Jukka Vaari & Jukka Hietaniemi

Smoke ventilation in operational fire fighting

Part 2. Multi-storey buildings

TECHNICAL RESEARCH CENTRE OF FINLAND ESPOO 2000

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Abstract

The effect of Positive Pressure Ventilation (PPV) on compartment fires in a 1:4 scale four-storey building was investigated experimentally. The main goal in the experiments was to find out the optimum ventilation path and ventilation rate as a function of the elevation of the fire room. Also, the smoke movement in the staircase was studied to evaluate issues related to evacuation of the building. The main quantities measured were the total rate of heat release (RHR) and the vertical temperature distributions in the fire room and rooms connected to it, as well as in the staircase.

When the PPV was arranged in accordance with the generally adopted practices in fire-fighting, the benefits of PPV could be well reproduced: the visibility along the path of the fire-fighter attack was improved, and the gas temperatures were lowered. However, the RHR of the compartment fire was increased by the application of PPV. An implication of this is that there exists an optimum PPV rate which sufficiently improves the operating conditions of the fire-fighters while keeping the thermal load on the structures in the fire room to a tolerable level.

Preface

This investigation is Part 2 of the project ‘Smoke ventilation in operational fire fighting’, funded by the Fire Protection Fund of Finland. It expands the scope of Part 1, which delt with single-storey compartments, to multi-storey compartments with a staircase. Part 2 specifically evaluates the effect of the elevation of the fire in the ventilation scenario, and also examines the various ways in which PPV can be applied when a staircase is present. The effect of PPV on the heat release rate of the fire is determined quantitatively.

The main goal of the two-part project was to produce guidelines, to be adopted by fire brigades on how to implement PPV in operational work. Such guidelines, are by necessity quite general and qualitative, and cannot take into account the multitude of scenarios that can be encountered in the field. Therefore, one of the main conclusions of this report is that an essential feature of the PPV technique remains the proper training of the personnel applying the PPV. The authors hope that this report will be a useful tool in such training by introducing and examining the variables affecting the effectiveness of PPV.

The experimental set-up was constructed by Mr. Risto Latva and Mr. Seppo Ruokonen.

Jukka Vaari

Contents

1. Introduction

The principles of Positive Pressure Ventilation (PPV) in fire fighting have been known and applied in practical fire-fighting for over 50 years (Pesonen 1946). Experience has demonstrated the benefits of the technique in terms of the operating conditions of the fire-fighters, yet concerns prevail regarding the safety of the technique with respect to feeding fresh air into the fire in general, and creating potential backdraft situations in particular (Kriska 1999).

The existing concerns have been the motivation of some scientific studies into the technique (Ziesler et al. 1994a, Ziesler et al. 1994b), although the interest has been generally (and perhaps surprisingly) weak. The VTT series of experiments is an attempt to evaluate the benefits and drawbacks of the PPV technique in a quantitative way. The first part of the VTT experiments focussed on the effects of PPV in a single-storey, 3-room compartment (Tuomisaari 1997). The results of these studies generally agreed with the practical experience; the overall visibility was improved, the temperatures were lowered and the flame direction was reversed to facilitate fire-fighters to better approach the seat of the fire. However, the studies also revealed that a prerequisite for obtaining such positive results was the proper application of the technique, both in terms of the positioning and operating condition of the fan, and the ventilation path for the smoke and heat.

This report presents the main results of the second part of the VTT series of PPV experiments. The primary objective in this part was to expand the study to multi-storey buildings in order to evaluate the influence of the elevation of the fire into the PPV performance, and to obtain information about the smoke filling of the staircase. The level of quantification was maintained in this second part, with a strong emphasis on the measurement of the rate of heat release (RHR) in the various fire scenarios. It is demonstrated that applying PPV invariably increases the RHR of the compartment fire. The implication of this is that there exists an optimum PPV rate that affects proper smoke and heat removal while keeping the fire as small as possible.

2. Experimental

2.1 General

The principal approach in the experimental set-up was to carry over as much design from Part 1 of the study as possible. This was done primarily to ensure that the results of Part 1 can be utilized in the planning of the test series of Part 2. When the compatibility of the results can be reasonably established, it will not be neccessary to repeat all experimental efforts of Part 1, and some new measurements can be included for additional information.

For these reasons, the design of the single 3-room compartment was held same as in Part 1, and four similar floors were constructed on top of each other. The new element in the construction was the staircase. The comparison between the experimental results of Parts 1 and 2 was primarily done by re-characterizing the fire load in terms of RHR, and by the similar temperature measurement set-up in the compartment. Gas sampling was not performed in any single point inside the compartment or in the staircase. Instead, gas analysis was performed to determine the RHR in all experiments by collecting all combustion gases with a large hood. This was done to obtain quantitative information on the effect of PPV on the RHR.

2.2 The model building

A photograph of the model building used for the experiments is shown in Figure 1, and detailed drawings of the building are found in Appendix A. Neither the dimensions of the rooms, doors and windows, nor the properties and dimensions of the construction material (lightweight concrete) have been altered from Part 1. One exception to this was the ceiling of the top floor which was built of gypsum board and insulated with ceramic wool simply for practical purposes. This construction has a somewhat smaller heat absorption than a lightweight concrete ceiling, but the possible effect on the burning of the fire load cannot be resolved from other possible sources of variation. The other exception was the outer walls of the entrance and target rooms which were also of gypsum board.

Since there were no fires in these rooms, the choice of the material for these walls was not crucial. The third floor was a dummy floor; no fires were burned there. The elevation from one floor to another was simply the room height plus the thickness of one lightweight concrete slab. Compared to a full scale building, the elevation in the model is slightly too small, and leads to a too small height for the staircase. However, since the model has only 4 floors, the effect remains moderate.

Figure 1. Photograph of the model building used in the experiments.

The walls, the ceiling and the landings of the staircase were all of gypsum board. In the largest wall, a perspex was installed to enable visual observations on the smoke movement in the staircase and in the entrance and target rooms. The stairs were mimicked by two parallel wood sticks to which pieces of hardboard were stapled. The staircase was equipped with a ground-level door and a smoke vent at the center of the ceiling. The dimensions and construction of the staircase were chosen simply to produce some essential features of a staircase. From the physical point of view, all constructions inside the starcase act to add hydraulic resistance for the flow of gas, and to cause extra turbulence.

2.3 The fire load

2.3.1 The standard fire load

The fire load used in the experiments was the same as used in Part 1 and documented there in detail. In this text, this fire load will be referred to as "standard fire load". In brief, standard the fire load consisted of a propane burner (10 kW), a wood crib (24 sticks of 175 x 17 x 17 mm in 6 layers) and two plywood panels (600 x 250 mm, 4 mm thick). The fire load was chosen such that it produced all the phases of a fire development curve in roughly 10 minutes, was large enough to be ventilation controlled, but was small enough not to cause backdraft. The fuel package was placed in a corner of the fire room so that the panels were fixed to the corner walls and the crib was placed above the burner, both of which were in contact with the panels.

2.3.2 Other fire loads

The need for using other than the standard fire load arose in the course of the test series and was primarily connected with the observation that the standard fire load was self-extinguished when the air to the fire was supplied only from the ground level door of the staircase. To study whether a different fire load would sustain the fire, three different fire loads were used: a modified standard fire load with 48 wood sticks (a 12-layer grid), a standard fire load together with polyether foam, and a 0.1 m^2 heptane pool. All of these have a higher RHR compared to the standard fire load when burning in a fuel-controlled mode. Furthermore, polyether foam and heptane produce thicker smoke, which was desired for a better visual observation of the smoke movements during the self-extinguishment experiments. The heptane pool was also used to demonstrate the significant effects PPV may have on the RHR of a fire.

2.4 Instrumentation

2.4.1 The fan

The fan used in the experiments was a pressure blower of type ABBA HA 219, (the same that was used in Part 1), capable of producing a primary flow rate of 8.3 m^3/min. The flow rate could be adjusted continuously from zero to the full capacity. The primary flow rate could be found out using a pressure differential measurement across a circular plate inside the blower and using the calibration sheets supplied by the manufacturer.

2.4.2 Pressure and gas flow

The measurements of the pressure differentials associated with gas flow velocities were measured with Setra bi-directional pressure transducers of the 264 series. Four transducers with a range of ± 25 Pa were used in connection with gas flow measurements in the doors to the compartment and to the fire room. Five others with a range of ± 250 Pa were used in the window of the fire room (2), in the ground level door (2) and in the smoke vent of the staircase (1).

The pressure differential between the outside and inside of the staircase was measured with Huba unidirectional pressure transducers of type CH-8116 (1 mbar) and CH-5436 (10 mbar).

The characterization of the blower induced flow pattern in the ground level door was performed with a hot-wire anemometer of type Airflow TA2. Results from these measurements are presented in Appendix B.

2.4.3 Temperature

Gas temperatures were measured with bare Ø0.5 mm K-type thermocouples. As in Part 1 of the study, thermocouple trees were positioned centrally in each three rooms of the compartment; a fifth thermocouple was added to these trees 15 cm above the floor. Thermocouple trees were also installed to the doors 1 and 2 (see the layout in Appendix A) and to the large window of the fire room of each compartment to provide the temperature data for the measurement of the gas flow velocities. Similarly, a thermocouple tree was installed in the ground level door of the staircase. A tree of 16 thermocouples was used in the middle of the staircase to measure the vertical distribution of temperature. The top element of the tree was used as the temperature in association with the bidirectional probe of the smoke vent. A detailed account on the thermocouple positions is found in Appendix A.

2.4.4 Gas analysis and heat release rate

The measurement of the RHR was performed using the gas collection and analysis system of the ISO 9705 (ISO 1992) room test facility. The model building was constructed under the hood of the test facility, and fire gases were directed to the hood using large portable aluminium screens. The heat release rate was calculated from the known flow velocity in the exhaust duct, the measured O_2 and CO_2 concentrations and the gas temperature. The gas sample was analyzed for O_2, CO_2 and CO. The oxygen analysis was performed with a Hartmann&Braun Magnos 4G paramagnetic analyzer, and the CO_2 and CO were analyzed by a Siemens Ultramat 22 infrared transmission analyzer.

2.4.5 Video & photo

The smoke movement in the staircase was recorded on video through the large perspex wall. Photographs of the experimental set-up and representative fire tests were taken.

2.4.6 Data acquisition

Data acquisition was performed using InstruNet data acquisition hardware in connection with DasyLab 4.0 software running in a Windows NT workstation. A total of about 60 channels were recorded in each experiment with a time resolution of 1 s. The measurement of the RHR was performed with a HP 75000 Series B data acquisition hardware and a Labtech Control software running in a 486 PC.

3. Results

The test programme divided into two parts. The first part consisted of preliminary measurements. These concentrated on characterizing the fan and optimizing the positioning and flow rate with respect to the door geometry and the ventilation conditions in the fire tests. Also included was the re-characterization of the standard fire load.

In the second part were the 28 fire tests, which further subdivided into the main series with the standard fire load in the first, second and fourth floors, and additional experiments to elaborate on special issues that arose in the course of the main series.

The objective of the main series was to obtain systematic and quantitative information on the effect of PPV on the heat and mass balance in the fire compartment and the RHR of the fire, and also to study different methods of ventilation. The additional experiments were performed to study the effect of varying fire load on the smoke movement and to demonstrate how the use of PPV may result in the transformation of a ventilation controlled fire into a fuel controlled fire. Some experiments on mild negative pressure ventilation in the staircase were also conducted.

3.1 Characterization and positioning of the fan

In Part 1, the fan was only characterized in terms of the primary flow and a qualitative statement on the air cone. For the quantitative purposes of this study, more precise data was needed, i.e. the flow pattern of the air cone and the secondary flow at various distances from the cone. Furthermore, the flow pattern in the doorway of a ventilated enclosure was studied to estimate the actual amount of air entering a compartment in the fire test.

A schematic presentation of the fan is shown in Figure 2. The length of the tube is 900 mm and the inner diameter is 173 mm. The dotted line represents the removable head piece that was used in Part 1. This had the effect of reducing the width of the air cone and increasing the velocity gradients in the cone. With the head piece installed, it was not possible to properly cover the staircase door with the air cone and thus in Part 2 the head piece was removed.

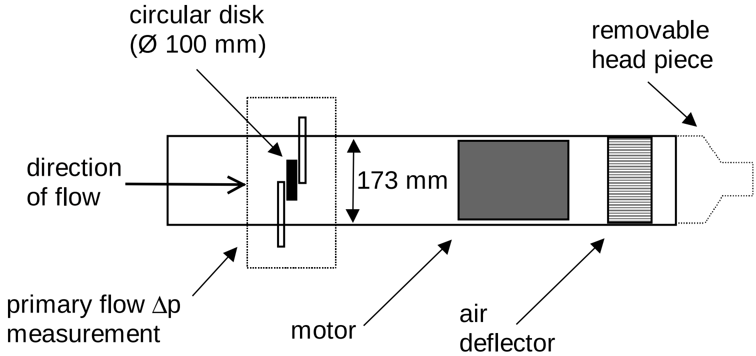

Figure 2. A schematic presentation of the fan.

The primary flow was determined by a pressure difference measurement over a Ø100 mm circular plate for 20%, 50% and 90% of the full capacity of the blower. Using the calibration charts, primary flow rates of 2.2, 5.6 and 10.1 m^3/min, respectively, were obtained. Thus, the 8.3 m^3/min. full scale specification applies with the head piece installed.

