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ABSTRACT

Ventilating a fire compartment during operational fire fighting procedures may have unpredictable consequences. In some cases the ventilation is advantageous: the hot gases are removed from the fire enclosure, the visibility improves and the enclosure cools down. In some cases the opposite happens: with the accelerated burning rate, more smoke is spread around, and the temperatures rise. The most dramatic consequence is the initiation of a backdraft, where the pyrolyzed gases ignite instantaneously, in the worst case causing a severe explosion.

The effect of ventilating the fire compartment was studied systematically by quarter scale laboratory tests. The fire was initiated in a one-storey three-room compartment subject to different horizontal ventilation conditions. Both natural and positive pressure ventilation (PPV) were applied. The tests revealed many critical factors affecting the success of the attack. When properly used, PPV clearly improves the survival probability in the compartment: the visibility dramatically improves, and the temperatures are low everywhere outside the fire room.

A fire spread zone model code (BRI2T) was applied to a few principal test scenarios. The model simulates well scenarios with no vigorous turbulent mixing of the gas layers, but predicting dependences between different parameters is tedious because the model (like all zone models) does not contain a feedback between varying ventilation conditions and the heat release rate. Due to these limitations, the available zone models are not suitable for PPV applications.

PREFACE

During the last few years the Fire Protection Fund of Finland has been financing research projects aiming at improved understanding of operational fire fighting procedures. During the years 1992 - 1994 a project *Suppression of compartment fires with a small amount of water* was carried out. Within the project the performance of the most common automatic fire hose nozzles was compared, and a user-friendly interface to a computer code simulating fire suppression (Fire Demand Model) was developed for training purposes.

In the present project the effect of smoke ventilation during operational fire fighting procedures has been studied. The fire brigades have taken a somewhat contradictory attitude in the issue of forced ventilation: a few fire officers realize the potential benefits, a large majority, however, fear that the consequences may be disastrous. The objective of this project is to provide systematic and neutral information on smoke ventilation as a part of the suppression procedures.

Most of the practical test arrangements were made by Mr. Risto Latva, Research Engineer at VTT.

Maarit Tuomisaari

CONTENTS

1 INTRODUCTION

Extracting smoke from the fire compartment as a part of operational fire fighting would be most beneficial, but it always poses some risks when initiated during the fire. In some cases the smoke ventilation is advantageous: the hot gases are removed from the fire enclosure, the visibility improves and the enclosure cools down. In some cases the opposite happens: with the accelerated burning rate, more smoke is spread around, and the temperatures rise. The most dramatic consequence is the initiation of a backdraft, where the pyrolyzed gases ignite instantaneously, in the worst cases causing a severe explosion.

The positive effects of forced smoke ventilation carried out by external fans were known in Finland already in the 40's /1, 2/: "The objective is that the accumulation of heat and production of smoke gases is stopped altogether by starting the ventilation as early as possible. In a cool room, a bright flame is easy to extinguish." The inventor of the so-called Fenno-Vent method, Mr. Leo Pesonen, wrote in 1958 that he planned to "initiate scientific research on Fenno-Vent that he had been vainly expecting for 22 years." Only now in the 90's, over 30 additional years later, scientific interest is finally being shown in the method.

In spite of the strong one-man-campaign for forced ventilation, which today carries the name Positive Pressure Ventilation (PPV), the method has mostly been ignored ever since. It has been extremely difficult to get the fire service to accept a technology where large amounts of fresh air are introduced into a burning building. In actual fire fighting procedures the fear of the possible negative effects has always dominated actions, even though many fire officers agree that PPV, *when used correctly*, dramatically increases visibility in a burning structure. In addition, it drastically reduces the heat concentration in a fire situation.

Until the 90's the PPV was almost totally forgotten, it was not applied in practice or studied any further. Yet, beginning in the 90's, fire brigades in the US /3, 4/ have started to apply PPV, and research projects have even been initiated /5, 6/ to minimize the dangers of PPV and to maximize its benefits. Furthermore, a novel technique has been developed in the US to conduct underwater, scale-model PPV simulation applicable to both research and training. Also, a PC -based simulation and training package is being developed for fire fighter training.

One practical reason for forgetting or ignoring the ventilation for such a long time has probably been the fact that earlier the method was slow and required many fire fighters. It was also tedious with the old fans that required special door adapters. The modern lightweight fans work at totally different ventilation rates, and no door adapters are required. One person alone can take care of the arrangements.

Even though PPV is not applied in Finland generally, the fire service has shown interest in it; more specifically, instructions and rules for its safe and proper implementation would be highly appreciated. This interest initiated the present project. The most important phenomena governing the fire under ventilation conditions were studied experimentally. Also, computer simulation was applied to deepen the understanding.

The report is organized as follows. A literature review based on a very limited number of available sources is given in Chapter 2. Chapter 3 contains the experimental details and Chapter 4 the experimental results. Some computer simulations are described in Chapter 5. The results are discussed in Chapter 6.

2 POSITIVE PRESSURE VENTILATION

2.1 PRACTICAL CONSIDERATIONS

Positive Pressure Ventilation is accomplished by using high powered fans outside the burning building – typically close to a door opening – to force heat and smoke out of the building. An exhaust opening, e.g. a window, is required to direct the smoke out in a controlled way. At its best, the PPV technique rapidly reduces temperatures, and the removal of smoke and toxic gases improves visibility inside the structure and increases the survivability potential for victims.

