room and same fire types as the first set, but with 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 opening was located at 0.6m height from the floor on one wall of the room. In the first group, there was not ventilation system, only leakage opening. In the second group, the room was equipped with an exhaust system, shown in the top part Fig.3. A supply network (Fig. 3 lower part) was added in the third group.

The HVAC model components 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 only limit the volume flow through the ducts to 25 l/s.

The exhaust network was modelled using 8 nodes, starting from Node 1 which connects the computational domain to the main duct which is also connected to three fictive compartments maintained at ambient pressure. The total length of the duct from Node 1 to 5 was about 7.5 m. Nodes 5,6,7 and 8 are maintained at ambient pressure. The exhaust fan that drives the flow is placed in the last duct connecting nodes 4 and 5. The fan curve was defined by specifying the flow rates (0, 60 and 120 Ls) at three static pressures (310, 190 and 18 Pa), respectively.

3.2. Aalto University test series

The third series of validation experiments consists of experiments carried out in 2015 in a 1970's apartment building in western Finland. A detailed explanation of the experiments is given in [5]. The apartment (see Fig. 4) had two exhaust ventilation ducts leading to the roof. All the other ventilation paths were closed during the experiments. The originally natural ventilation had been enforced by post-installed fan in the bathroom exhaust. Two different fires (Fig. 5) and

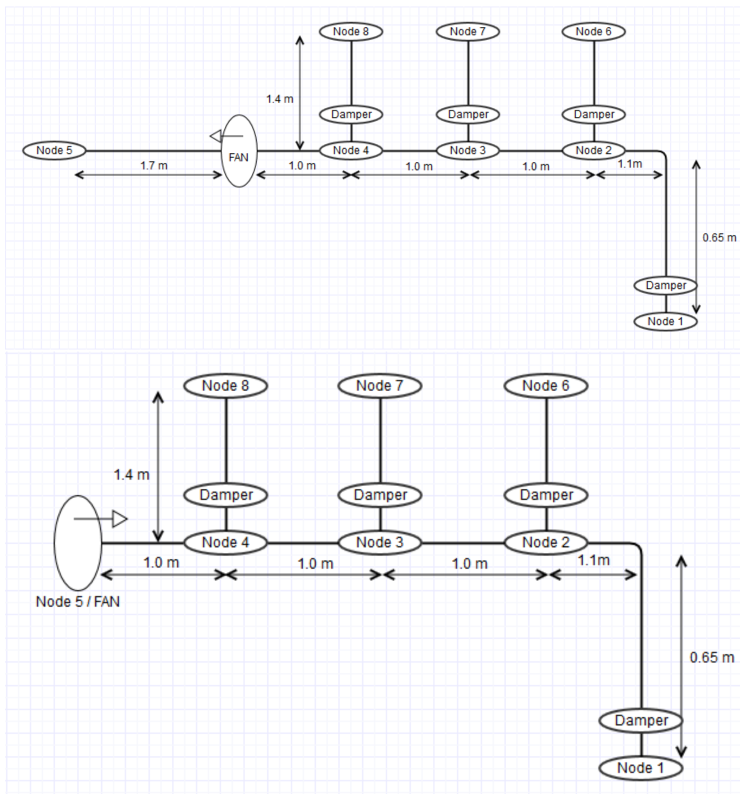

Figure 3. FOA exhaust and supply ventilation systems.

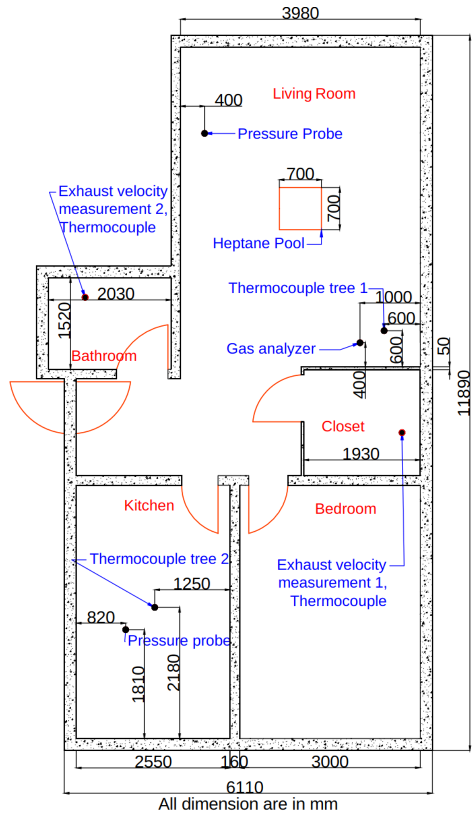

Figure 4. Geometry of the Aalto experiments.