The flow velocities in the air cone were analyzed at distances of 50 and 100 cm from the front end of the blower for 50% of the full capacity using a hot-wire anemometer. Figure 3 displays the flow velocity component parallel to the cone axis as a function of the radial distance from the cone axis. The markers denote the anemometer measurements and the solid lines are Gaussian fits to the data. From the fits, the total flow rate in the air cone may be calculated. At d=50 cm, the flow rate is 19.6 m^3/min, and at d=100 cm the flow rate is 32.1 m^3/min. By subtracting the primary flow of 5.6 m^3/min, secondary flows of 14 and 26.5 m^3/min, respectively, are obtained.

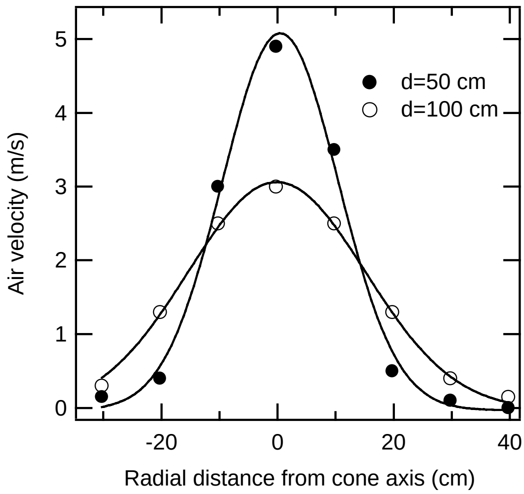

Figure 3. The air velocity component parallel to the cone axis as a function of the radial distance from the cone axis.

3.2 Characterization of the fire load

The rate of heat release of free burning standard fire load and the standard fire load augmented with two additional plywood panels are shown in Figure 4. The RHR measurement was made using the SBI apparatus. Flaming combustion of wood was observed between 400 and 900 s, and the total heat release in this time interval was 20 MJ. The mass for the fire load with two plywood panels was 1.46 kg. The RHR curve is in good agreement with the one measured for the free burning fire load in Part 1 of this study.

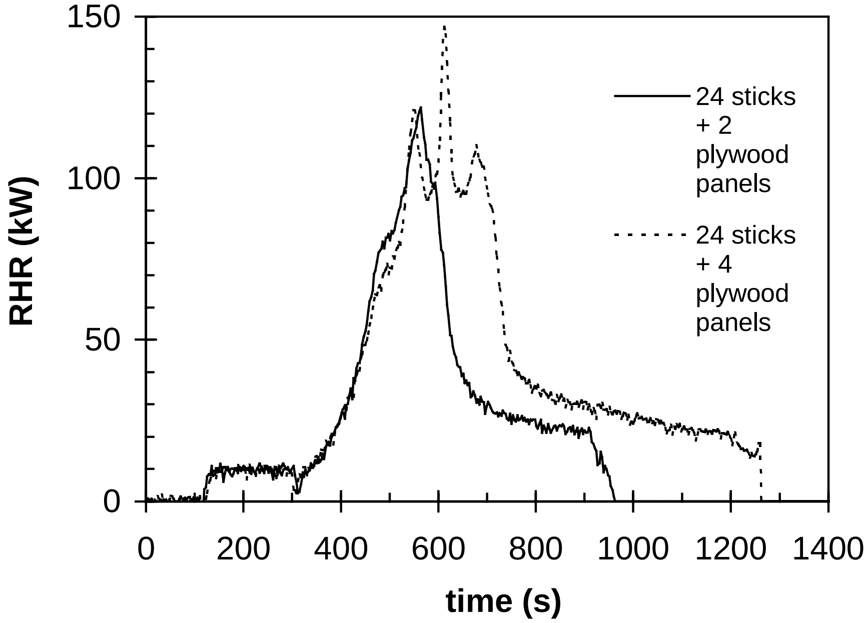

Figure 4. Rate of heat release of the free burning standard fire load (solid curve) and a fire load with double plywood panels yielding ca. *50 % increased mass as compared to the standard fire load.*

3.3 The fire test programme

The list of the 28 fire tests is presented in chronological order in Table 2. The notation used for the different ventilation configurations is given in Table 1.

Table 1. The ventilation modes.

Ventilation mode	
A	Through the large window of the fire room
B	through the smoke vent
C	A+B
D	a 7 cm opening in the small window of the fire room
E	all windows and smoke vent closed
F	D + the target room window
G	B+D
H	the small window of the fire room

Table 2. The fire test programme in chronological order.

Test ID	Floor	Fire load	Ventilation	PPV
ST2-1	1st	Standard	A	50%
ST2-2	1st	Standard	A	50%
ST2-3	1st	Standard	A	no
ST2-4	1st	Standard	A	90%
ST2-5	1st	Standard	E	no
ST2-6	1st	Standard	B	no
ST2-7	1st	Standard	B	50%
ST2-8	1st	Standard	B	50%
ST2-9	1st	Standard	B	90%
ST2-10	1st	Standard	A	50%(2min)
ST2-11	4th	Standard	C	no
ST2-12	4th	Standard	A	no
ST2-13	4th	Standard	A	50%
ST2-14	4th	Standard	A	90%
ST2-15	4th	Standard	E	no
ST2-16	4th	Standard	D	??
ST2-17	4th	Modified	D	??
ST2-18	4th	Modified+ polyether	F	no
ST2-19	4th	Standard	D	NPV
ST2-20	4th	Standard	D,G	NPV
ST2-21	4th	Standard	D,G	NPV, 50%
ST2-22	4th	Standard	B	no
ST2-23	4th	Pool	E,H	50%, 90%
ST2-24	2nd	Standard	A	no
ST2-25	2nd	Standard	A	50%
ST2-26	2nd	Standard	E,H	??
ST2-27	2nd	Pool	E	no
ST2-28	2nd	Pool	E	90%,50%

The tests performed to obtain systematic and quantitative information of the effects of PPV on the RHR of the fire are summarized in Table 3. The different modes of ventilation were compared as summarized in Table 4.

Table 3. The tests focusing on the effect of PPV flow rate.

The effect of PPV flow rate			
Floor	PPV	Test ID	Ventilation
1st	No	ST2-3	A
1st	50%	ST2-2	A
1st	90%	ST2-4	A
1st	No	ST2-6	B
1st	50%	ST2-7	B
1st	90%	ST2-9	B
2nd	No	ST2-24	A
2nd	50%	ST2-25	A
4th	No	ST2-12	A
4th	50%	ST2-13	A
4th	90%	ST2-14	A

Table 4. Tests comparing different modes of ventilation.

Natural ventilation		PPV	
1st floor	4th floor	1st floor	4th floor
ST2-3,5,6	ST2-11,12,15,22	ST2-2,7	ST2-13,21

By default, the PPV was applied 1 min after the ignition, as done in Part 1. The effect of delaying the PPV was studied in tests ST2-10,16,17,21,26 and 28. The smoke filling of the staircase was studied in tests ST2-15, 16, 17, 18 and 19 (4th floor) and ST2-26, 27 and 28 (2nd floor).

3.4 Fire in the 1st floor

The basic fire scenario used in these experiments was the same as in Part 1. The fire took place in the large room of the 3-room compartment, and the large window of the fire room was open. The positive pressure ventilation was applied in most cases 1 min after ignition. However, the large window was kept open from the ignition, since the burning of the standard fire load in the fire room was fuel controlled during the first minute and because the probes and thermocouples in the window could be utilized from the start. The main difference to Part 1 was the method of applying the positive pressure. In the present study, the pressurization of the compartment was done by locating the fan outside the ground level door of the staircase (which was open in all tests) and keeping the door to the fire compartment open. By this method, a uniform overpressure could be applied to the compartment door, eliminating the need for studying the effect of fan direction at the door.

3.4.1 Natural ventilation

We begin the presentation of the results by looking at the various ways of applying natural ventilation to the fire at the ground floor compartment. The lowest degree of ventilation was applied in test ST2-5, in which all windows of the fire compartment were closed, the door to the staircase was open, and the smoke vent of the staircase was closed. The air supply to the fire was provided by the open ground level door of the staircase. The other applied natural ventilation modes were through the fire room (ST2-3) and through the smoke vent of the staircase (ST2-6).

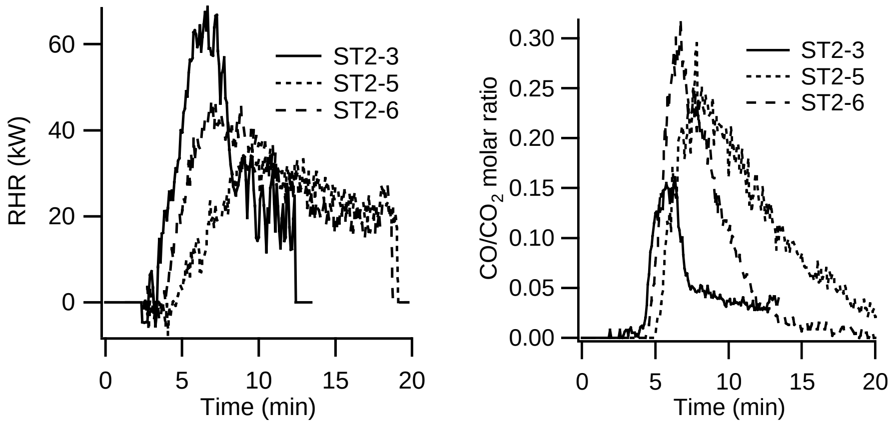

Figure 5. Left: The RHR of the tests ST2-3,5 and 6. Right: the CO/CO_2 ratio for the same tests.

Figure 5 displays the measured RHR of the different ventilation scenarios. It is observed that the degree of ventilation increases together with the rate of heat release, indicating that the fire scenario is ventilation controlled. In the case of ST2-5, there is approximately a 1 minute delay between the ignition and the onset of a RHR signal, due to the smoke filling of the compartment and the staircase.

Also shown in Figure 5 is the ratio of CO and CO_2 measured from the gas sample of the exhaust duct. In experiment ST2-3 the conditions are typical for a low ventilation, fully developed fire. The principal risk to humans in this case would presumably be incapacitation (ISO 1989). However, in the other two experiments with a lower degree of ventilation, the concentration of narcotic gases has increased to lethal level.

The effect of the ventilation mode on the temperature distribution in the staircase is displayed in Figure 6. It is observed that the temperatures do not rise in general to dangerous levels. When the ventilation is through the fire room or only via the staircase door, the hottest spot in the staircase is just above the door to the fire compartment. However, if the smoke vent is kept open, the hottest part of the staircase is close to the smoke vent opening. The data also suggests that there is some buildup of heat below each staircase landing.

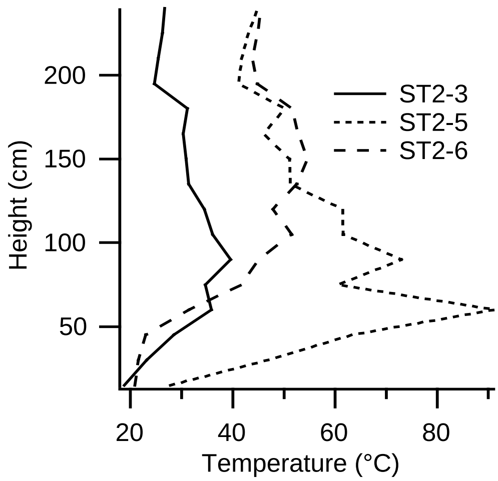

Figure 6. The vertical temperature distribution in the staircase for different ventilation modes.

3.4.2 Positive Pressure Ventilation

The effect of the PPV volumetric flow rate on the RHR of the fire was studied with the ventilation through the large window of the fire room. The result is shown in Figure 7.

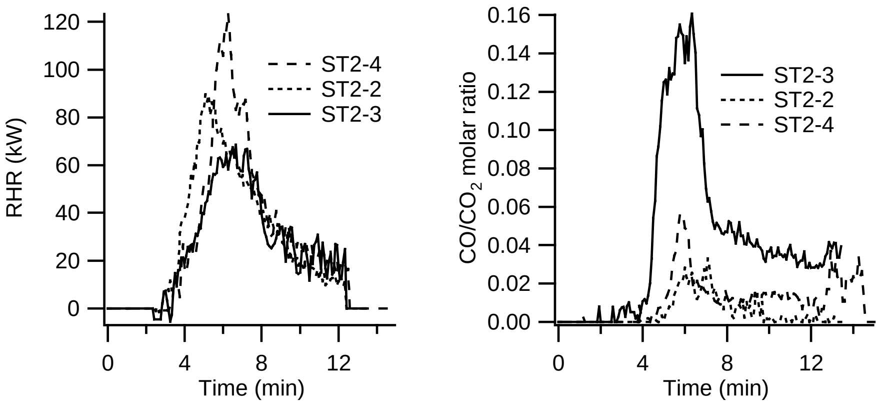

Figure 7. Left: The RHR in the tests ST2-3, 2 and 4, corresponding to the operation of the blower at 0%, 50% and 90%, respectively. Right: the CO/CO_2 ratio for the same tests.

Figure 7a, which displays the measured RHR for the tests ST2-3, 2 and 4, with ST2-3 being the reference case with no PPV. It is clearly observed that the peak RHR increases as the volume flow increases. From Figure 7b it is seen that as PPV is applied, the burning efficiency increases. As a result, the total amount of heat released during the fire is also slightly increased (20.4 MJ with no PPV, 24.5 MJ with 90% PPV). From the CO/CO_2 curves it may be seen that the application of PPV has a strong positive effect on the tenability conditions.

The effect of PPV on the distribution of gas temperature in the fire room is illustrated in Figure 8. Figure 8a shows the gas temperature in the top element of the TC chain in the fire room (5 cm below the ceiling) as a function of PPV, and Figure 8b shows the same information for the bottom element (15 cm above floor). It is seen that PPV does not increase the heat exposure to the ceiling, but it significantly increases the heat exposure in the lower part of the room, making it dangerous for humans to enter the room. The increased gas temperature in the lower part of the room reflects the PPV induced increase in the RHR of the fire.