PPV has been used for many years as an aid in ventilating structures after extinguishing the fire. Already over more than 30 years ago it was applied as a way to clear smoke from ships. Only quite recently, PPV has been recognized as a potential fire attack technique, i.e. PPV can be initiated before fire fighters enter a burning structure (pre-attack PPV).

Experimentally verified advantages of PPV include /5, 6/:

1. Reduced temperatures: at key fire fighting positions, for example, PPV contributed to temperature reductions from 450 °C to 50 °C within 1 minute.
2. Improved air quality: PPV was shown to contribute to oxygen addition and carbon monoxide removal.
3. Faster smoke removal and faster restoration of visibility: when PPV was used, fire fighters had water on a residential fire 6 min after it began and were walking upright in a cool, high-visibility environment. By contrast, 8 min after the start of a second, identical fire in which PPV was not used, fire fighters were still crawling around a hot, smoke-filled environment.
4. Reversal of the direction of flames away from the fire fighting location: for example, flashover flames that entered a hallway were pushed back into the burning room soon after the start of PPV.
5. No spread of heat damage.

Based on the above, PPV seems to have obvious benefits, but still it is not in common use by fire departments. There are at least two reasons for this. First, the fire service tradition is typically such that it is difficult to get new technologies or methods accepted; fire fighters are resistant to change. Second, the concept of introducing large amounts of fresh air into a burning building is not popular. The fear of actively causing a backdraft is dominant among fire fighters. (A backdraft is a rapid deflagration following the introduction of oxygen into a compartment filled with accumulated unburned fuel.) The dangerous consequences of a backdraft are well known to all fire fighters.

In some pioneering fire brigades in the USA, PPV has become a standard operating procedure /3, 4/. The Los Angeles department is already routinely using PPV to pressurize stair shafts in high-rise buildings. Based on experience, probably the most amazing benefit of PPV to the fire fighter is the increase in visibility. "The fire was not this faint orange glow in smoke and total darkness, it was there in the corner of the room. After applying water to the fire, the steam took the same route as the smoke and heat..."

According to a study made on the US fire departments, 57 % of the departments responding to the survey used PPV. Of these departments, 31 % used it for smoke removal only; 67 % employed it for smoke removal and fire attack.

The increasing popularity of PPV in the US is indicated also by the following figures: in 1988, there were three companies selling PPV equipment, and some five years later there were already 14.

No negative situations using PPV have been published and "if things go bad or it doesn't work, just turn the fan off". Common misconceptions about PPV feeding fires and increasing risks are not founded, is one conclusion of the experience.

As for the fear of a backdraft occurring, it is claimed that a missed backdraft situation is going to explode on the fire crews once a window or door is opened, long before the PPV fans have even been turned on.

In contradiction to all the good experience in the US, one problem has been raised in Finland /9/: applying PPV may increase the damage caused by soot, smoke and humidity pushed all over the building and its ventilation system. An alternative and opposite method is proposed, i.e. Negative Pressure Ventilation. This method requires a fan to be placed at a strategic exhaust opening. The blow is directed outwards causing a suction from the smoky room to the outside. This method, however, is intended to be used only *after* the fire has been extinguished and not as a part of the initial attack.

It has also been claimed that using short bursts of water from a fog or combination nozzle directed at the ceiling is a more efficient way to cool the fire enclosure and hence prevent flashover. The method certainly has merits in a simple room – provided that the fire room has first been located. However, according to US fire officers /3, 4/ in a large warehouse fire, it is not enough to cool all of the heat and gases.

Based on the US experience it seems that if there is a problem in applying PPV, it is because of lack of training. Many practical aspects in applying pre-attack PPV are discussed in Ref. 10. Its effective use involves at least the following primary considerations:

1. The location of the fire should be known.
2. Before initiating PPV, there must be a discharge opening in the compartment. The closer the opening is to the seat of the fire, the better. The opening must provide an exit wide enough for the free flow (¾ - 1¾ of the area of the inlet opening is suggested).

3. The entrance door must be pressurized so that the air blowing from the fans covers the whole opening.
4. It must be confirmed that there are no obstructions disturbing or even preventing the flow between the entrance and exhaust openings.
5. The fire fighters must be well-trained, and the communication between the inside and outside must be working.

PPV is not recommended if the conditions above are not fulfilled and

1. if a potential for backdraft exists (In the case of a possible backdraft, traditional vertical ventilation is still the safest method, as the concentrated smoke and heat close to the ceiling are first released and the conditions for a backdraft vanish.),
2. if the building has too many natural ventilation openings preventing a directed and controlled flow,
3. in a potentially explosive situation or in a flammable atmosphere, or
4. when people could be endangered.

Some US officers are so convinced of the efficiency of PPV that they believe: “One day the fire service will wonder how it ever got by without it.”

2.2 RESEARCH ACTIVITIES

Since 1992 a research programme is being conducted in the US /5, 6/ to evaluate the effectiveness of PPV as an active fire fighting technique. Live fire tests form a part of the programme.

Two single-room fires were arranged so that they were similar in as many ways as possible – in geometry, in size of fire and fire load, in size of ventilation exhaust point, in distance from fire fighter entry point, and so on. These two fires were used to compare PPV with a common horizontal ventilation method. The results showed that PPV significantly reduces temperatures and toxic gas levels and that it improves visibility better than conventional techniques. PPV reversed the spread of flames from the fire room and contained the fire between the fire fighting location and the exhaust point in the fire room. The PPV fire was also extinguished more quickly than the fire fought with conventional techniques.

