Smoke spread in a ventilation system - Room fire experiments and technical solutions in a prison environment with active ventilation

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Abstract. This paper presents an overview of results from full-scale tests with a limited amount of combustible material adjusted to the conditions that can be expected in prison cells. The results are combined with theoretical calculations where the ratio between pressure drop across supply and exhaust air devices is studied to achieve an optimal ventilation solution without fire dampers with active ventilation and adequate personal safety. In Sweden, the most common protection method to prevent fire smoke spread in a buildings ventilation system is active ventilation in combination with non-return dampers on the supply air ducts to each fire compartment. In the initial stage of a fire, high pressures can occur due to the thermal expansion. At this stage, the fire room is assumed to be relatively airtight and thus, there is a risk of smoke spreading via openings and the ventilation system due to the increased pressure caused by this expansion. In the later stages of the fire, the fire room is normally depressurized due to glass breakage and thus the fire also has free access to oxygen. In the initial pressure build-up phase of the fire, a stratification will occur in the fire room with a dense smoke-filled upper layer at ceiling and less dense smoke in the lower layer close to the floor. With supply air close to the floor the concentrations of dangerous smoke will decrease.

1 Introduction

The ventilation system supplies many different parts of a building. One of the fundamentals of fire protection in buildings is fire compartmentation, i.e., to divide buildings according to function and activity into different fire compartments. The purpose is to limit fire and smoke spread from the compartment of origin, e.g., an apartment. However, in reality, installations such as the ventilation system, will penetrate the boundaries of the fire compartment. This means that the building also needs to be protected from fire and smoke spread through the ventilation system since several fire compartments may be connected through the ventilation duct system. The traditional protection method is to stop the fans and close fire dampers on both the supply and exhaust air for each compartment. In Sweden, performance-based design is common for the protection of smoke spread through the ventilation system. With such design, the fans are usually kept in operation and non-return dampers are mounted on the supply air ducts to each fire cell. With pressure and flow calculations, using for example the calculation software PFS (Program Flow System) [1], such a system can be designed to avoid smoke spread to other fire compartments through the exhaust air system. This protection method has also been presented in reports and handbooks in Sweden [2,3]. It has also been discussed. in nuclear plant applications [4] and in regard to validation of software FDS (Fire Dynamics Simulator) [5]. The greatest risk of smoke spreading through the ventilation system occurs in the initial stage of the fire when the air expands in the fire compartment, which cases the pressure to increase. If pressure relief takes place, e.g., if a window collapses or similar, the smoke will mainly be transported out through this opening and pressure in the fire compartment will drop. In a development of the protection method mentioned above, previous model-scale experiments have shown that, in some cases, it is possible to limit the spread of smoke also in the supply air system without using non-return dampers if the ventilation supply are positioned close to the floor [6]. In the full-scale experiments [7], it was shown that in the initial stage of the fire, there was a spread through the supply system, but the concentrations of dangerous smoke were negligible. A possible explanation for this is that in the initial stages of the fire, when the pressure build-up in the fire compartment is most severe, there is also a smoke stratification in the room, meaning that the air volumes that are being pressed out of the fire compartment close to the floor are mainly composed of air and not smoke.

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The expansion of the fire can be described in different ways. One way is to use a fire induced flow, thoroughly described in [2,3]. In BBRAD (Boverkets allmänna råd om analytisk dimensionering av byggnaders brandskydd, the Swedish National Board of Housing, Building and Planning's general recommendations on the analytical design of a building's fire protection), which is the Swedish regulation on performance-based design, the fire induced expansion is described as being 1500 Pa in the initial stage. The fire induced flow method is a suitable way because the resulting pressure in a fire room is dependent on both the expansion and the total leakage in the fire room including any open ventilation ducts and leakage in building components. Supply and exhaust air devices to a room are often adjusted with a fixed flow and pressure drops. There is a negative pressure in the exhaust air system and a positive pressure in the supply air system. In the event of a fire, these conditions will change. The system design (pressure conditions in the device and duct system) will also affect the spread of smoke and air in both the supply and exhaust air systems during active ventilation which is illustrated in Fig 1.

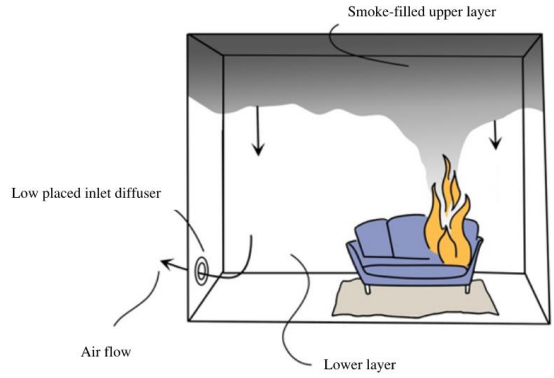


Fig. 1. Illustration of a fire with the ventilation supply close to the floor.