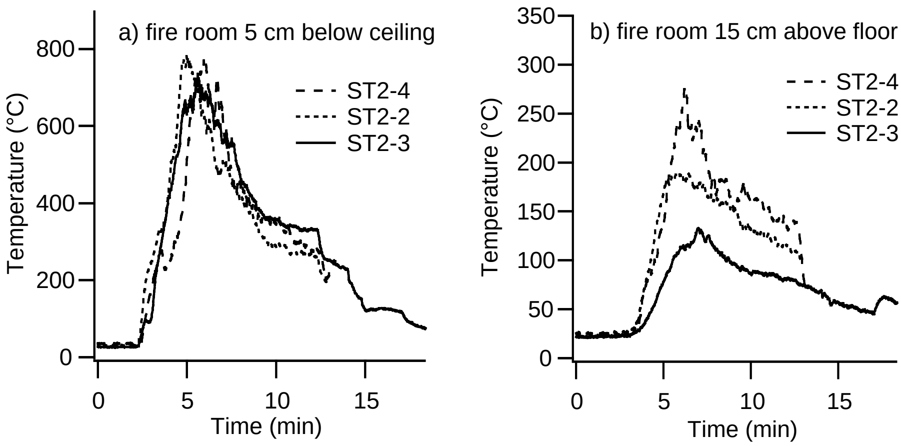

Figure 8. The gas temperature in the fire room in the tests ST2-3, 2 and 4 a) 5 cm below the ceiling, b) 15 cm above floor.

Assuming that the gas temperatures in the doorways approximately correlate to the smoke density, the effect of PPV on smoke movement can be estimated by comparing representative gas temperatures in the various experiments, as displayed in Figure 9. The temperature data clearly illustrates the beneficial effect of PPV both in terms of visibility as well as heat exposure on the firefighters approaching the fire room.

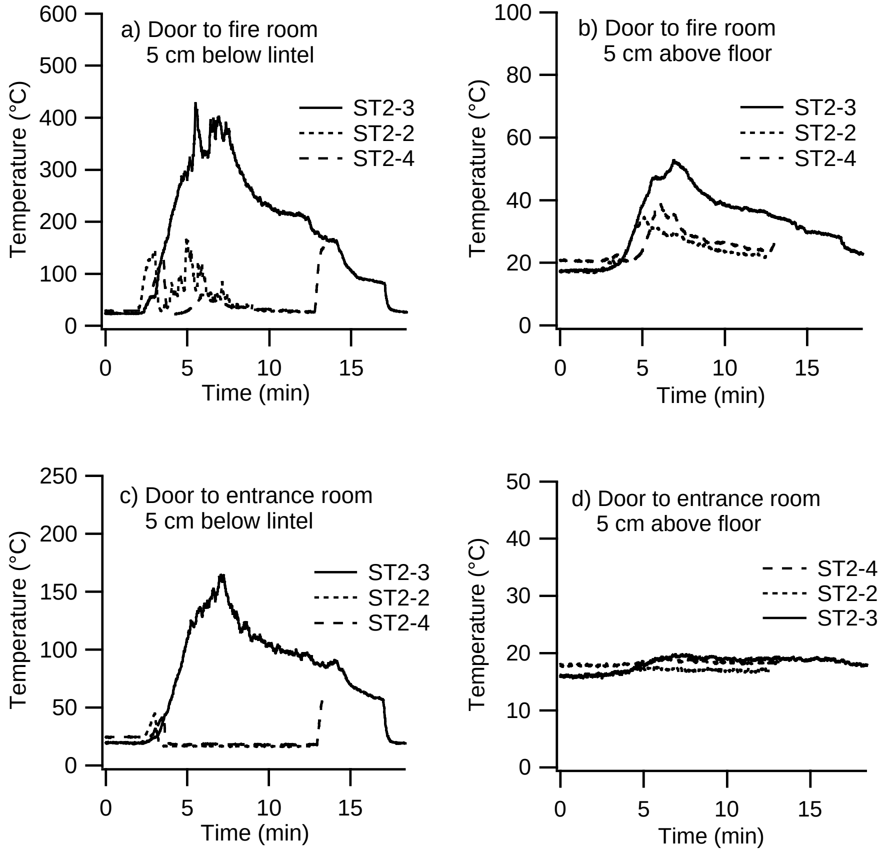

Figure 9. The temperatures measured at the top and bottom of the doorways: a) door to fire room 5 cm below lintel, b) door to fire room 5 cm above floor, c) door to entrance room 5 cm below lintel, d) door to entrance room 5 cm above floor.

The net mass flow rate through the door and the large window of the fire room is displayed in Figure 10. A positive sign corresponds to mass flow towards the fire, and a negative sign to mass flow away from the fire. Looking at Figure 10a it is seen that in all cases, including the fire with natural ventilation (ST2-3), the net mass flow at the door to fire room is into the room. Comparing the magnitudes of the mass flow, it is observed that already at 50% of the full PPV capacity, the forced flow clearly exceeds the fire induced flow.

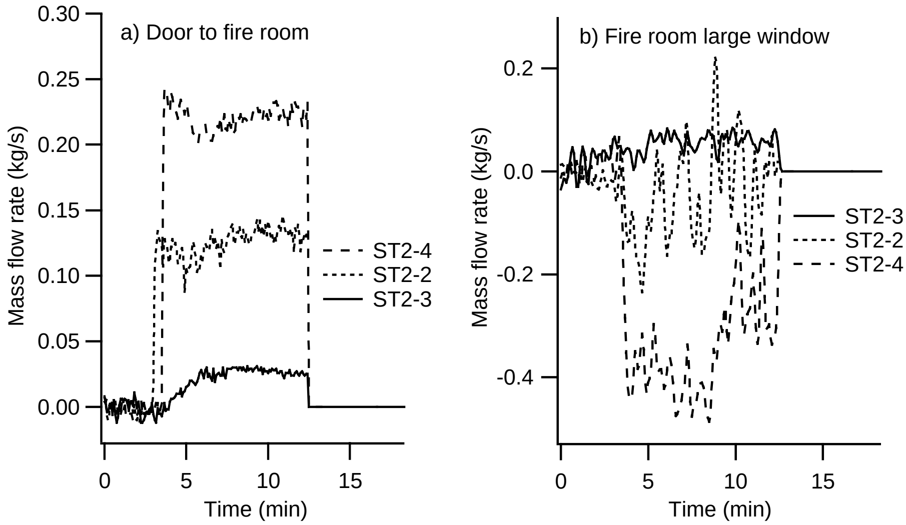

Figure 10. Representative mass flow rates through openings in tests ST2-2, 3 and 4. A) door to the fire room, b) fire room large window.

The mass flow data for the window (Figure 10b) has much more noise, which is due to the larger width of the window compared to the door, and the pressure transducers which were less sensitive than those at the doors. Basically, by subtracting the mass flow rates at the window and at the door, the contribution of the fire to the mass flow could be resolved. In practice, the noise level makes the subtraction difficult, if not impossible. For example, assuming an effective heat of combustion of 15 kJ/g for wood, a RHR of 60 kW would correspond to a mass flow of 0.004 kg/s, which cannot be resolved with the present accuracy. Despite the noise, the data clearly shows how the flow rate caused by the PPV fan greatly exceeds the flows induced by naturally ventilated fire.

The same information is illustrated in more detail in Figure 11, which shows the static overpressure measured at the staircase (the difference of the static pressures in the staircase and in the ambient), and the pressure difference over the upper bidirectional probe in the door to the fire room. The latter gives the best measure for the ability of the overpressure to prevent the smoke from entering the entrance room and the staircase. Looking at the curve corresponding to natural ventilation, it is seen that the probe indicates a -0.1 Pa pressure difference at maximum, corresponding to net mass flow from the fire room to the entrance room through the top part of the door.

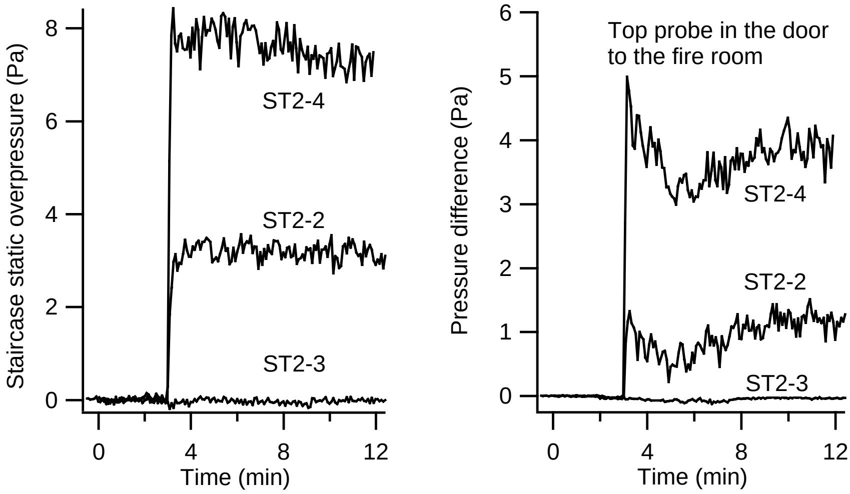

Figure 11. Left: the static overpressure in the staircase. Right: the pressure difference over the top probe in the door to the fire room.

With PPV applied, it would thus seem reasonable that a 0.1 Pa overpressure in the entrance room would suffice to prevent smoke from spreading to the entrance room. This is, however, not the case. From the curves corresponding to 50% and 90% PPV, it is seen that the required overpressure increases as the PPV flow is increased. At 50%, the data indicates a 0.5 Pa drop in the pressure difference due to the fire, and at 90% the corresponding drop is close to 2 Pa. The origin of this effect lies in the increased RHR of the fire due to PPV.

The data of Figure 11 suggests that there exists an optimal overpressure, which, when applied, prevents smoke and heat from spreading into the apartment, but simultaneously keeps the RHR of the fire as low as possible. If the heat release grows too much, unneccessary structural damages may occur in the fire room. Also, an excessive overpressure increases the rate of smoke and heat transport into openings such as ventilation shafts.

The delaying of the PPV from 1 to 2 min was studied in ST2-10. However, there was no proper smoke filling of the staircase at that point, and more informative tests studying delayed PPV are presented together with 2nd floor results.

The effect of PPV was also studied with the windows of the fire room closed and the smoke vent of the staircase open (tests ST2–6, 7 and 9). In this ventilation scenario, the gas flow patterns in the fire room and entrance room are only slightly altered, due to increased turbulence. This has the effect of slightly improving the efficiency of combustion. However, the measured RHR of the fires with PPV is about 10–20 % lower than without PPV. One reason for this may be the presence of small leaks in the overpressurised compartment, which may have caused part of the fire gases to miss the hood.

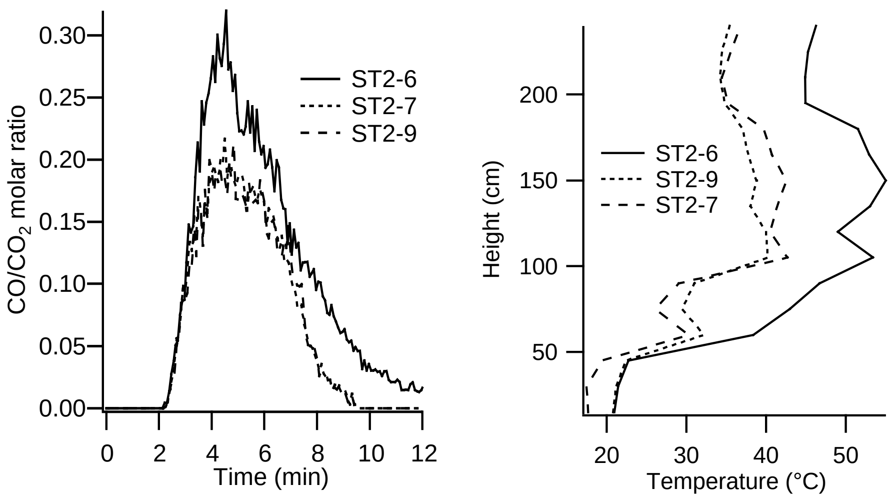

Figure 12. Left: the ratio of CO and CO2 in the tests ST2-6, 7 and 9. Right: the gas temperature profile in the staircase for the same tests, corresponding to the time of peak RHR of the fire.

The most notable effects are observed in the staircase. Figure 12 displays the gas temperature profile in the staircase for the tests ST2-6, 7 and 9 corresponding to the time of peak RHR. The application of the PPV brings down the gas temperature everywhere in the staircase. The videos taken from these tests indicate that the drop in the gas temperatures is associated with a lower smoke density. Thus, from the viewpoint of visibility and heat, PPV appears to be beneficial. It also improves the air quality somewhat, due to smaller CO production of the fire. It does not, howeved, prevent smoke spreading from the fire room to other rooms and the staircase. Also, it can be seen that increasing the PPV flow rate above 50% does not improve the situation in the staircase any more.

3.5 Fire in the 4th floor

3.5.1 Natural ventilation

The main feature in the ventilation scenario of a fire in the top floor is that the smoke spreading along the staircase to upper floors is not a problem. Therefore, the use of the staircase smoke vent is a possible option, should the door to the fire compartment be open. Three different natural ventilation scenarios were studied: through the large window of the fire room (ST2-12), through the large window and through the smoke vent (ST2-11) and only through the smoke vent (ST2-22). In all cases, the staircase ground floor door as well as the door to the fire compartment were open.