three exhaust damper configurations (Fig. 6) were used. Open configuration means that the dampers were removed completely, normal configuration that the original dampers were in place, and closed configuration that the exhaust ducts were tightly sealed.

The ventilation ducts were modelled as combinations of two or three duct segments. The first duct was installed for the measurements, and the third segment of the bathroom duct was used for including the fan.

3.3. Validation results

The experimental and simulated fire room pressures in FOA Series 1 are shown in Fig. 7. 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 three validation series. Figure 8 shows the corresponding comparisons for the heptane pool tests of the Aalto University's series. The simulations were performed using both bulk and localized leakage method. The with the bulk

Figure 5. Heptane pool (top) and Polyurethane foam fires.

Figure 6. Ventilation system configurations. Open, normal, and closed.

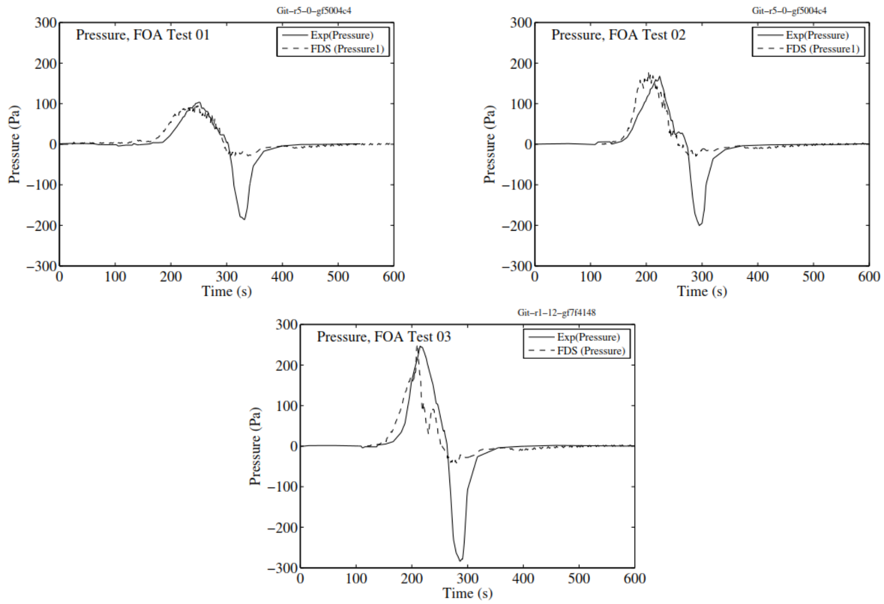

Figure 7. Measured and simulated gas pressures in FOA series 1.

method, the peak overpressures are overpredicted by 21 % but the underpressure peaks are captured at least qualitatively. With localized leakages, the peak pressure predictions varied from overprediction (Test 3) to underprediction for Test 8. The difference between the bulk and localized methods is at least partially explained by the different pressure value used for driving the flows: In bulk method, the background pressure drives the flow and in localized method the driving pressure is the local pressure at the vent, including the hydrostatic and perturbation components.

A summary of the validation results is presented in Fig. 9 for the peak gas temperature and peak gas pressure. Gas temperature comparisons were made for all the individual temperature measurements, not for the averaged layer temperatures as in the FDS Validation Guide. The temperatures are overpredicted by 11 % in average. Overall, the temperature uncertainties are satisfactory, considering the uncertainties associated with the input HRR curves. For the peak pressures, localized method data was used. The peak pressures are underpredicted by 13 % in average. The model relative standard deviation is dominated by the combined experimental uncertainty.