A live attic fire test demonstrated that PPV did not spread the heat damage when compared to a conventional attic fire attack method, and an interior room (without exhaust openings) fire test showed that the flames did not spread to the adjoining room with the ventilation opening.

The tests indicated, however, that effective training for fire fighters is needed to use the PPV technique properly. Full-scale PPV research and training can be expensive, though. For training and demonstration purposes, small-scale PPV simulation has been conducted underwater with transparent scale models of residences. The thermodynamics of the fire and the fluid mechanics of PPV are simulated by injecting colored water dyes at rates determined from actual fire measurements.

Results from the live fire tests and water model simulations are being incorporated into a personal-computer-based simulation and training package.

Recently the feared phenomenon of backdraft has also been studied systematically on a more scientific basis /7, 8/. A scenario describing the phenomenon assumes a fire in an enclosure without openings. The hot gas layer descends over the fire as the oxygen concentration is reduced and the combustion efficiency decreases. Excess pyrolyzates accumulate in the upper layer forming a fuel rich mixture of low oxygen content. Suddenly, a new ventilation opening is provided (e.g. a window breaks due to thermal stress or a fire fighter enters the compartment) and cool, fresh air enters the compartment and propagates across the floor as a gravity current. Large-scale mixing of the gravity current provides mixed zones within the flammable range that ignite when they contact an ignition source (a small flame or smoldering fire). Once ignited, a flame propagates through the compartment and drives the remaining unburned fuel out through the opening to burn outside the compartment in a spectacular fireball.

The dramatic moments of the backdraft phenomenon do not occur immediately upon opening a vent, but only after a delay caused by the gravity current propagation. This delay creates a hazard to fire fighters who may enter a compartment and become trapped in the backdraft process.

The backdraft phenomenon was quantitatively studied in a test compartment of 1.2 m × 1.2 m × 2.4 m dimensions. A methane burner, flowing at either 70 kW or 200 kW, was ignited inside the closed compartment and burned until the initially available oxygen was consumed. After the fire self-extinguished, the burner was left on, allowing the unburned fuel mass fraction in the compartment to increase. After removing a hatch, a gravity current entered the compartment. It travelled across the floor, mixed with the unburned fuel, and was ignited by a spark near the burner. After mixture ignition, a backdraft occurred as a deflagration ripped through the compartment culminating in a large external fire ball.

Results of the tests indicate that unburned mass fractions (hydrocarbon concentration) > 10 % are necessary for a backdraft to occur. Up to 73 Pa overpressures were measured at backdraft. When the concentration is < 10 %, the flame travels slowly and the compartment overpressure is much lower, a few Pa. No backdraft was ever observed when a ceiling vent was open.

3 EXPERIMENTAL

3.1 GENERAL

The objective of the present project was to study systematically the effects of horizontal ventilation during fire fighting operations. Since full-scale tests are so time-consuming and expensive, small-scale fire tests were applied to approach the problem. The number of tests could be considerably increased on a small scale as compared to full scale and hence more dependences and trends could be focussed on.

For the tests, a quarter scale was chosen (S = 1/4). It has been postulated /11/ that the following scaling rules apply to the other fire parameters:

- Heat release rate: $S^{5/2}$
- Temperature: S^0
- Volume flow: $S^{5/2}$
- Time: $S^{1/2}$

3.2 TEST COMPARTMENT

The test enclosure was a three-room compartment shown in Figures 1 and 2. It consists of the entrance room (1), the target room (2) and the fire room (3). The two inner doors were always open, the outer vents (one door, three windows) were opened and closed as appropriate. The vents were closed by 50 mm or 100 mm mineral wool pieces that could be instantaneously removed when the ventilation conditions had to be changed. The compartment dimensions with the corresponding full-scale dimensions are given in Table 1.

Table 1. Compartment dimensions. Overall dimensions 1.8 m × 1.2 m × 0.6 m high. (Full scale 7.6 m × 4.8 m × 2.4 m high)

Room #	width (m)	length (m)
1, 2	0.6 (2.4)	0.9 (3.6)
3	1.2 (4.8)	0.9 (3.6)
Opening	width (m)	height (m)
doors	0.2 (0.8)	0.5 (2.0)
large window	0.5 (2.0)	0.25 (1.0)
small window	0.25 (1.0)	0.25 (1.0)

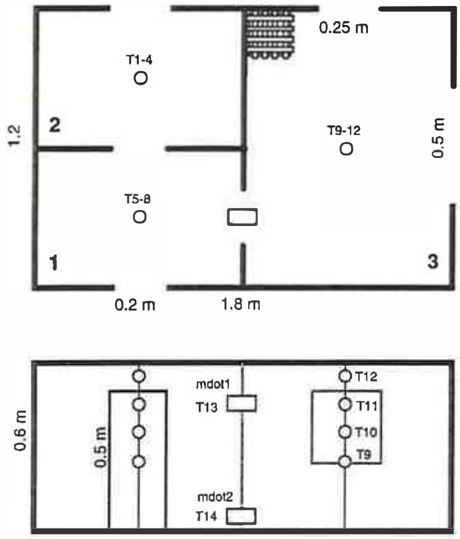


Figure 1. The three-room fire compartment with part of the instrumentation (thermocouples T1 - T14 and bidirectional probes mdot1 -mdot2) and the fuel package in the corner of room 3.