Generally, if the large window of the fire room is open, the opening of the smoke vent makes very little difference. The RHR, combustion efficiency, tenability conditions as well as the temperatures in the fire and entrance rooms remain practically unaltered. The main difference is illusterated in Figure 13 displaying the gas temperatures in the top elements of the staircase TC chain. It is observed from the figure and also from the video tape that opening the smoke vent almost completely eliminates smoke from the whole staircase. If the smoke vent is closed, there is buildup of smoke and heat to the top part of the staircase. In particular, since the element S15 is located below the lintel of the compartment door, there will be smoke damages in other compartments in the top floor, if doors to these are opened while the smoke vent is closed.

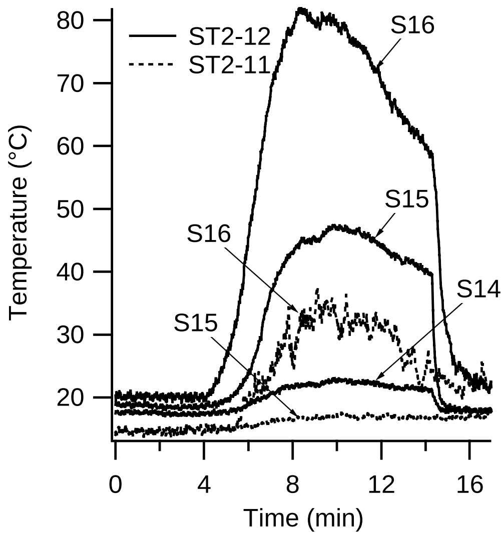

Figure 13. The gas temperatures in the top elements of the staircase TC chain in the tests ST2-11 and 12.

If the fire compartment is ventilated only through the staircase, (smoke vent open, fire room window closed, test ST2-22), there is a clear difference to natural ventilation through the fire room (ST2-12). Following the general trend of RHR vs the degree of ventilation, the RHR and combustion efficiency in ST2-22 are lower than in ST2-13. The difference in the conditions inside the fire compartment is illustrated in Figure 14 comparing the gas temperatures measured by the entrance room TC chain in the two tests. In the case of ST2-22, the gas temperatures are higher in general. This is despite the lower RHR of the fire, since the gas flow entraining the fire returns by the same path. In particular, the gas temperatures are higher close to the floor, indicating a thicker smoke layer and thus poorer conditions in terms of egress of people and smoke damages.

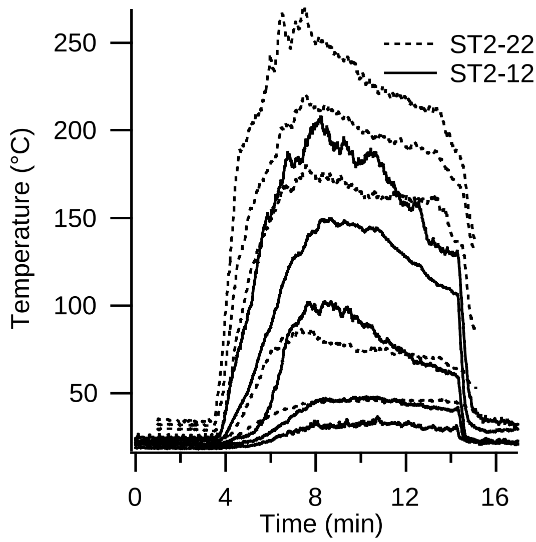

Figure 14. The gas temperatures in the TC chain of the entrance room (R1) in the tests ST2-22 (ventilation through the staircase smoke vent) and ST2-12 (ventilation through the fire room).

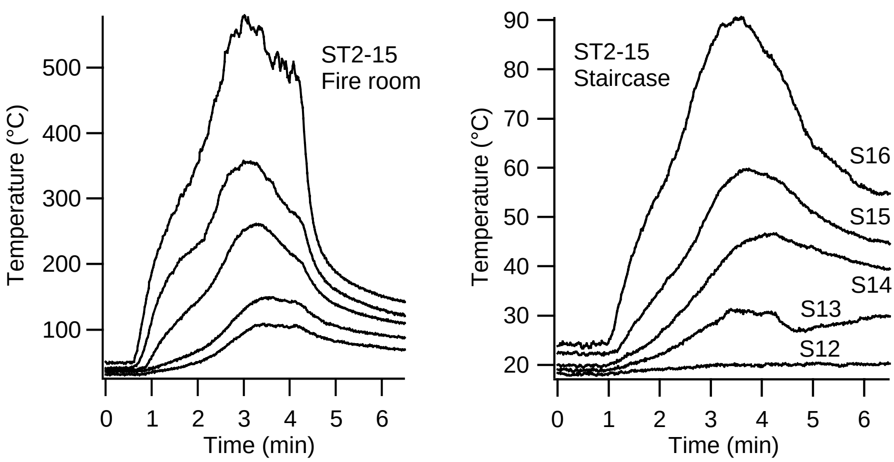

Figure 15. Representative temperatures from test ST2-15. Left: the gas temperatures in the fire room TC chain. Right: the gas temperatures in the top elemets of the staircase TC chain.

There is a dramatic difference to the results if both the smoke vent and the window of the fire room are closed (ST2-15). The experiment is illustrated in Figure 15, which shows the temperatures in the fire room and in the top elements of the staircase. The sudden drop in the fire room temperatures after 4 min is an indication of the self-extinguishment of the fire. Looking at the staircase temperatures, it is seen that the temperatures (and the smoke concentrations) increase due to the fire only above the floor level of the 4th floor. There is no mixing of fresh air into the gas stream going into the fire, and therefore the oxygen concentration drops so low that combustion cannot be sustained. After extinguishment, the temperature distribution in the top part of the staircase starts to even out, but even at that stage, the smoke layer is confined to the top floor portion of the starcase.

At about 7 min, the propane flow was turned off and the window to the fire room was opened. As expected based on the results of Part 1, there was no backdraft. Visual inspection of the fire source indicated that the extinguishment occurred already before all surfaces of the wood crib had properly caught fire. In fact, the same wood crib was used as the fire load of test ST2-16.

3.5.2 Positive Pressure Ventilation

The effect of PPV on a fire in the 4th floor was studied in tests ST2-12, 13 and 14. These three tests were identical to ST2-3, 2 and 4 conducted in the 1st floor, and the purpose was to verify that the principal effects of PPV do not depend on the elevation of the fire, as long as ventilation through the fire room is applied.

As expected, this was the general conclusion on these tests, although the RHR measurement was somewhat affected by the gypsum board ceiling which was covered with combustible carton. Whenever a fresh ceiling element was installed, the first RHR measurement included a component from the gypsum board. Despite this, the qualitative behaviour of the RHR, the efficiency of combustion, the temperatures in the fire room and the smoke spreading was identical to the 1st floor case. The location of the PPV fan at the bottom of the staircase does not affect the results, since the key parameter, the static pressure in the staircase, is the same everywhere, due to the identical geometry of the inlet and outlet openings. There is a small change in the hydraulic resistance of the ventilation path due to three additional floors, but it is expected that such an effect only plays a role in taller buildings or with a substantially more complex path for the air flow.

An additional experiment, ST2-23 was conducted using a 0.1 m^2 square-shaped heptane pool (2.5 l heptane) in the corner of the fire room. This test had two separate purposes. In the first part of the test, the smoke vent and the fire room window were closed, and the goal was to see if a different (higher) fire load could result in sustained combustion instead of self-extinguishment. However, also this fire was self-extinguished, and the experiment was continued by opening the small window of the fire room. No backdraft occurred, and the fire was re-ignited, this time to observe the effects of PPV.

Representative data from the experiment is displayed in Figure 16. From the fire room temperatures it is observed that te extinguishment occurs in two minutes from ignition. Comparing to the standard fire load used in ST2-15 this is about two minutes faster. This is understood in terms of the very rapid development of the heptane pool fire to full RHR. A difference between the fire loads can be observed just before extinguishment: the heptane fire goes to flashover, as indicated by the upward jump of the lowest TC readings in the fire room.

The small window of the fire room was opened about 1 min 30 s after the extinguishment. The fire room data at that point indicates that the gas temperatures remain above the boiling point of heptane, which means a potential backdraft situation. To prevent the possible backdraft, the staircase and the fire compartment were overpressurized (PPV 50%) some 10 seconds before opening the window. The opening is observed as a sudden decrease of all gas temperatures. About 8 minutes after ignition the PPV was turned off.

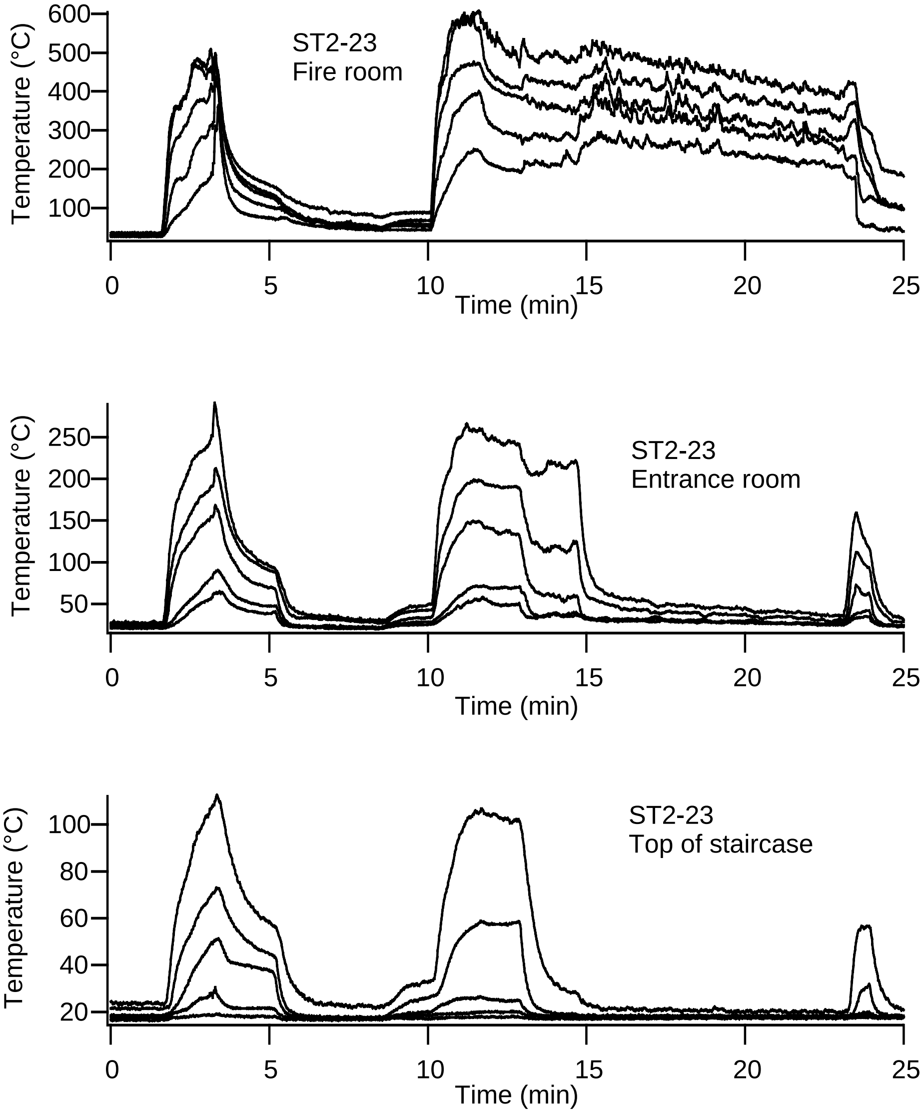

Figure 16. Representative temperatures from test ST2-23. Top: the fire room TC chain. Middle: The entrance room TC chain. Bottom: Top five elements of the staircase TC chain.

The fire was re-ignited at 10 min, leaving the small window open. After an initial increase in the gas temperatures, a small drop follows at 11 min, accompanied by a decrease in the measured RHR. This is probably due to the fact that the smoke layer in the entrance room and in the staircase has reached the level of the lower lintel of the fire room window, blocking the flow of fresh air into the fire through the fire room window.

At 13 min, the PPV was again applied with a flow rate of 50%. It is observed from the temperature distribution of the entrance room that this pressurization is not sufficient to prevent smoke from spreading from the fire room to other rooms. Keeping in mind that the fire scenario is ventilation controlled, the primary reason for this is the smaller outlet opening (compared to e. g. ST2-3 in the 1st floor or ST2-12 in the 4th floor) which reduces the flow rate through the fire room. Just before 15 min, the PPV power was increased to 90%, which is immediately followed by a sharp decrease in the entrance room temperatures, indicating the reduction of smoke spread entirely to the fire room. Towards the end of the experiment, the fire room temperatures drift slightly downwards, which is explained by the cooling of the walls due to the increased air flow rate.

3.5.3 Smoke filling of the staircase: Negative Pressure Ventilation

Prompted by the results of ST2-15 and 23, in which the fires were self-extinguished, it was decided to run fire tests to obtain a qualitative explanation for why the staircase has been reported to fill with smoke in full-scale fires even below the level of the fire. These tests included changing the ventilation scenario in the 4th floor and increasing the fire load. Tests were also run with applying a slight negative pressure ventilation (NPV) into the staircase.

In ST2-16, the fire room was ventilated through a 7 cm wide opening in the small window of the fire room (the rest of the window was covered with ceramic wool). The remaining fire load from ST2-15 was used. This resulted, after the initial growth period, in a steady-state burning of the fire with a RHR of 30 kW. In ST2-17, the same ventilation scenario was employed, but the fire load was doubled by using 48 instead of 24 sticks in the wood crib. The differences due to the increased fire load remained negligible. The steady-state RHR of the fire was little less 30 kW. The temperatures in the fire and entrance rooms were also slightly lower than in ST2-16, but these differences are explained by the higher moisture content of the sticks in ST2-17 (the fire load of ST2-16 was dried during ST2-15). In both tests, the smoke layer in the staircase remained above the floor level of the 4th floor.