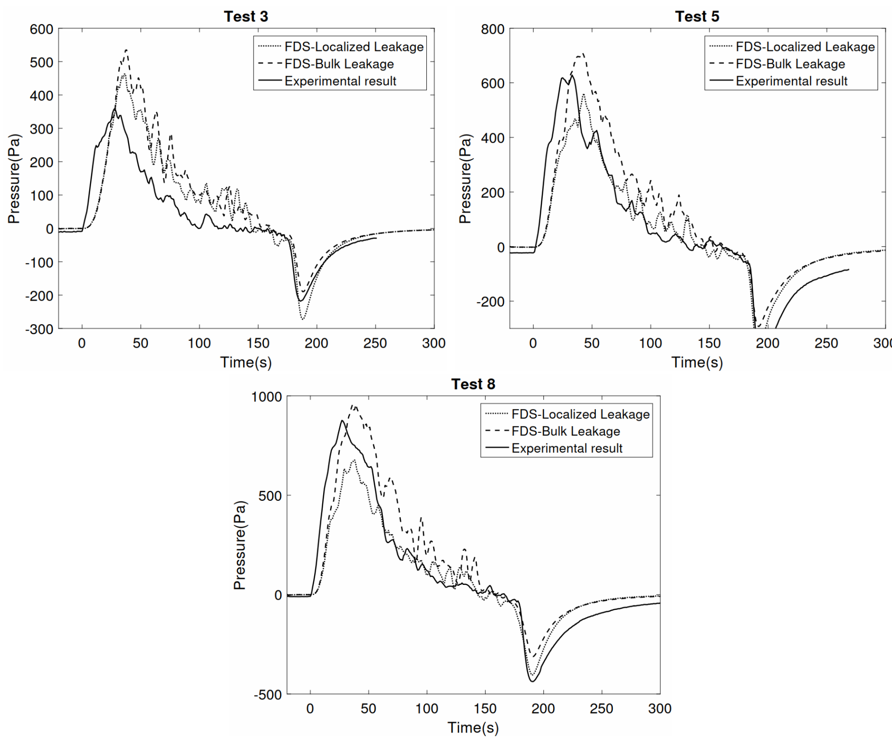

Figure 8. Measured and simulated gas pressures in heptane pool tests in Aalto series. Simulations using Bulk leakage.

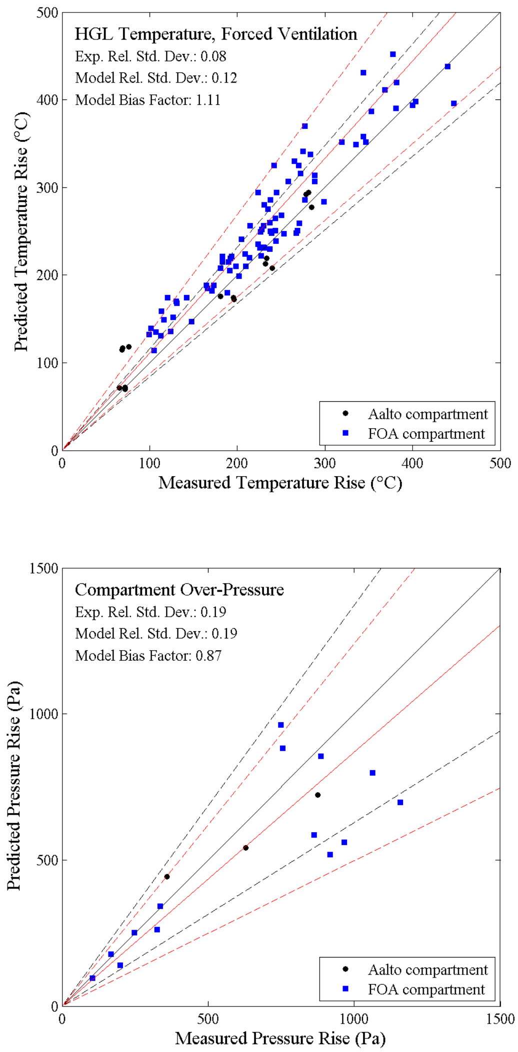

Figure 9. Summary of validation results.