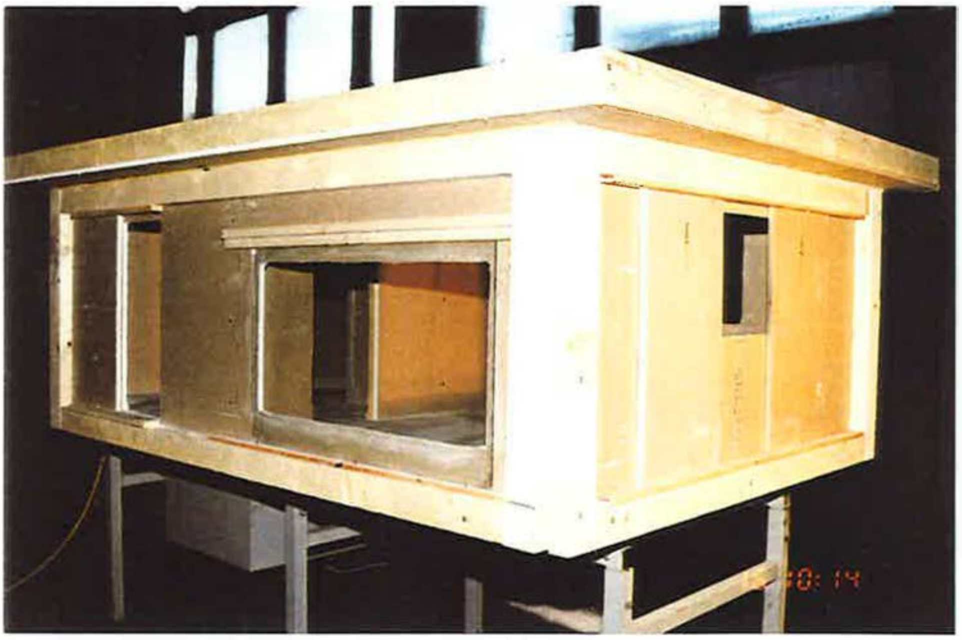


Figure 2. The first version of the test compartment from outside. In final tests the fire room walls were made of Siporex (see Figure 4), and there was no observation window in front because the tempered glass broke during the preliminary tests.

The compartment was originally made of 11 mm thick Gyproc wall boards, but it turned out to be too weak for a series of fires. Hence, the fire room (3) walls were replaced by 65 mm thick Siporex tiles. The ceiling was made of Gyproc board, because it was easy to handle and replace when damaged.

3.3 TEST FIRE

The test fire was chosen to be as repeatable and reproducible as possible. The size of the fire sufficient to produce flashover was minimized by using highly insulating wall materials, and the fire was arranged in a corner to minimize the burning rate required for flashover.

The fire load was adjusted to be such that it provided all the phases of a fire curve in a reasonable time without having to extinguish the fire by active procedures. Any suppression agents would change the conditions in the fire compartment if not properly cleaned or dried. The fire growth phase, the flashover, the fully developed fire and the declining region were all seen within 10 min after ignition. The flames were extinguished within 20 min.

The test fire was arranged in one hidden corner (from the entrance door) of the fire room (see Figure 1). The fuel package consisted of the following components (see Figures 3 and 4):

1. Propane burner made of ∅12 mm o.d. stainless steel tube in the form of a rounded square of 0.15 m side. On top of each side there were three ∅3 mm holes at 40 mm distance from each other. The flow rate was adjusted to about 1.28 g/min corresponding to a heat release rate of 10 kW.

2. The propane burner was lying under a wood crib constructed of 24 sticks (0.175 m × 0.017 m × 0.017 m) arranged in six layers, 4 sticks in each layer. Two sticks were supporting the crib above the gas burner. Prior to the tests, the sticks were conditioned in 50 °C more than 24 hours.

3. The corner walls next to the wood crib were covered by 4 mm thick plywood panels (0.25 m × 0.6 m). Double layers were attached to the wall.

Burning rate in an enclosure depends on the amount of available oxygen, i.e. whether the fire is ventilation or fuel controlled. In case of cellulosic material, the following relationships are recommended to be applied to define the type of fire /12/:

$$\text{ventilation control} \qquad \frac{\rho g^{1/2} A_w H^{1/2}}{A_f} < 0.235 \ . \tag{1a}$$

$$\text{fuel control} \qquad \frac{\rho g^{1/2} A_w H^{1/2}}{A_f} > 0.290 \ . \tag{1b}$$

where A_w and H are the area and height of the ventilation opening, respectively, A_f is the surface area of the fuel, ρ is the gas density in the compartment (in post-flashover fires typically 0.2 - 0.6 times the ambient air density), and g is the gravitational acceleration constant.

Assuming that only the door is open in the fire room, and that all the open surfaces of the wood crib as well as the two plywood wall surfaces are involved in the fire, the value of the left-hand-side of Eqs. 1 is between 0.09 ... 0.28 (depending on the gas density). In the actual tests, part of the available oxygen is consumed by the propane burner, and the topmost plywood layer becomes loose exposing more pyrolyzing surfaces and, hence, the fire is clearly ventilation controlled.