In ST2-18, the degree of ventilation was increased by opening the window of the target room. This immediately increased the RHR of the fire, and the RHR evolution was comparable to that of ST2-12. However, no major differences in fire or entrance room temperatures to ST2-16 were observed. The temperatures in the top part of the staircase (displayed in Figure 17) were slightly lower than in ST2-16, suggesting a smaller smoke concentration in the staircase due to the better ventilation of the fire compartment. At 8 min, the degree of ventilation was further increased by fully opening the small window of the fire room. This is observed in Figure 17 as a drop in the gas temperatures of the staircase. At 10 min, the ground floor door of the staircase was closed. As the air exchange now goes via the 4th floor windows, the position of the smoke layer quickly adjusts accordingly. However, no smoke transport to lower parts of the staircase happens.

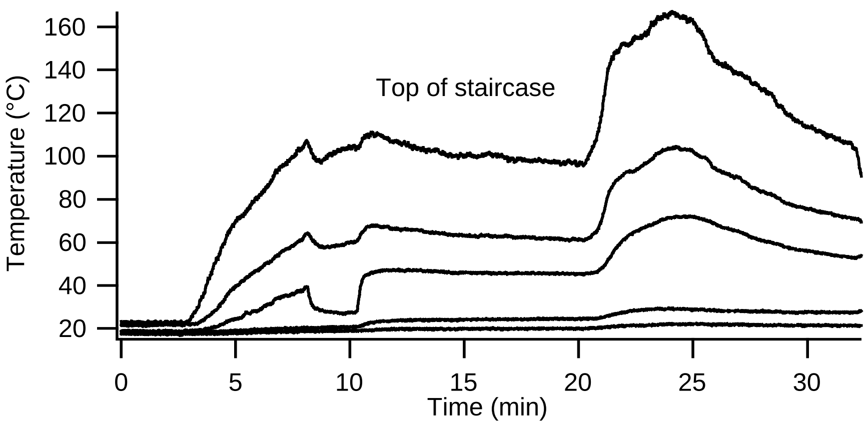

Figure 17. The gas temperatures in the top part of the staircase (elements S12-S16) in the test ST2-18.

The test ST2-18 was further continued by adding a 1200 g piece of polyether foam into the fire room at 20 min. to increase the RHR and to see whether the increased suction of air into the fire would be able to cause smoke spreading downwards in the staircase. The adding of the polyether caused an immediate flashover in the fire room and the RHR peaked at 160 kW. The temperature in the top of the staircase increased to about 160 °C. Even this did not alter the position of the smoke layer in the staircase; the small increase in the reading of the element S13 in the staircase is due to radiation from the hot gas layer and does not indicate smoke spread.

The conclusion from the tests ST2-16 to 18 is that in all naturally ventilated scenarios there is no smoke spread below the level of the fire floor. Whenever such an effect is observed, there is reason to suspect the presence of cold wall jets or forced convection. There are a number of possibilities when considering forced convection, and a separate study would be needed for the systematical charting and evaluation of these. In this study, one reasonable possibility was considered, namely a staircase underpressure with respect to the ambient. A conceivable origin of such an underpressure can be the mechanical ventilation system of the building, which is often designed to prevent various odours from spreading to the staircase. This is only possible if the pressure in the apartments is less than in the staircase. However, should there occur a fire in one of the apartments, there also develops an overpressure in that particular apartment with respect to all other apartments and the staircase.

Such a situation was simulated in ST2-19, in which the fire load as well as the ventilation openings were identical to ST2-16 (standard fire load, and a 7 cm opening in the fire room small window). However, the suction of the PPV fan was placed 15 cm in front of the staircase door, causing a 0.2 Pa underpressure in the staircase. The steady-state value of the RHR was again about 30 kW. The outputs of the bidirectional probes at door 1 were practically identical to ST2-16, and in particular, the lower bidirectional probe in door 1 indicated mass flow from the staircase into the fire apartment. No changes in the staircase gas temperatures were observed below the 4^{th} floor, and no visual observation of smoke spread could be made in the staircase. Due to the similar RHR:s of tests 16 and 19, this had to be the case, because smoke filling of the staircase would have resulted in smoke suction through the PPV fan, and this smoke would not have reached the hood to contribute to the RHR.

At 12 minutes, the experiment was continued by adding a 600 g piece of polyether foam into the fire room, causing the RHR to peak at 60 kW but returning back to a steady-state value of about 20 kW. Again (see ST2-17 above), the increase in the RHR of the fire was not sufficient to cause smoke spreading downwards in the staircase. At 14 minutes, the PPV fan was brought 5 cm in front of the door, resulting in a 0.7 Pa underpressure in the staircase.

From Figure 18 it can be seen that the flow velocity measured by the lower probe at door 1 changes sign, and there is net flow of mass from the fire apartment to the staircase. Figure 18. Left: the flow velocity measured by the bidirectional probes of door 1 in test ST2-19. Right: the gas temperature distribution in the staircase at 9 min (solid line) and at 20 min (dashed line) in the same test. also displays the temperature profile in the staircase at 9 min (solid line) and at 20 min (dashed line). The increase in the gas temperatures below the 4th floor indicates convective heat transfer, and the visual observation of the smoke situation in the staircase indicates a qualitative correlation between smoke density and temperature.

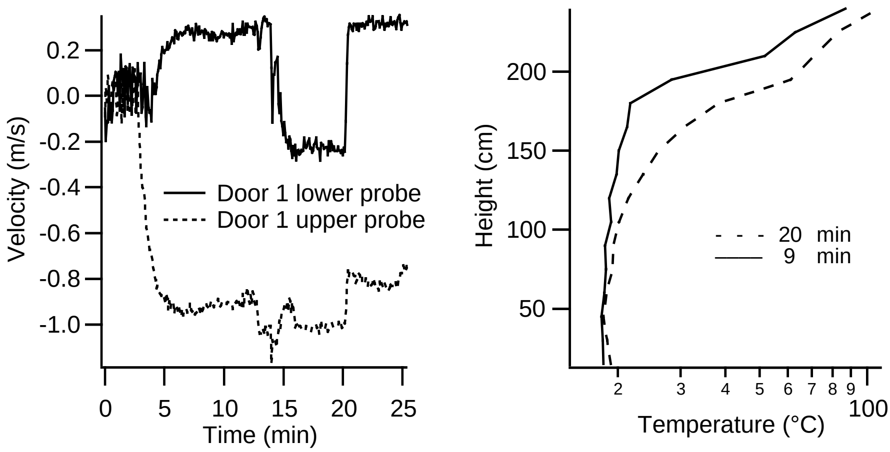

Figure 18. Left: the flow velocity measured by the bidirectional probes of door 1 in test ST2-19. Right: the gas temperature distribution in the staircase at 9 min (solid line) and at 20 min (dashed line) in the same test.

In test ST2-20 the suction of the PPV fan was immediately placed 5 cm in front of the staircase door. The standard fire load was used, and the small window of the fire room was 7 cm open. The staircase temperature data and visual observation indicates that the smoke filling of the staircase begins immediately after ignition. However, the smoke and heat production from a wood fire is less than from a polyether foam fire, and visually the smoke filling is poorly observed. (A good indication was the smell of smoke coming from the outlet of the PPV fan). The bidirectional probe at the smoke vent (and visual observation) indicated mass flow out of the staircase. Because of this, the gas temperature at the top of the staircase remained close to 100 °C throughout the test, but the hot gas layer extended only to halfway of the 4th floor door.

The test ST2-21 was identical to ST2-20, except that some 180 s after ignition, the fan was re-positioned for PPV, and a 50% PPV power was applied for the rest of the test. This was a combined PPV through the staircase smoke vent and the 7 cm opening in the fire room small window. As expected, this test presented an intermediate form of tests ST2-12 and ST2-22 in terms of smoke spread and gas temperatures. The staircase was fairly well clear of smoke. There was significant smoke spread from the fire room to the entrance room, and some of this smoke was capable of drifting to the top of the staircase through the topmost part of door 1, as the opening in the fire room window was too small to accommodate the transport of all smoke.

3.5.4 Fire in the 2nd floor

The fire tests performed in the 2nd floor were intended basically to verify the observations already made in the 1st and 4th floor tests, in terms of RHR, the efficiency of combustion, and temperature levels in the staircase. The general conclusion from the tests is that the phenomena associated with both natural (ST2-24) and positive pressure ventilation (ST2-25 to 28) are repeatable, and therefore essentially independent of the elevation of the fire, at least as long as the building is not very high.

As a new ingredient to the study, the effect of a delayed PPV on the heat and smoke levels in the staircase were investigated. This was done to allow smoke filling of the staircase, and thereby to enable the study of the ventilation of the staircase using PPV. The primary interest in this case is the time evolution of the temperatures measured by the staircase TC chain.

In test ST2-25 the standard fire load was used, and the ventilation was through the large window of the fire room. The PPV (50%) was applied about 150 s after ignition. At this point, the RHR of the fire is approaching the peak value, and the smoke filling of the staircase is clearly visible. Representative temperatures in the staircase are displayed in Figure 19. The effect of PPV is seen as a sharp drop in the gas temperatures everywhere in the staircase.

However, it is apparent that the rate with which the temperature is falling depends on the elevation.

To further analyse this, the temperature evolutions were fitted with exponential functions to obtain a characteristic time τ_{PPV} as a function of elevation, describing the rate of air exchange due to PPV. This is displayed on the right of Figure 19. The general trend of the time constant is that it increases linearly as a function of elevation. Interestingly, the plot also reveals the effect of the staircase landings, observed as an oscillation superposed on the linear increase. It may be noted that the heat exposure to the staircase walls during the smoke filling was very small, and therefore the time constants should not contain a contribution from the thermal inertia of the walls.

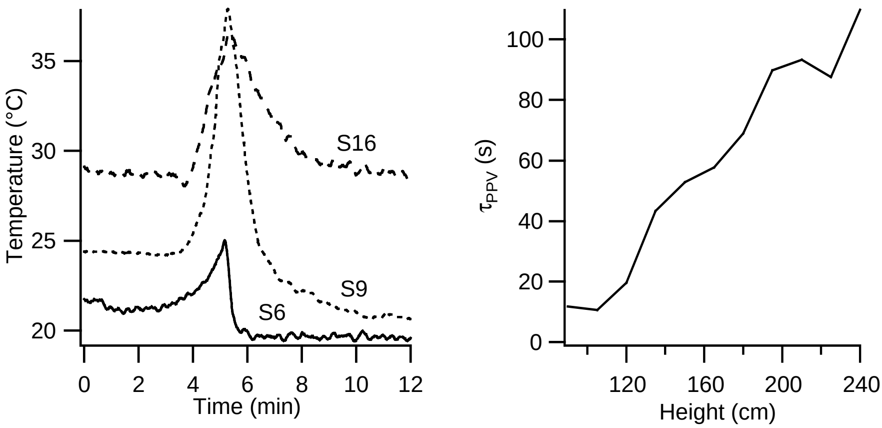

Figure 19. Left: gas temperatures measured by the elements S16, S9 and S6 in test ST2-25. Right: the time constant for air exchange in the staircase during the PPV stage of test ST2-25.

The mass flow rates discussed in the case of the 1st floor fires indicated that the flow rates caused by the PPV fan are significantly higher than those caused by the fire itself. This should also be reflected in the time constant of the staircase smoke filling, time τ_{fill}, when compared to τ_{PPV}, the time constant associated with PPV. To this end, the tests ST2-26 and ST2-27 were conducted by keeping the fire compartment windows closed, and following the temperatures in the staircase. The test ST2-26 utilized the standard fire load, whereas ST2-27 was run using the 0.1 m^2 heptane pool. In both tests, the fire was self-extinguished after the smoke layer had descended to the floor level of the 2^{nd} floor.

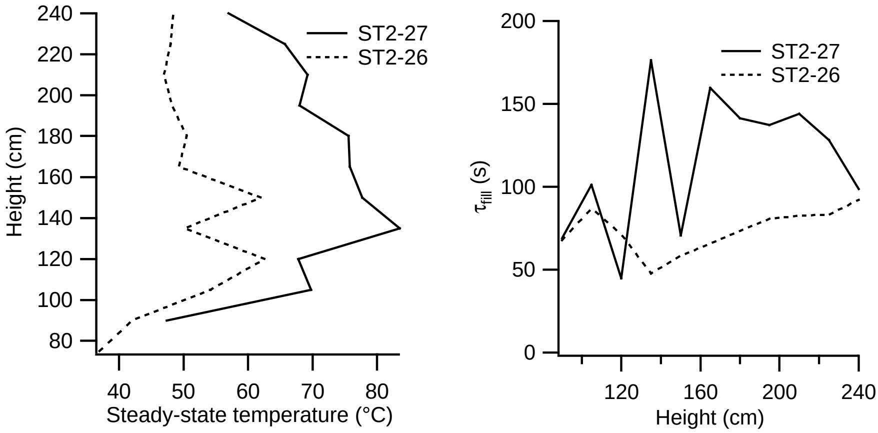

Figure 20. Left: the estimated final temperature distribution in the staircase for tests ST2-26 and ST2-27. Right: the time constant for smoke filling of the staircase for the same tests.