2 Experimental set-up

The full-scale tests were carried out at RISE in Borås. The test setup is shown in Fig. 2 below. A total of 18 tests were performed and the full spectrum of results are described in the report [7]. In this paper, experiments with limited combustible material corresponding to prison environments is discussed. The fire compartment is a full scale version of the room used in previous model tests [4]. Walls and roofs were built with wooden studs and covered with fire rated gypsum boards on the inside. The joints between the frames and between frames and the concrete floor were insulated with glass wool. A fire rated sealant was used to seal the joints between the boards. A door, 1 m × 2 m (width × height), for access to the room as well as two windows with fire-rated glass for visual inspection were installed. In Fig. 2, A is a supply air duct with a diameter of 125 mm, which was connected to a ventilation inlet diffuser in the cases with active ventilation. In all tests except two, the height of the upper edge of the inlet diffuser was placed 200 mm above the floor. In the remaining two tests, the diffuser height was adjusted using a 90° bend on the inside of the room to a height of 25 mm above the floor. In the figure, C is the exhaust duct with a diameter of 125 mm and B is a measurement device to measure the difference between the air pressure in the fire compartment and the ambient pressure. Temperatures were measured in the ducts, i.e., A and C, as well as in the fire compartment, using a thermocouple tree with thermocouples (type K with a thickness of 0.5 mm) every 10 cm from floor to ceiling. The levels of CO, CO_2 and O_2 were measured in ducts A and C as well as within the fire compartment adjacent to the thermocouple tree. Visibility and flow measurements were also performed in the ducts, using laser measurement devices and bi-directional probes. The supply and exhaust fans were connected to duct A and C, with A connected to a supply fan and C connected to an exhaust fan. The ducts were connected to the fans using a T-joint which simulated a connection to a larger ventilation system. The flow and pressure drop across the diffusers were adjusted to 30 l/s and 50 Pa.

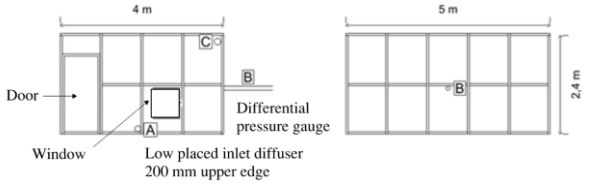


Fig. 2. Principle sketch of the test set-up for the full-scale tests.

Before and after each test, the tightness of the construction was measured. The fire load was designed to fulfill the Swedish Prison and Probation Services recommendation for a prison cell, i.e., fire-resistant, but vandalized, mattresses measuring 0.8 x 2.0 m and with a weight of 8.5 kg. Bedding, clothes, towels and plain printing paper was part of the fire load. In total, the fabric material for each trial weighed approximately 17 kg and the paper for each trial weighed approximately 0.3 kg (60 folded A4 sheets).

3 Results from the full-scale tests

The temperatures, room pressure build-up and oxygen levels were measured along with the spreading of smoke. For the spreading of smoke, both the volume of air/smoke travelling backwards through the inlet system, as well as the composition of the smoke, i.e., the gas concentrations, were measured. The effects of opening and closing the door was also studied in one scenario. A total of four tests were performed with the specified fire load. The other 14 tests were carried out with different fire loads. The results from the measurements in the room and duct temperatures as well as the room pressure build-up for test number 3 are presented in figure 3. This test is called KV3 in the previously mentioned report [7].

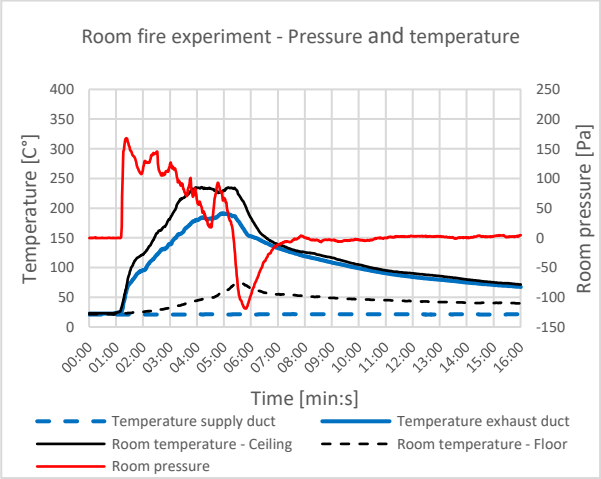


Fig. 3. Temperatures in the room, in the ventilation system and room pressure build-up in the experiment

The maximum temperature in the ceiling was measured to approximately 250 °C and at the floor 70 °C. The highest temperature in the exhaust duct was measured to 200 °C. In this case, the temperature in the low-placed supply air duct was not affected. The measurements also show that flow in supply air duct reversed briefly but contained no soot and no CO. These results are reported in detail in [7]. The experiments show that an operating ventilation system, in combination with supply vents close to the floor can significantly reduce or prevent the spread of dangerous smoke in the ventilation system during the early high-pressure stage of a fire.