The burning rate of a wood crib in a ventilation-controlled compartment fire obeys the following approximate relationship /12/

$$\dot{m} = 0.09 A_w H^{1/2} (kg / s) \ . \qquad (2)$$

In the one-door-open scenario the calculated burning rate is 6.4 g/s corresponding to a heat release rate between 75 ... 95 kW, depending on the humidity of the wood.

The heat release rate of the fuel package measured without the ceiling (fuel controlled fire) is shown in Figure 5. The propane burner in this measurement was turned off at 2 min; in actual tests it was on throughout the experiment.

The heat release rate was measured also for the scenarios with (i) only the (outer) door open and with (ii) the door and the large window open. The results are shown in Figure 6. The maximum heat release rate stabilized to a value of 75 kW and 90 kW, respectively. As expected, in both cases the fire is clearly ventilation controlled. Using the scaling rules given in Chapter 3.1, the corresponding full-scale RHR values are 2.4 MW and 2.9 MW.

In each test the propane burner was first ignited. This moment was taken as time $t = 0$. The fire was then allowed to evolve freely until appropriate ventilation measures, i.e. opening the door and/or windows and/or starting the PPV fan, were taken.

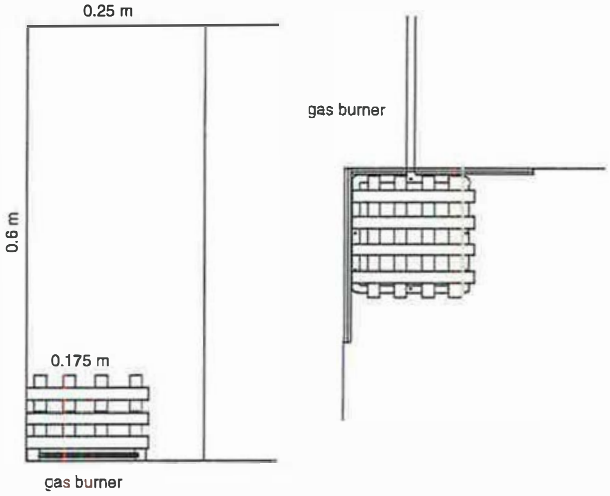


Figure 3. The fuel package: the propane burner, the wood crib and plywood panels.

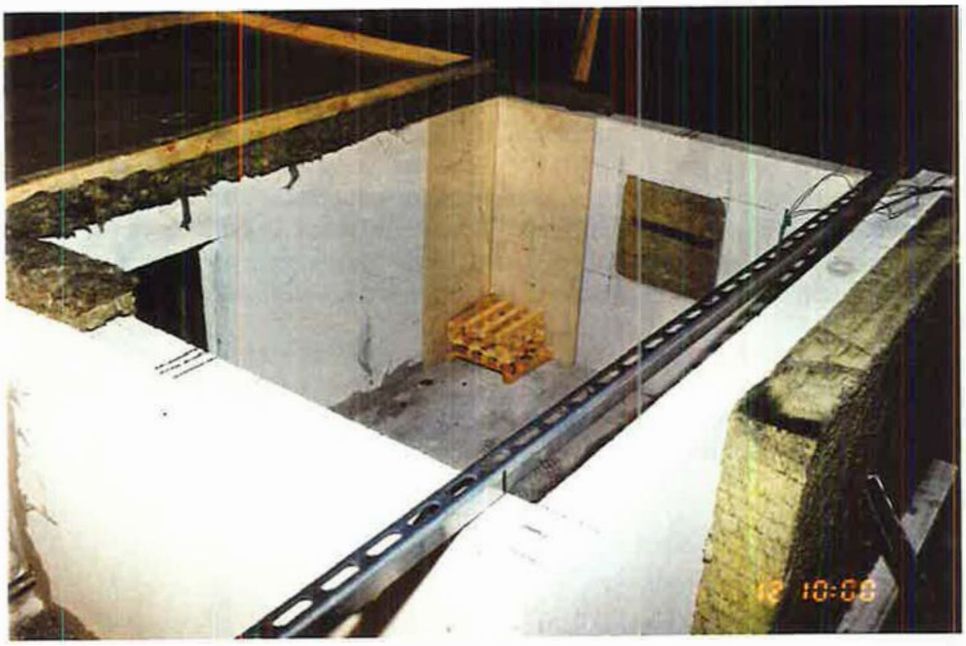


Figure 4. The fuel package in the corner. The fire room walls are made of Siporex tiles, and the two windows are closed with pieces of glass wool.

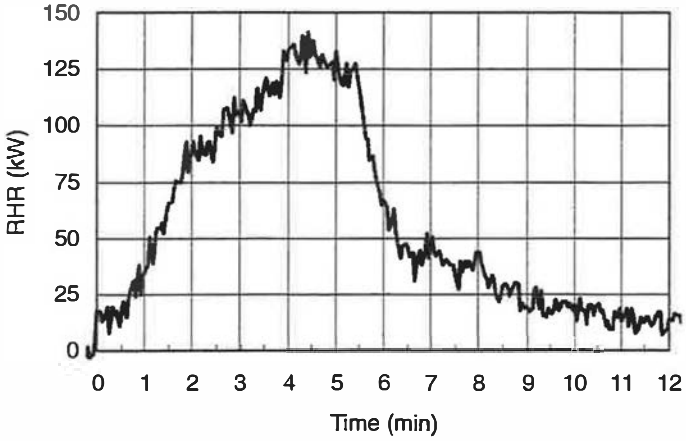


Figure 5. Heat release rate of the fuel package in open. (Propane burner was turned off at 2 min.)