The staircase temperatures were fitted with exponential fuctions, yielding both the estimated final temperature distribution in the staircase, as well as the time constant for smoke filling. The results are displayed as Figure 20. It is observed that the estimated steady-state temperature in the staircase is higher for the pool fire. This is a direct consequence of the higher heat of combustion of heptane, since both fires have the same amount of oxygen available before they are self-extinguished. The time constant for smoke filling of the staircase as a function of elevation is generally longer for the heptane fire, although in the case of ST2-27, there is some ambiquity in the interpretation of the values close to the door to the fire apartment, due to the turbulent flow pattern. By comparing to the PPV time constant of ST2-25 (Figure 19), it is seen that generally $\tau_{fill} > \tau_{PPV}$, the difference decreasing with increasing elevation. This is an important reminder on the fact that the effect of PPV drops quickly along closed-end paths. At the top of the staircase, all time constants (ST2-25, 26 and 27) come very close together, suggesting that at the top, diffusion and conduction become important processes in smoke and heat transport.

Finally, test ST2-28 was conducted to demonstrate what may result if PPV is applied with no consideration on the sufficient flow rate. Again, the 0.1 m^2 heptane pool was used, and the fire room windows were initially closed. Wood sticks were placed into the pool to act as reignition source. The fire was first burned until it was self-extinguished. After that, the staircase and fire compartment were overpressurized (PPV power 90%), and the small window of the fire room was opened. No backdraft occurred, and the fire was re-ignited, keeping the PPV power at 90%. This resulted in a steady-state burning of the fire with a RHR of 300 kW. For comparison, a freely standing 0.1 m^2 heptane pool with 2.5 l heptane burned for 12 min, corresponding to a mean RHR of about 100 kW. This suggests flashover conditions in the fire room. The applying of PPV did not cool the compartment enough to reduce the RHR; instead, it provided enough oxygen so that an RHR over three times greater than produced by the standard fire load could be sustained in the fire room. However, the benefit of keeping the staircase cool and free of smoke was preserved.

4. Discussion

The main conclusion from Parts 1 and 2 of the study is that with sufficient prerequisites and proper execution, PPV can significantly improve the operating conditions of fire-fighters, the survivability of people during egress, and limit the smoke damages in the building. The most basic of the prerequisites is the existence of a well-defined path for the ventilation flow, which in turn implies that the location of the fire must be accurately known, and there are well-defined inlet and outlet openings in the fire room. The principal requirement for proper execution is a well trained personnel with every member understanding the basics of PPV. Also, training is required to assess whether the necessary inlet and outlet openings can be created without the risk of a backdraft.

Technically, the proper way of generating the overpressure is such that the whole area of the inlet opening into the fire room is subjected to the overpressure. This immediately implies that the fan used for PPV cannot be positioned too close to the inlet opening of the fire room, since otherwise the dynamic pressure of the air cone will not overcome the static pressure created in the fire room at every position in the inlet opening. It is also possible to place the fan further away from the fire room in order to cause a static overpressure in the entrance room to the fire room. In practice however, the further the fan is placed, the more difficult it is to maintain a well-defined path for the ventilation flow. One reason for this is the natural leakiness of buildings, and another is the changes in the ventilation path due to human measures. For example, as people are evacuated from their apartments via the staircase of multi-storey buildings, a random number of doors are open at random locations along the ventilation path at any given time.

The present study focussed largely on the quantitative measurement of the rate of heat release of the fire under ventilated conditions. It was consistently observed that increasing the rate of ventilation, whether natural or forced, incresed the RHR in the simulated compartment fire scenario. On the other hand, since a fire generates an overpressure in the fire room, a succesfull PPV must overcome this overpressure at every point in the inlet opening. Unless it can be safely assumed that an increased RHR will not result in structural or other damages in the fire room or along the outlet pathway of the fire gases, there exists an optimum PPV rate (or equivalently, an optimum overpressure in the inlet opening) which is just sufficient to block the spread of heat and smoke along the inlet path while minimizing any adverse effects due to thermal load.

The most desirable ventilation path in any fire scenario is through the fire room. The present study revealed, however, that in certain cases PPV may improve conditions even if ventilation through the fire room is not possible. One such example is the staircase of a multi-storey building. If the door from the staircase to the fire compartment is open, and smoke and heat are transported to the staircase, performing natural or forced ventilation through the staircase smoke vent improves conditions in the staircase, while the RHR and temperatures in the fire compartment are not significantly affected. This was observed regardless of which floor the fire was in.

It was also observed that ventilation simultaneously through the fire room and through the staircase smoke vent is possible, provided that the capacity of the fan is sufficient. This has significance especially if the fire is in the lower floors, and the upper part of the staircase gets filled with smoke. Ventilation of the staircase in that case is needed to improve conditions for the people trying to escape the building via the staircase.

A key aspect of any PPV scenario is the relation between the fan capacity and the size of the inlet and outlet openings. These together determine the achievable flow rate through the ventilation path. Frequently, the only parameters known about the PPV are the primary and secondary flow rates produced by the fan. However, the way in which the air cone covers the inlet opening affects the air current that actually goes through the opening. Also, the finite size of the outlet opening further limits the air flow. In principle, the geometry of the ventilation path also affects the hydraulic resistance to the air flow, but this effect can be neglected unless there are significant blockades, complexity or leakiness in the path.

The effect of the inlet and outlet opening areas on the flow rate can be derived from simple geometric considerations. Denoting the area of the inlet and outlet openings by A_{in} and A_{out}, respectively, the volumetric flow rate Q depends on the ratio of the areas $x=A_{out}/A_{in}$ in the form (Ingason & Fallberg 1998)

$$Q = k \frac{x}{\sqrt{1 + x^2}}, \qquad (1)$$

where the constant k depends on the primary flow rate of the fan and the relative geometry of the fan and the inlet opening. Setting A_{out} as infinite in the above formula, it is seen that Q=k, corresponding to the maximum air flow that can be directed through the inlet opening. For a finite A_{out}, $Q<k$. The determination of the absolute value for the constant k requires practical experiments, as the properties of different types of fans (air cone width, flow velocity profile etc.) are not similar. Quantitative analysis on the interaction between the air cone and inlet opening for the present test series is presented in Appendix B.

Assuming that the values of k and x are known (making it possible to adjust the flow rate to any known value), one may ask what is the value of the optimum flow rate Q for a given fire. In the experiments performed in this study, the extraction of heat and smoke out of the model building was accomplished by a flow rate of 6.25 m^3/s. This corresponds to a full-scale value of 200 m^3/s, equivalent to approximately five air exhanges per minute in the fire room. This value should be regarded only trend-setting, first and foremost because the optimum value of Q depends on the actual RHR which varied as a function of time in the experiments. A more quantitative treatment of the optimum flow rate is presented in Appendix C.

Finally, it is stressed that during a real fire-fighting attack, the rapidly evolving and changing scenario requires that any PPV operations be constantly controlled and executed by a properly trained personnel to obtain best and safest possible results.

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Appendix A: The model building: design and instrumentation

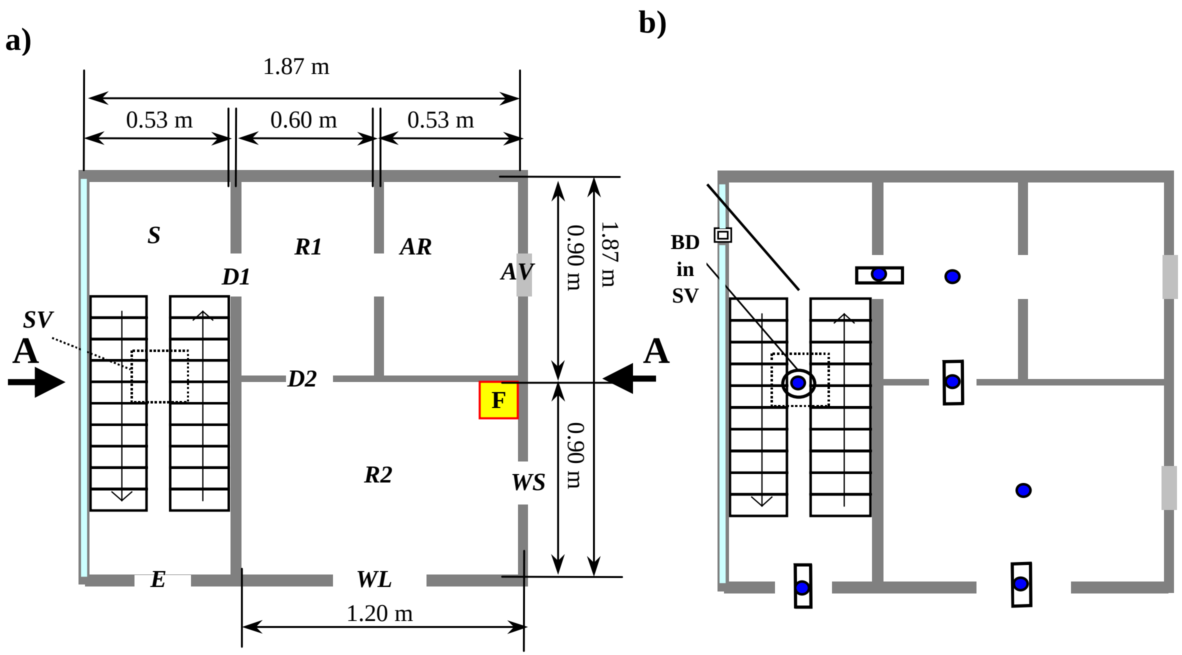


Figure A1. Layout of the model house (a) and the positions of the instruments (b). To enable visual inspection of the tests, the large wall of the staircase was made of an acrylic sheet. The dimensions of the rooms and openings are given in table A1. View along the cut A-A is shown in figure A2.

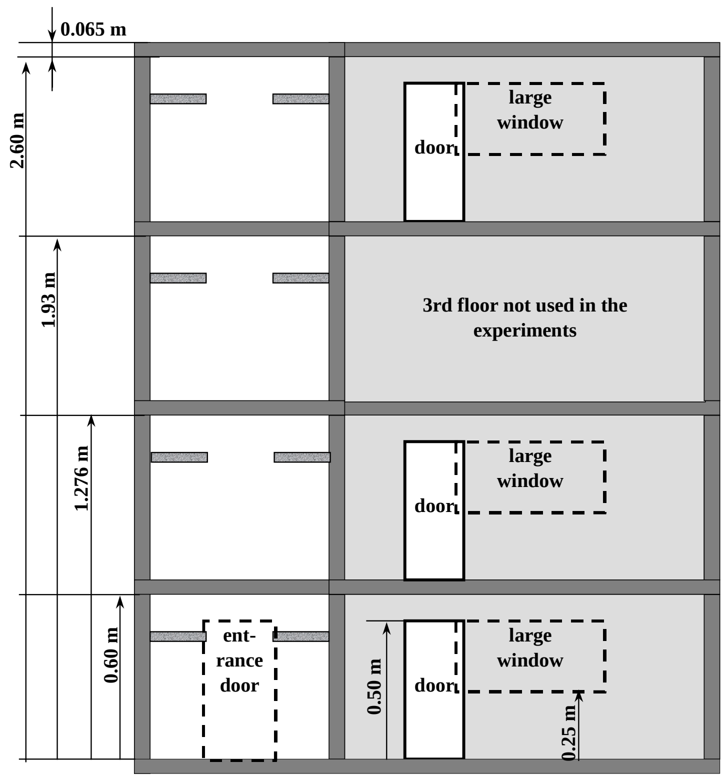


Figure A2. View along the cut A-A depicted in figure A1.

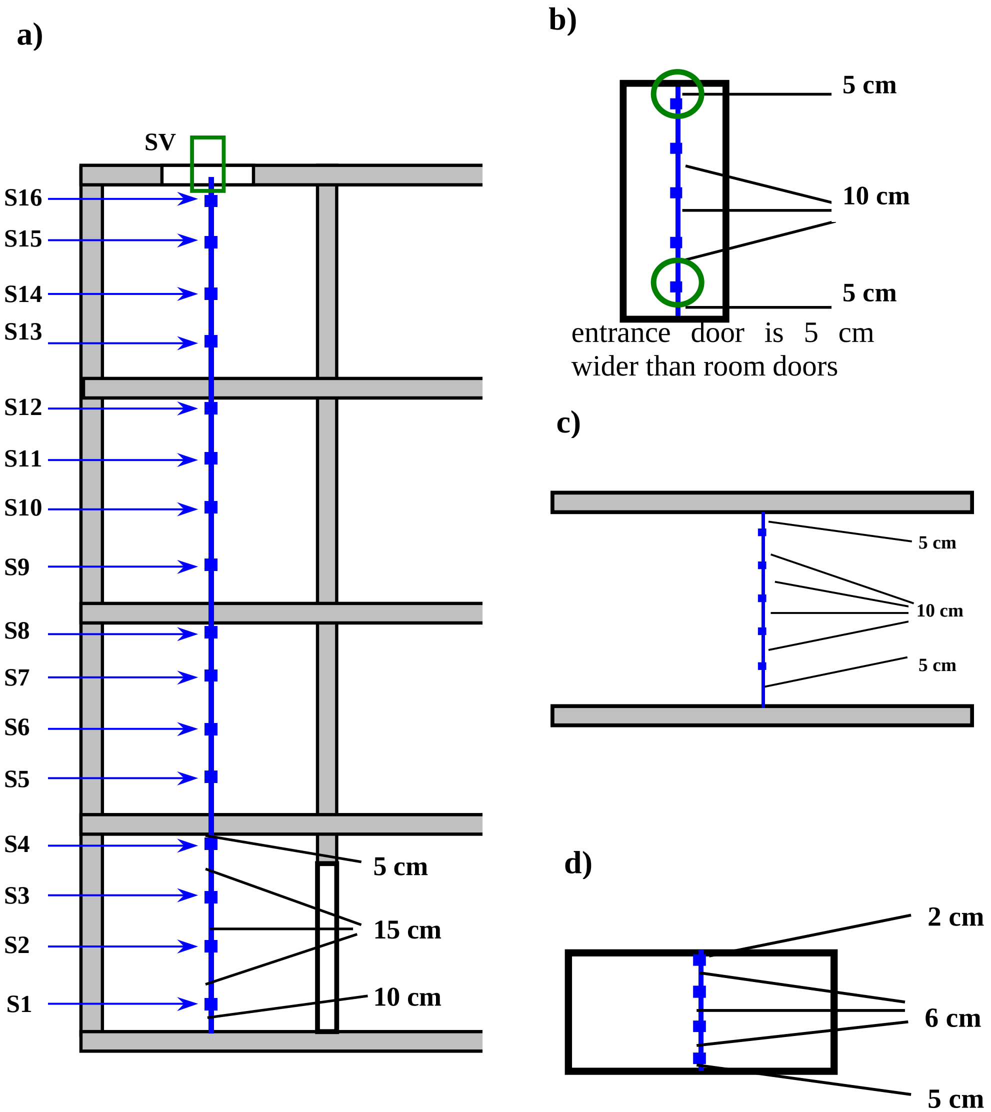


Figure A3. Vertical positions of the thermocouples and bi-directional probes in the rooms and openings: a) staircase, b) doors, c) rooms and d) large window.