4 The impact of the ventilation system design

With the fire represented as a fire induced flow, the air/smoke mixture will first spread via the exhaust air system. As soon as the resulting pressure in the fire room exceeds the pressure across the supply air duct it will also spread into the supply air system. Based on the described situation with a low-placed supply air device and approx. 50 Pa across the supply and exhaust air devices, calculations have been carried out to further study the situation. The pressure difference between the room and the space outside is, as in normal ventilation systems, zero. As can also be seen from the figure 3 before and after the fire. If the pressure drop across the supply air device is increased and the pressure drop across the exhaust air device is reduced, a larger proportion of the fire induced flow will be transported out of the fire room through the exhaust air system and a smaller proportion will spread through the supply air system. The calculations have been performed in PFS [1] with a model consisting of four rooms with 125 mm duct connections (1 m each), 30 l/s and 25-125 Pa over supply and exhaust air devices connected to distribution boxes (both on the inlet and exhaust system). The fire induced flow is set to 500 l/s and the temperature 350 °C. In the reference case, the amount of air flow that is pushed into the supply air duct is calculated when the pressure drop of both the supply and extract air devices is 50 Pa. In the other calculations, the pressure drops were varied and the flow into the supply air system was calculated and related to the reference case (50 Pa over both inlet and exhaust device). See Figure 4.

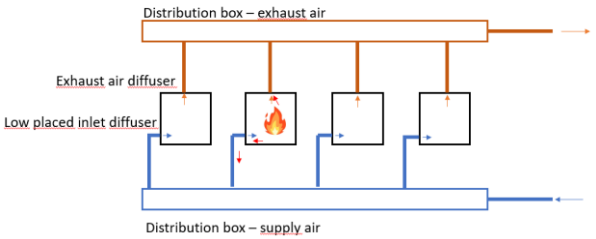


Fig. 4. Ventilation system - schematic design with low placed diffuser and distribution boxes

Another measure to improve the situation is to create diffusion points in the supply air system. This means that the amounts of air/smoke that spread via the supply air are distributed (diluted) over many volumes, and thereby the impact on other fire compartments will be further reduced. Such an effect can be reached by connecting several supply air ducts to a distribution box or a distribution duct with a low pressure drop. The results are presented in Table 1.

Table 1. Results from calculations.

Inlet diffuser (Pa)	Exhaust diffuser (Pa)	Inlet/ exhaust quota (-)	Back flow quota (-)
50	50	1	1
75	50	1,5	0,9
100	50	2	0,8
50	25	2	0,8
75	25	3	0,7
100	25	4	0,7
125	25	5	0,6

The inlet/exhaust quota is calculated as the pressure quota between the inlet diffuser and the exhaust diffuser. The back flow quota is calculated as the back flow at different inlet/exhaust quota compared with the quota at 50/50 Pa (1). The calculations show that the air/smoke mixture spread into the low-placed supply air diffusers can be influenced via the ratio between pressure drops across supply and exhaust air diffuser. At ratios 4-5 between supply air and extract air, the dispersed volume can be reduced to approx. 60-70% of what it is if the pressure drop across the supply and extract air devices is equal. With a distribution box with a low pressure drop, the dispersed air volume will also be evenly distributed over several volumes. The method can be described as making it as easy as possible for the spread volume to get into the exhaust air duct system and as difficult as possible to get into the supply air system. When the air mixture has entered the supply air system it can be distributed relatively evenly over as many volumes as possible.

5 Conclusions

The full-scale tests show that the method with low-placed supply air device and fans in operation can be

applied in rooms with limited fire load, for example in prison environments and other premises where the combustible material is controlled and minimized. The method may be useful in other situations with supplementary measures to reduce the risk of smoke spread via the ventilation system. Examples of measures are to minimize the fire load, place the supply air device as low as possible, design pressure drops across the devices so that the risk of smoke-air mixture spreading via supply air is reduced, create diffusion points in the supply duct system and increase the supply and exhaust air fan speeds in the event of a fire (which creates an increase in flow and pressure drop across the diffuser).

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