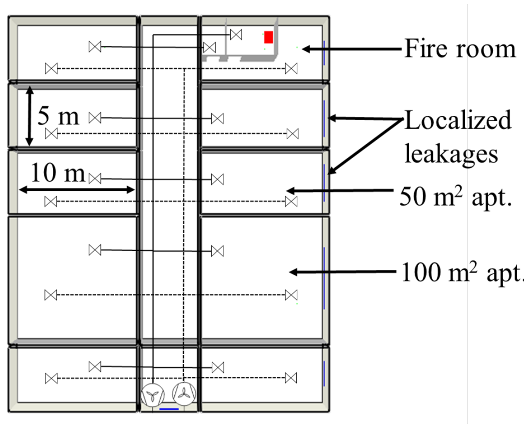

Figure 10. Apartment building geometry

4. APARTMENT BUILDING CASE STUDY

4.1. Case study 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. There are 11 apartments with 50 m^2 or 100 m^2 floor areas and a corridor. The model does not include a staircase connecting the domain to the other floors of the building, and the corridor pressure conditions are not studied here. The ceiling height is 2.5 meters. 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. 10 shows the geometry.

Each room in the model has a designated mesh. The discretization is 10 cm for the fire room and 50 cm elsewhere, meaning they mainly serve as a volume reserve for pressure and gases. 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 (D=250 mm) and smaller (D=125 mm) 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 40 l/s ventilation rate and slightly negative pressure for the apartment.

Envelope type	q_{50} ($\mathbf{m^3m^{-2}h^{-1}}$)	q_{50} ($\mathbf{l\ m^{-2}s^{-1}}$)	V_{50} ($\mathbf{m^3/s}$)	n_{50} ($\mathbf{h^{-1}}$)	A_L ($\mathbf{m^2}$)
Traditional	3	0.83	0.146	4.2	0.02690
Modern	1.5	0.42	0.073	2.1	0.01345
Near-zero	0.75	0.21	0.036	1.05	0.006725

Table 1. Envelope specifications

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 studying 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 investigated. These levels were defined using the air permeability values q_{50}, listed in Table 1. The class *Traditional* represents an average of the required and reference value (for heat loss calculations) in the current Finnish building code (Part D3: Energy efficiency, 2012, Ministry of Environment). The *Modern*, in turn, corresponds to the measured air-tightness in the concrete element multistorey buildings [6] and the *Near-zero* represents the current, technically achievable target level.

Simulations were carried out using t^2 fire scenarios with peak heat release rate of 4 MW.

4.2. Peak pressures in fire compartment

The observed peak pressures are summarized in Fig. 11. These results were corrected for the estimated model bias of 0.87, and the error bars indicate the 95 % confidence limits. The trends in the results are clear and consistent. All the 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 and normal buildings, but can become crucially important very air-tight buildings. The results of Fig. 11 were found to be independent of the fan operation (on or off) and the position of the fan unit's damper. This means that the combined volume buffer and envelope leakages provided by the other apartments can compensate for the reduced exhaust through the main

duct if the fan is closed. Of course, this means that smoke will spread to the other apartments through the network.
Assuming that opening the inwards-opening door is not possible if the overpressure is more than 100 Pa, we can conclude that escaping should be possible from traditional buildings if the fire growth rate is medium or slower. For more air-tight buildings and faster fires, the door opening would be challenging. The times when the 100 Pa overpressures were reached were in the range 76-151 s for medium fires and 34-107 s for fast fires. The durations of the high pressure varied between 30 and 250 s.

Challenges for the structural integrity can be expected if the fire develops at a rate corresponding to the fast design fire type, or even faster. If we choose the failure criterion based on our own experimental observation (1500 Pa), the fast fires could pose a risk when the envelope is very airtight. This could be the situation in Near-Zero or high-rise buildings.