Table A1. Dimensions of the rooms and openings in the model house. In the two rightmost columns are given the areas and volumes of a corresponding full-scale house.

					MODEL		**FULL SCALE**	
		width (m)	**length (m)**	**height (m)**	**area (m^2)**	**volume (m^3)**	**area (m^2)**	**volume (m^3)**
AO	**Auxiliary opening**	0.25		0.25	0.063		1.0	
AR	**Auxiliary room**	0.53	0.90	0.60	0.477	0.286	7.6	18.3
E	**Entrance, ground floor**	0.25		0.50	0.125		2.0	
F	**Fire**	0.18	0.18		0.032		0.5	
D1	**Door to the staircase**	0.20		0.50	0.100		1.6	
D2	**Door of the fire room**	0.20		0.50	0.100		1.6	
R1	**Entry room**	0.60	0.90	0.60	0.540	0.324	8.6	20.7
R2	**Fire room**	0.90	1.20	0.60	1.080	0.648	17.3	41.5
S	**Staircase**	0.53	1.87	2.66	0.991	2.636	15.9	169
SV	**Smoke vent**	0.25		0.25	0.063		1.0	
WL	**Window, large**	0.5		0.25	0.125		2.0	
WS	**Window, small**	0.25		0.25	0.063		1.0	

Appendix B: Characteristics of the blower inducec flows into a chamber and pressure inside the chamber

B1 Flow distributions

Two different test chambers were used for characterizing the blower-induced flows into the space and the pressures in it.

One test chamber was the actual model staircase shown in Figure B1b. The other test chamber, shown in Figure B1a, was constructed to assess how the staircase of the ¼ model house should designed; this setup will be referred below as a trial chamber. Two outflow configurations were studied, one with size of 0.25×0.25 m^2 and the other with size of 0.25×0.50 m^2.

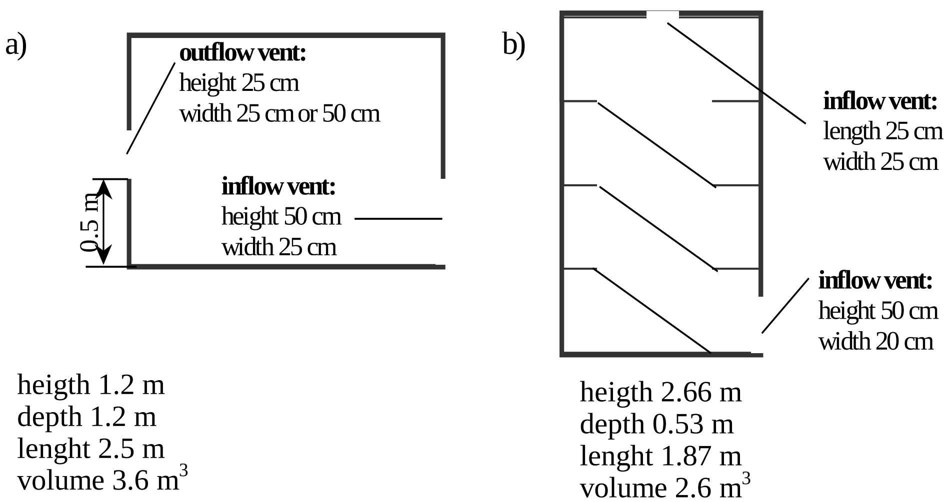
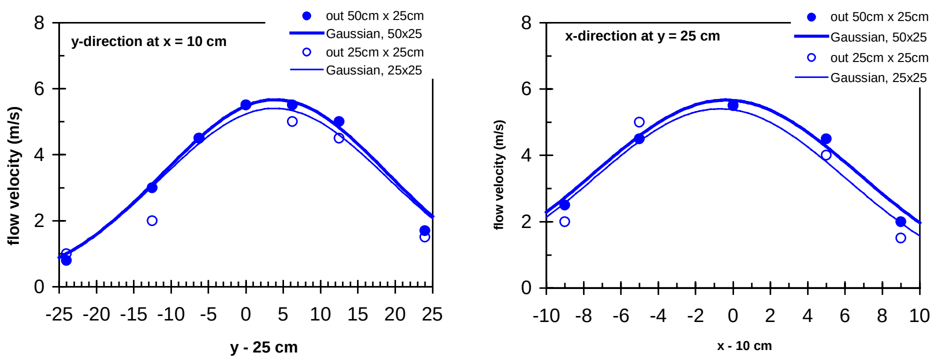


Figure B1. Schematic illustrations of the trial chamber (a) and the staircase(b).

To study the distributions of the flow velocities at the input vent, the blower was operated at distance of 1 m from the inflow opening at 90 % of full scale which corresponds to a primary flow of 0.168 m^3/s (10.1 m^3/min). The velocities were measured by an anemometer. The flow velocity distributions at the inflow vents are shown in Figure B1 (trial chamber) and Figure B2 (staircase). The flow velocities at the output vents were rather flat with average values of 2.4 m/s (trial chamber) and 2.95 m/s (staircase).

As the input flow pattern does not cover the whole input opening there occurs also some backflow out of the chamber. This is reflected in Figure B3 by the two readings at the upper end of the entrance door with velocities deviating from the Gaussian pattern. Thus, the amount of air flow which actually enters the chamber and ultimately traverses to the output vent is less than the air current that is directed to the opening. Due to the build-up of static pressure inside the chamber, to enter the chamber the inflow volume elements must have sufficiently high energy, *i.e.*, dynamic pressure.



a) b)

Figure B2. Velocity distributions in the tests with trial chamber: a) distribution along the y-direction at the center of the door and b) distribution along the x-direction at the center of the door. The results obtained with the larger (smaller) outflow vent are shown with filled (open) markers and the corresponding fitted Gaussian shapes and shown with the solid curves.

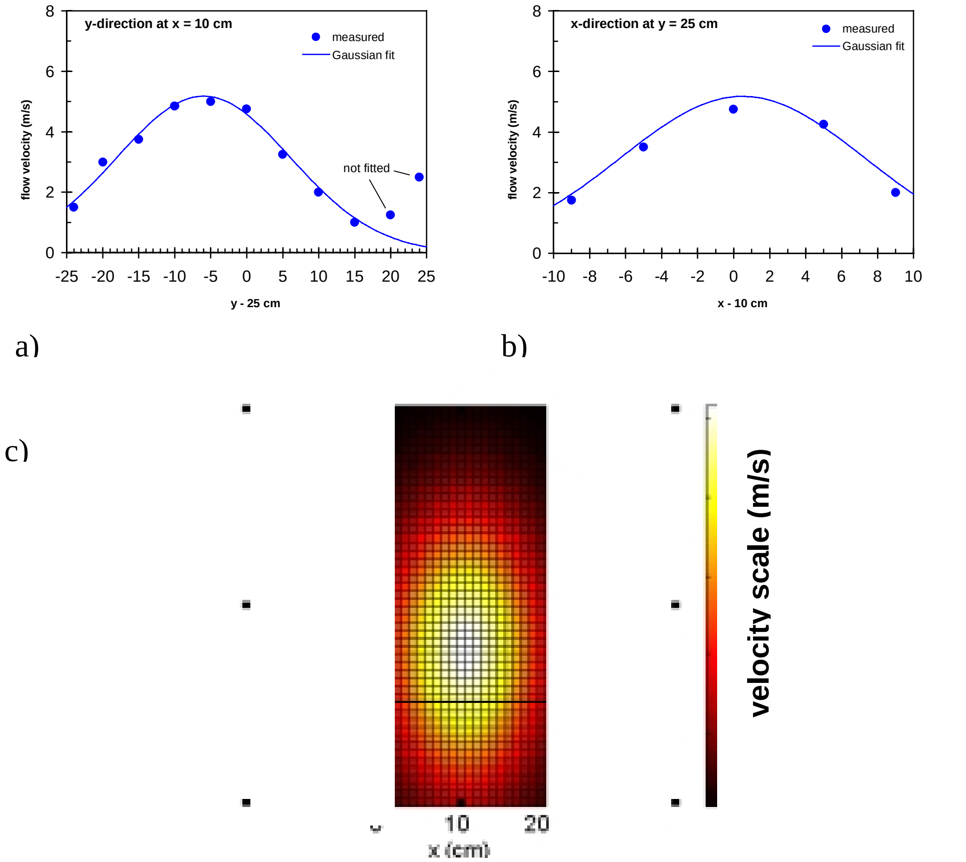


Figure B3. Velocity distributions in the tests with the staircase: a) distribution along the y-direction at the center of the door and b) distribution along the x-direction at the center of the door and c) contour plot. The two velocity readings at the upper edge of the floor in Fig. a) correspond to flow out of the door.

We analyzed the actual inflow rate via the output flow rates: in a chamber with negligible leaking these two should be equal. In the case of the staircase tests, using a flow coefficient C_d = 0.67, one obtains outflow rate of 0.124 m^3/s, or 7.4 m^3/min for the outflow rate. At the inflow vent this flow rate corresponds to a case where flow velocities below 2.8 m/s do not contribute to the actual flow inside the chamber. In terms of dynamic pressure values, a velocity limit of 2.8 m/s reads 4.7 Pa. Using the model given below for the flow rates, one obtains an estimate of 5.5–6.0 Pa for the static pressure in the chamber.

B2 Mathematical model and check on its validity

The mathematical model given below is basically a reproduction of the model presented by Ingason and Fallberg in reference [Ingason & Fallberg 1998]. We consider some plausible options to assign values to some parameters of the model.

Let us consider the configuration shown schematically in Figure B4. The blower diameter is D_0 and it generates a flow with a primary flow rate equal to Q_b. Only some portion, Q_{in}, of the air current flowing towards the opening actually enters the room.

We assume that the inflow takes place through a door of height H_{in} and width W_{in} (area $A_{in} = H_{in}\ W_{in}$). The outflow (rate Q_{out}) passes through an opening with an area of A_{out}. For a room with sufficiently small leaks, Q_{in} and Q_{out} are roughly equal. Due to the forced flow at its entrance, the room becomes pressurized to a static pressure P_{stat} above the ambient pressure P_{amb}.

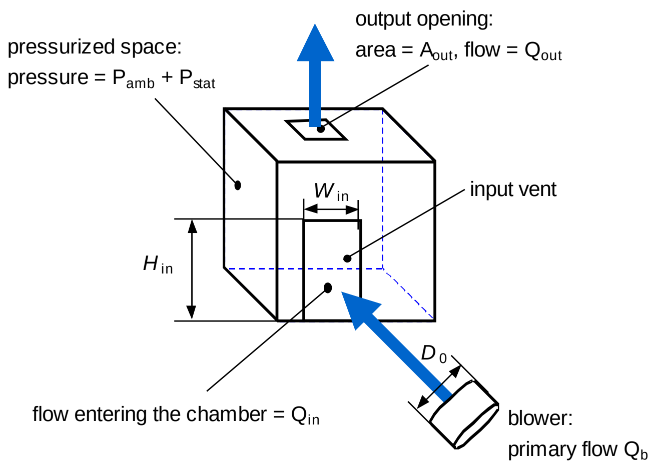


Figure B4. Configuration and factors considered in the mathematical treatment following Ingason and Fallberg [Ingason & Fallberg 1998].

With some parameters renamed, the model presented by Ingason and Fallberg enables to relate the outflow rate to the flow rate at the entrance as

$$Q_{out} = \frac{4}{\pi} \frac{C_d}{\sqrt{\xi}} \frac{A_{in,eff}}{D_0 D_{eff}} \frac{x_{eff}}{\sqrt{1+x_{eff}^2}} Q_b , \tag{B1}$$

where C_d is the outflow coefficient, ξ is a pressure-loss coefficient, $A_{in,eff}$ is the effective area of the flow pattern at the entrance, D_{eff} is its effective dimension and $x = A_{out} / A_{in,eff}$.