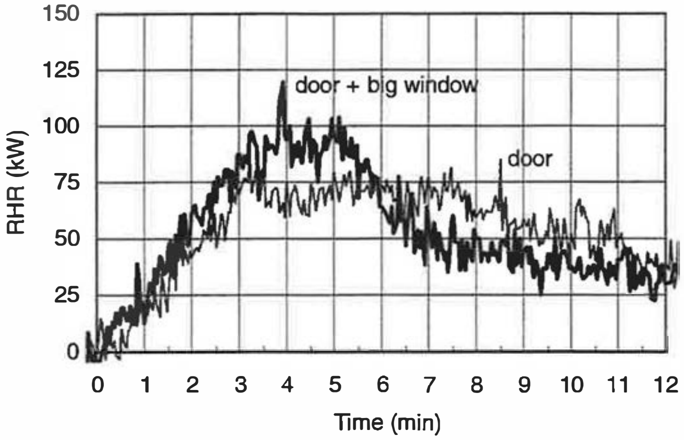


*Figure 6. Heat release rate with only the door open (grey thin curve) and with the door and the large window open in the fire room (**black thick curve**). Compared to Figure 5, there is an undefined delay in the measurement due to a longer path of the smoke through openings and also accumulation of smoke in the compartment.*

3.4 INSTRUMENTATION

Temperature

Gas temperatures were measured with bare Ø0.5 mm K-type thermocouples. There was a thermocouple tree of four thermocouples in the centre of each room (see Figure 1). The heights were 0.25 m, 0.35 m, 0.45 m, and 0.55 m.

Gas temperature was measured also at the door between the fire room and the entrance room about 5 cm above the floor and 5 cm under the lintel. Additional gas temperature measurement points were applied where appropriate.

Gas analysis

Gas samples were collected in the fire room with a sampling tube at about 5 cm below the ceiling, close to the centre of the room. On the outside, the sampling tube (SS Ø6 × 4 mm) was attached to a flexible tube connected to gas analysers for measuring the oxygen, carbon dioxide and carbon monoxide concentrations of the sample. The CO and CO_2 determinations were made with Siemens Ultramat 22 analyser, the measurement principle of which is based on infrared transmission. The O_2 concentration was measured with a Hartmann & Braun Magnos 4 G, an analyser of paramagnetic type.

More detailed chemical composition in a few tests was determined with a FTIR multicomponent analyser (GASMET). The accuracy for each component is ± 10 %.

Pressure

In a few tests, the pressure difference between the top of the fire room and ambient was measured with Setra Model 264 pressure transducers.

Mass flow rate

The mean mass flow rates at relevant openings were measured with bidirectional probes. The pressure difference over the probe was measured with Setra Model 264 pressure transducers, and the temperature in the vicinity of the probe with bare Ø0.5 mm K-type thermocouples.

Heat release rate

In a few tests, the gas samples for the O_2 and CO_2 analysers were collected from the exhaust duct, and the rate of heat released was calculated from the measured concentrations and the volume flow rate using oxygen consumption calorimetry. The flow rate was determined by measuring the pressure difference over an orifice in the exhaust duct and by applying the temperatures measured in the same positions. The measurements were made according to the standard ISO 9705:1993 *Fire tests -- Full-scale room test for surface products*.

Data acquisition

The data were recorded continuously during the tests by HP 75000 Series B data acquisition cards and a Labtech Control data acquisition system. The time resolution was 4 s.

4 EXPERIMENTAL RESULTS

4.1 TEST PROGRAMME

The present study concentrated on ventilation-controlled fires, which are the most common cases in actual operational fire fighting situations. The following issues were studied in the tests:

- natural horizontal ventilation
- PPV
- the initiation of a backdraft.

In total, 40 tests were conducted, of which the first ten were preliminary tests to define suitable structural materials and fuel packages. The actual tests are summarized in Table 2.

The repeatability of the test fire (indicated by the temperatures) was very good (see Figures 7 a - c, right-hand-side). The very first test in a series, however, was always somewhat different due to different initial conditions, e.g. the structures of the test enclosure differ in temperature and humidity from the typical values within a series of tests.

4.2 NATURAL VENTILATION

4.2.1 Basic effects of horizontal ventilation

The fire scenario for studying basic effects of horizontal ventilation was simple: the fire was ignited in the compartent, where the ventilation conditions remained constant during the test. The following cases were studied:

- Only the outdoor open, i.e. no through ventilation (ST11, ST23)
- The outdoor and the large window in the fire room open, i.e. ventilation through the fire room (ST12 and ST24)
- The outdoor and the window in the target room open, i.e. ventilation through the target room (ST38)

Figure 6 on page 17 shows the heat release rate in the first two cases: with ventilation through the fire room, more air is available than without through ventilation and the fuel burns faster.

Table 2. Test summary.