4.3. Smoke spreading through the ventilation network

Based on the above pressure results it seems that open ventilation ducts could be used as a potential path of pressure relief at least in the buildings built according to the current air-tightness expectations, and in very air-tight buildings with modifications. The possibility of smoke spread to the other apartments and the resulting loss of compartmentation becomes then an issue. Figure 12 visualizes the smoke concentration in the neighbouring apartments 170 s from the ignition. If no dampers are used, the smoke spreads to the neighbors regardless of the fan operation. The third figure corresponds to a situation where the damper is used only on the inlet side and the exhaust ventilation fan is kept running. Interestingly, the smoke is not spreading 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. 13 showing the minimum visibility over the entire fire duration in the different combinations. The red horizontal bars show the median values from all the neighbouring apartments, and the boxes indicate a “typical range”. The visibility values get down to few meters in all cases without any dampers, and closing the fan reduces the visibility down to about two meters. Making the building more air-tight increases the amount of soot in the neighbors and reduces the visibility. In the simulations with fan operating and damper only on the inlet side, smoke is not observed in the neighbors. If the inlet side is open, the operating fan makes the situation worse as the fan pressure head prevents smoke from escaping through the inlet branch.

5. CONCLUSIONS

We used experimental results (own and literature) to understand the pressure development in fires taking place within closed but mechanically ventilated compartments. We then used the experimental data to validate FDS modelling approach, including the modelling of HVAC systems and building envelope leak-

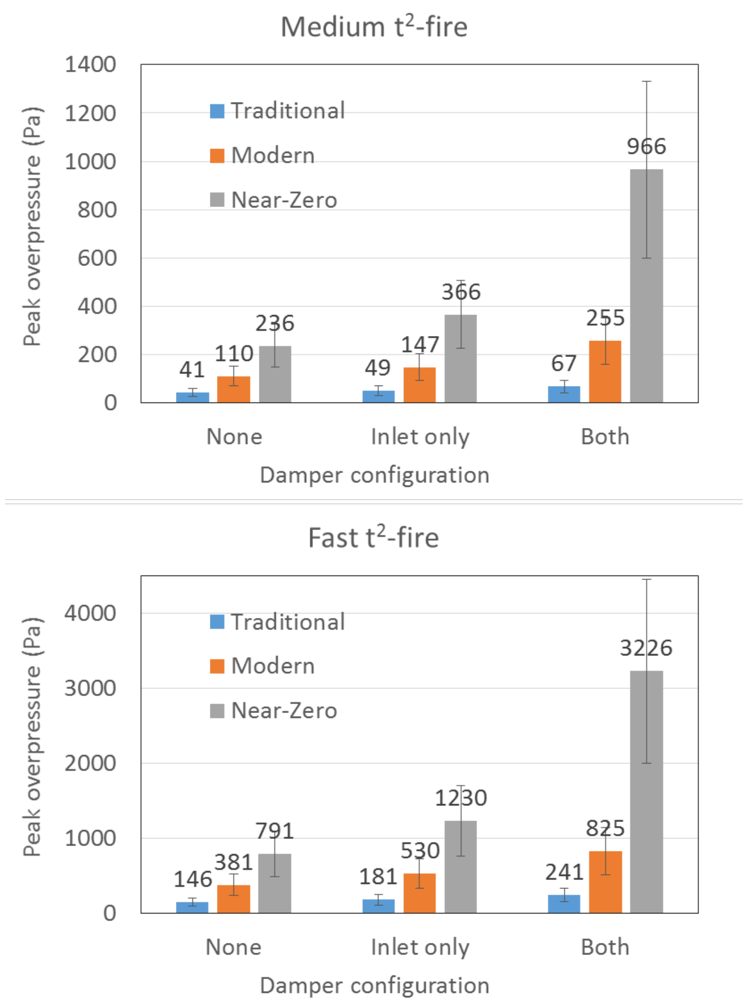

Figure 11. Simulated peak pressures in the apartment fire.