Using the values $D_{eff} = H_{in}$ and $A_{in,eff} = H_{in} W_{in}$, one obtains the form given in Ref. [Ingason & Fallberg 1998] :

$$Q_{out} = \frac{4}{\pi} \frac{C_d}{\sqrt{\xi}} \frac{W_{in}}{D_0} \frac{x_{eff}}{\sqrt{1+x_{eff}^2}} Q_b . \tag{B2}$$

Assigning the width of the entrance door to D_{eff} , $D_{eff} = W_{in}$ and $A_{in,eff} = H_{in} W_{in}$, yields

$$Q_{out} = \frac{4}{\pi} \frac{C_d}{\sqrt{\xi}} \frac{W_{in}}{D_0} \frac{x}{\sqrt{1+x^2}} Q_b . \tag{B3}$$

One alternative is to employ an elliptical shape with half axes $\frac{1}{2} H_{in}$ and $\frac{1}{2} W_{in}$ to the flow pattern entering the room. This approach yields $D_{eff} = \sqrt{H_{in} W_{in}}$, $A_{in,eff} = \frac{\pi}{4} D_{eff}^2$ and

$$Q_{out} = \frac{C_d}{\sqrt{\xi}} \frac{D_{eff}}{D_0} \frac{x_{eff}}{\sqrt{1+x_{eff}^2}} Q_b , \tag{B4}$$

Finally, we fit our data using expression Equation B1 by choosing the effective area as the adjustable parameter and assigning $D_{eff} = \sqrt{\frac{4}{\pi} A_{in,eff}}$. The least-squares fitting gives values $A_{in,eff} = 0.01$ m^2, *i.e.* equal to the actual opening area, and $D_{eff} = 0.28$ m.

The results of the exercise described above are shown in Figure B5. It may be seen that equation B2 gives too small values as compared to our data whereas Equation B3 exaggerates somewhat the outflow rate. Results calculated using

Equation B4 deviate from data slightly less than those obtained by using Equation B3 but to the lower direction. The least-squares fit gives essentially the same result as Equation B3.

Thus, two conclusions made be derived: First, the simple model of Ingason and Fallberg explains our data well and, secondly, best fit to our data is obtained by using the geometrical mean of the input opening height and width as the parameter D_{eff} .

The model of Ingason and Fallberg may used to estimate the static pressure inside the room. Using the above notation, the formula for P_{stat} reads

$$P_{stat} = \frac{8\rho}{\pi^2} \cdot \left(\frac{Q_b}{D_0 D_{eff}} \right)^2 \cdot \frac{1}{x^2 + 1}, \qquad \text{(B5)}$$

where ρ is the density of the fluid. The results calculated by Equation B5 are shown in Figure B6.

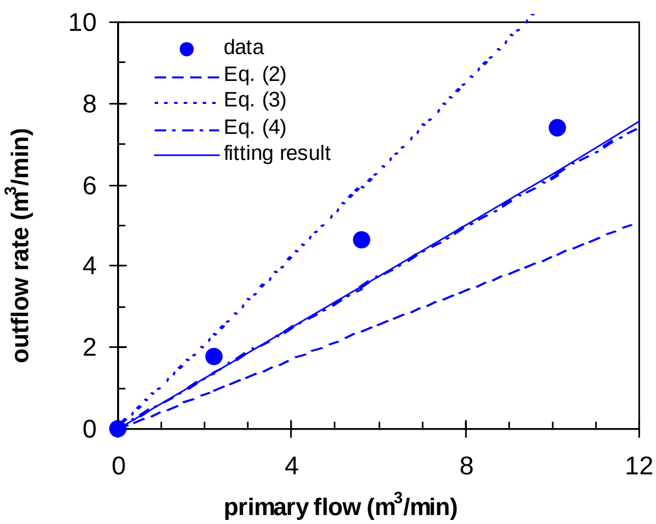


Figure B5. Measured outflow rate in the staircase (bullets) and a prediction of the model by Ingason and Fallberg (line).

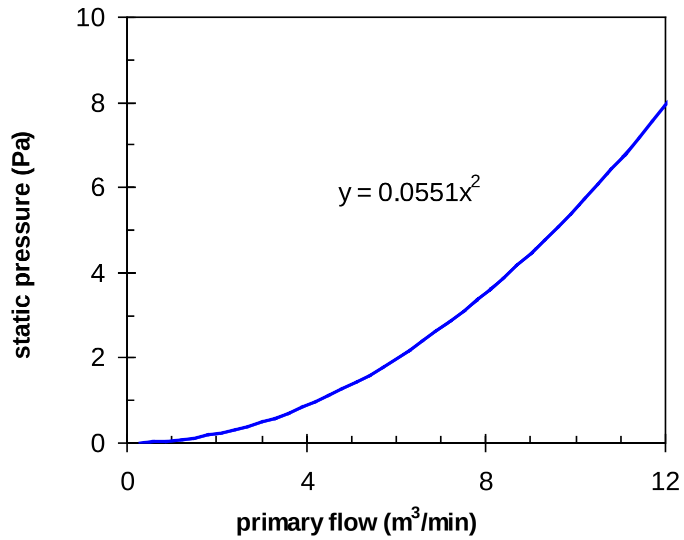


Figure B6. Calculated static pressure in the staircase.

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Appendix C: On optimal PPV

C1 Dependence of RHR on PPV

The experiments enable us to quantify the intuitively obvious fact that the rate of heat release (RHR) increases with increasing positive pressure ventilation (PPV). This is shown in Figure C1.

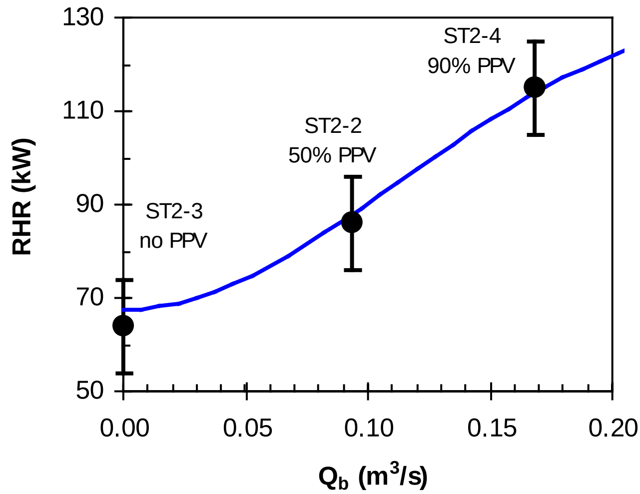

Figure C1. Increase of RHR with the PPV. The curve represents modeling of the data by a function which saturates to a value of 135 kW (for the reason for this particular value, see the text).

In Figure C1 we have fitted the data with a saturating function of the form

$$RHR = A + B \cdot \left[1 - \exp\left(-(Q_b/q)^2\right)\right], \qquad \text{(C1)}$$

where A, B and q are model parameters.

The value of A is fixed to the value of 67.5 kW which is roughly the same as the measured value at zero PPV, *i.e.*, 64 kW. This value can also be obtained by using the rate of heat release $Q_{\text{enclosure}}$ value derived from the Kawagoe formula for enclosure fire mass-loss rate [Karlsson & Quintiere 1999, p. 130]

$$\frac{\dot{Q}_{\text{enclosure}}}{\text{kW}} = 90 \cdot A_w \sqrt{H_w} \cdot \Delta H_{c,eff} \, , \tag{C2}$$

Here we have written the opening factor in terms of the window dimensions, area A_w (unit m^2) and H_w (unit m), tacitly assuming that the main source of ventilation is the window. The unit of the effective heat of combustion, $\Delta H_{c,eff}$, is MJ/kg. Assuming that PPV may roughly double the RHR, the parameter B is assigned a value of $2A$ = 135 kW. For the parameter q, the least-squares fitting yields the value $q = 0.1564 \text{ m}^3/\text{s}$.

C2 PPV static pressure and the pressure rise in an enclosure due to a fire

The static pressure rise in the staircase generated by the application of the PVV was considered in appendix B. Here we quote the result

$$P_{stat} = \frac{8\rho}{\pi^2} \cdot \left(\frac{Q_b}{D_0 D_{eff}} \right)^2 \cdot \frac{1}{x^2 + 1} \, , \tag{C3}$$

where the symbols are defined in Appendix B.

The pressure p inside the fire room may be estimated by starting from the following relation derived from the 1st law of thermodynamics [Quintiere 1989/1990] (often called the "pressure equations" in the context of modeling temperature and spread of smoke in enclosure fires)

$$\frac{V_{\text{room}}}{\gamma - 1} \frac{d}{dt} p + \frac{\dot{m}_\infty}{\rho_\infty} \left(\frac{\gamma}{\gamma - 1} \right) p = \dot{Q}_{\text{a}} \, . \tag{C4}$$

Here, $\gamma = c_p / c_v \approx 1.4$ is the ratio of the specific heats of air at constant pressure c_p and constant volume c_v, V_{room} is the volume of the room, ρ_∞ is the density of ambient air and Q_a is the rate of net energy added to the room gas. The quantity $\dot{m}_\infty$ is the outflow rate which may be expressed as

$$\dot{m}_{\infty} = \rho_{\infty} A_0 C \sqrt{\frac{2(p - p_{\infty})}{\rho_{\infty}}}, \tag{C5}$$

where p_{∞} is the ambient pressure, A_0 is the opening area and C is the flow coefficient.

The relevant quantity is the pressure rise $\Delta p = p - p_{\infty}$ induced by the fire. Defining a dimensionless time parameter

$$\tau = \frac{(\gamma - 1)\ \dot{Q}_a}{\varepsilon^2\ p_{\infty}\ V_{\mathrm{room}}}\, t, \tag{C6}$$

where

$$\varepsilon = \frac{(\gamma - 1)\ \dot{Q}_a}{\sqrt{2\gamma}\ C\ A_0\ p_{\infty}\ a_{\infty}}, \tag{C7}$$

and a dimensionless pressure rise parameter P as

$$P = \frac{\Delta p}{\varepsilon^2\ p_{\infty}}, \tag{C8}$$

Equation C4 may be written as

$$\frac{dP}{dt} = 1 - \sqrt{P}\ \left(1 + \varepsilon^2 P\right). \tag{C9}$$

The parameter ε defined in Equation C7 is very small as compared to unity, e.g., for $Q_a = 100$ kW, C = 0.67, $p_{\infty} = 101.3$ kPa, $a_{\infty} = 344$ m/s and $A_0 = 0.1\ \mathrm{m}^2$, $\varepsilon = 0.01$.

It has been shown [Rehm & Baum 1978] that $P \to 1$ as $\tau \to 1$. As the solution of Equation C10 is a monotonically increasing function of τ, from the equality $P = 1$ we obtain an upper limit to the pressure rise inside the room,

$$\Delta p_{\max} = p_\infty \cdot \left[\frac{(\gamma - 1)\ \dot{Q}_a}{\sqrt{2\gamma}\ C\ A_0\ p_\infty\ a_\infty} \right]^2 . \tag{C10}$$

By associating Q_a with the measured RHR values and introducing Equation C1 we obtain the following expression relating the pressure rise inside the fire room to the PPV blower primary flow rate Q_b:

$$\Delta p_{\max} = p_\infty \cdot \left[\frac{(\gamma - 1)\ \left(A_2 + B_2 \cdot \left(1 - \exp\left(-(Q_b/q)^2\right)\right)\right)}{\sqrt{2\gamma}\ C\ A_0\ p_\infty\ a_\infty} \right]^2 . \tag{C11}$$

C3 Optimal PPV

The influence of PPV on the conditions inside the fire room may be examined by comparing the static pressure P_{stat} in the staircase generated by the PVV and the pressure rise inside the fire room due to the PPV, $\Delta p_{\max}$. Such comparison is presented in Figure C1. The values of the blower primary flow rates for which the static pressure slightly exceed the room pressure rise may be considered as optimal PPV. In such cases the staircase pressure is enough to block smoke from entering the staircase but not excessively large to cause unnecessary damage to the fire room and compartments attached to it, *e.g.*, by ventilation ducts.

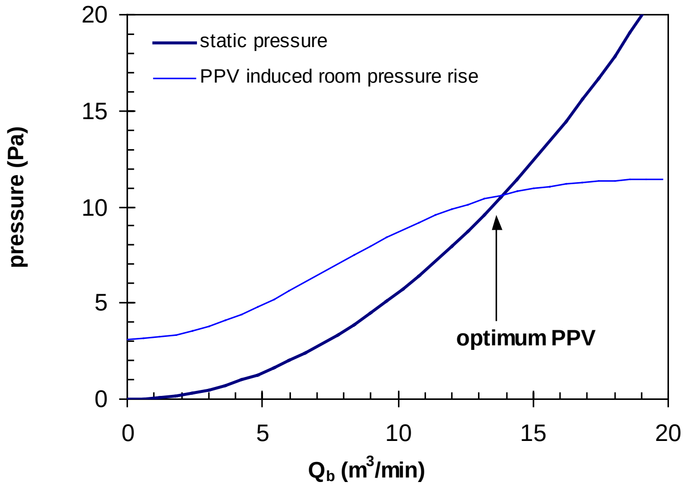

Figure C2. The static pressure in the staircase and the pressure rise inside the fire room due to the PPV as a function of the PPV blower primary flow rate Q_b*. The static pressure overcomes the room pressure rise above a primary flow rate of ca. 14 m*^{3}*/min.*

A straighforward extrapolation of the blower primary flow rate of 14 m^3/min to full-scale situation by using the scaling factor of $4^{5/2} = 32$ yields an estimate of *ca*. 400–500 m^3/min in the full scale. This is of the some order of magnitude as the PPV-flow rates mentioned in the pioneering work by Leo Pesonen [Pesonen 1946]: he estimates that flow rates of the order of 200-300 m^3/min will be generally used in practical PPV but that also larger ones will be used, admitting that he himself was readily seeking blowers with a capability of delivering 500-600 m^3/min.4

It should be borne in mind that the dependence of the RHR on the PPV is strongly dependent on the leakness of the fire room, in a very leak-proof enclosures the pressure may rise considerably higher than in a very leaky space. Thus, the main importance of this appendix is the development the algorithm on how one can quantitatively relate the PPV and the conditions[†] in the fire room.

[†] Here we have considered the pressure and RHR values but one could do similar calculations also to temperatures e.g. by using single-zone models.

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