Test #	initial conditions	vent opened	PPV (m^3/min)	timing (min)
ST11	door open	-	-	-
ST12	door + large window open	-	-	-
ST13	vents closed	door	-	1
ST14	vents closed	door	-	2.5
ST15	small window open	door	-	2.5
ST16	vents closed	large window	-	2.5
		door	-	4.5
ST17	vents closed	door + large window	1	1
ST18	vents closed	door + large window	5	1
ST19	vents closed	door + small window	5	1
ST20	vents closed	door + small window	5	1
			7	2.5
ST21	vents closed	door + large window	2	1
			3	2.5
ST22	vents closed	door	-	3
ST23	door open	-	-	-
ST24	door + large window open	-	-	-
ST25	vents closed	door + large window	2	1
ST26	vents closed	door	-	3.25
ST27	vents closed	door	-	3.75
ST28	vents closed	door + large window	3	1
ST29	vents closed	door + large window	4	1
ST30	vents closed	door + large window	5	1
ST31	vents closed	door + large window	6	1
ST32	vents closed	door + large window	7	1
ST33	vents closed	door + large window	8	1
ST34	vents closed	door + large window	4	1
ST35	vents closed	door + large window	4	1
ST36	vents closed	door + ½×large window	4	1
ST37	vents closed	door + small window	4	1
ST38	door + target window open	-	-	-
ST39	target window open	door	-	2.5
ST40	vents closed	door + large window	4	1

In Figures 7 a - e the two ventilation cases are compared in more detail: the left-hand-side and the right-hand-side show the results when only the door is open and when there is ventilation through the fire room, respectively.

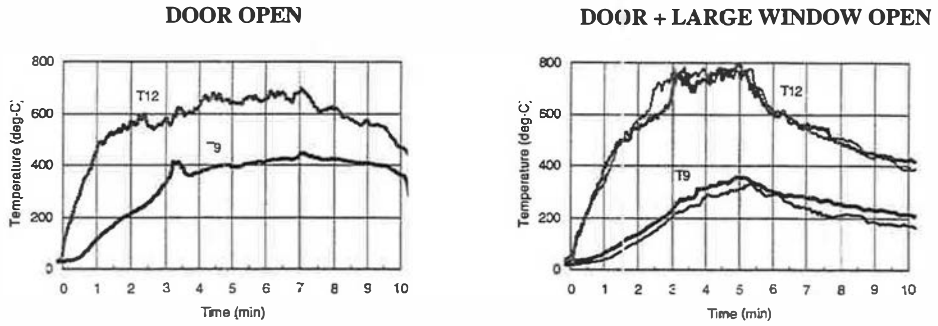
With only one ventilation opening, less oxygen is available and the burning rate is lower. All the gas exchange in and out of the fire room takes place through the same opening. In the fire room the temperatures are very high and visibility poor at levels corresponding to 1 m height full scale. Temperatures are intolerable without protective clothing almost everywhere in the compartment.

In spite of the accelerated burning rate and higher temperatures at the ceiling level of the fire room, natural ventilation through the fire room improves the conditions everywhere else in the compartment, including the operational levels of the fire room. However, with through ventilation, the flames grow longer and may extend through a doorway into a neighbouring room, which has to be taken into account when entering the building.

Photographs of the two basic ventilation cases are shown in Figures 8 and 9.

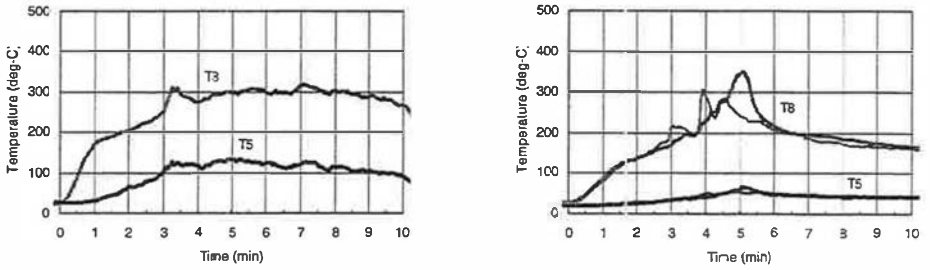
What happens if the natural ventilation is not through the fire room? Figures 10 a - e clarify the situation: ventilation through the fire room and through the target room are compared. If the natural ventilation is not through the fire room, the conditions everywhere in the compartment deteriorate: the temperatures rise and the visibility becomes poorer. Also, compared to the case where only the outdoor is open, the conditions worsen everywhere else except for the entrance room where they are similar in both cases. Hot gases are flowing out both through the door and window in a way similar to that through the door in the case where only the door is open (see Figure 7 e, left-hand-side).

In summary: natural horizontal ventilation improves the conditions in the compartment as compared to the case where only one vent is open – provided that the gas flow is directed through the fire room.



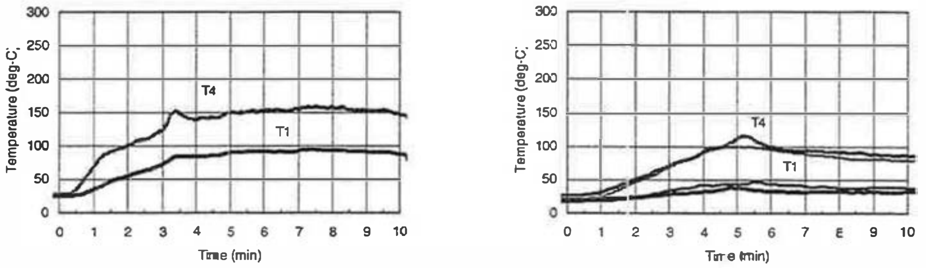
a) Fire room temperatures

With through ventilation, more air is available and the fuel burns faster resulting in a higher heat release rate and higher temperatures at the ceiling level. At lower levels, however, the temperatures are lower because of the more efficient gas exchange.



b) Entrance room temperatures

With through ventilation, hot gases are not retained in the entrance room, only during the fully developed state of the fire, flames enter the entrance room and raise the ceiling temperatures momentarily.