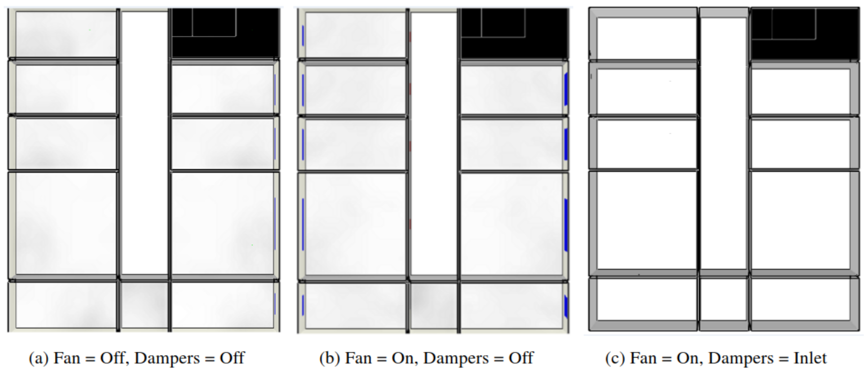

Figure 12. Visualization of smoke density in neighbouring apartments.

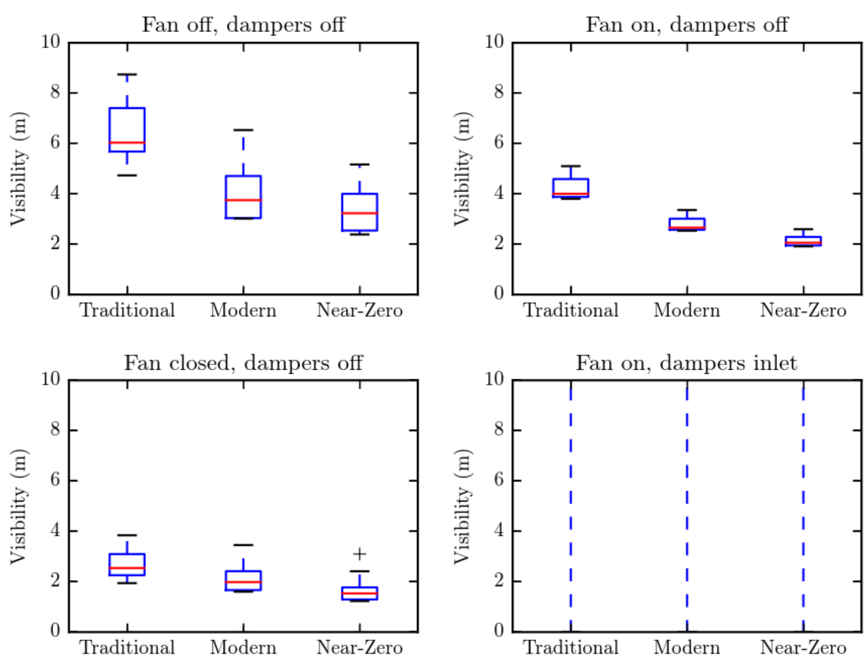

Figure 13. Minimum visibility in neighbouring apartments.

ages. In this context, mainly due to the high experimental uncertainties, the validation is focusing mainly to the modelling approach and procedure, not so much to the predictive capability of FDS. Nevertheless, using the validated modelling procedure, we investigated the influence of the damper configuration, envelope air-tightness and fire growth rate on the pressures and smoke spreading to neighbouring apartments in a mechanically ventilated building with many apartments.

The numerical simulations of the apartment building fire scenarios showed that the peak overpressure is sensitive to the damper configuration, envelope air-tightness and fire growth rate, but practically independent on 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 peak pressures were found to be sufficiently high to prevent escape through an inwards-opening door in modern, air-tight buildings. The durations of high pressure were found to be long enough to put the occupants in danger. The risk of structural damage was found to exist with fast fires. The risk of structural damage was limited to the very air-tight buildings with dampers installed in both inlet and exhaust ducts.

The simulations of the different damper configurations and fan operation modes showed that the smoke spreading to the neighbouring apartments can be avoided if only the inlet ventilation branch is closed with a damper and exhaust fan is kept at running. This mode of operation was found to be the only combination where the smoke spread can be prevented, simultaneously maintaining the pressure at acceptable level. The situation can of course be improved by introducing additional technical means of pressure management. These should be among the future applications of the newly developed simulation capability.

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