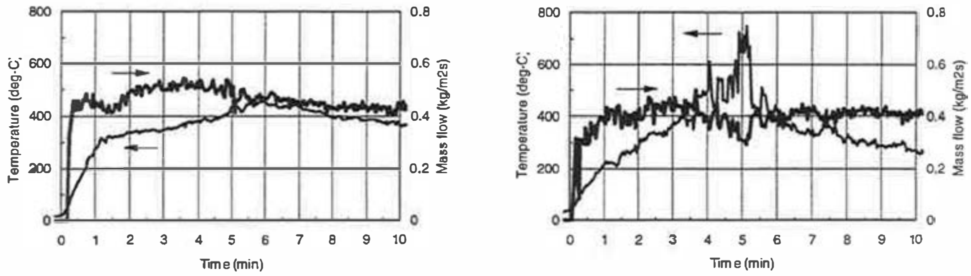
c) Target room temperatures

With through ventilation, hot gases do not accumulate in the target room, and the room is cooler.

Figure 7. Comparing two basic cases of natural ventilation:(1) no through ventilation (left) and (2) ventilation through the fire room (right).

Upper curves: close to the ceiling, at 0.55 m
Lower curves: close to midheight, at 0.25 m

DOOR OPEN **DOOR + LARGE WINDOW OPEN**

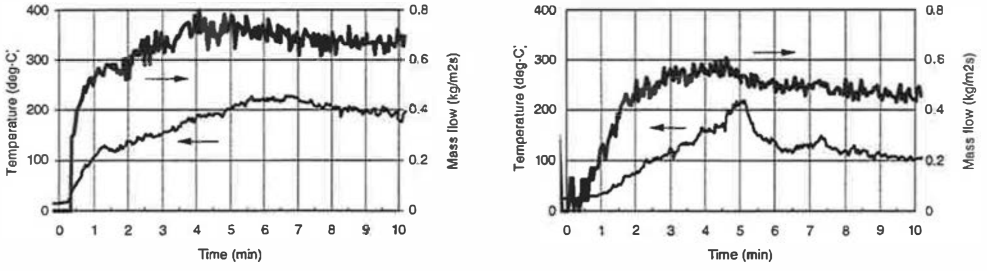


d) Mass flow and gas temperature at the top of the door between the fire room and the entrance room.

When only the door is open, all the mass transport takes place via the door. The overall smoke production rate, however, is lower and the net effect is that the mass flow rate is only slightly higher in the door-open-case.

The gas temperature at the door stabilizes at around 400°C when there is no through ventilation. With through ventilation, the temperatures are lower except in the fully developed state of fire, when the flames enter the entrance room.

The corresponding mass flow close to the floor level shows huge fluctuations, the maximum average value being around 0.5 kg/m²s (door open) and 0.7 kg/m²s (door + large window open). In both cases the temperatures at the floor level remain under 150 °C.

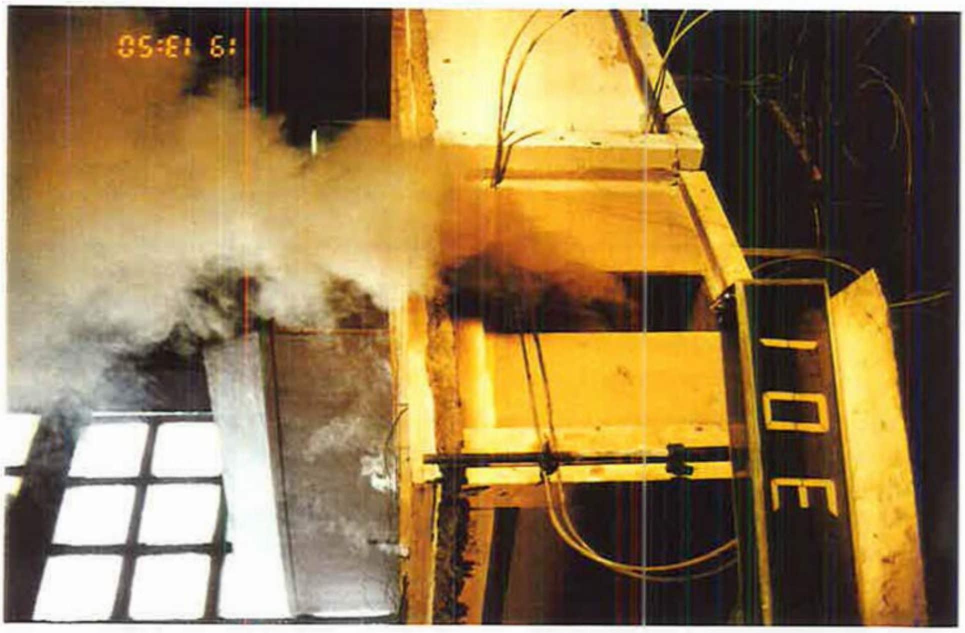


e) Mass flow and gas temperature at the top of the outdoor.

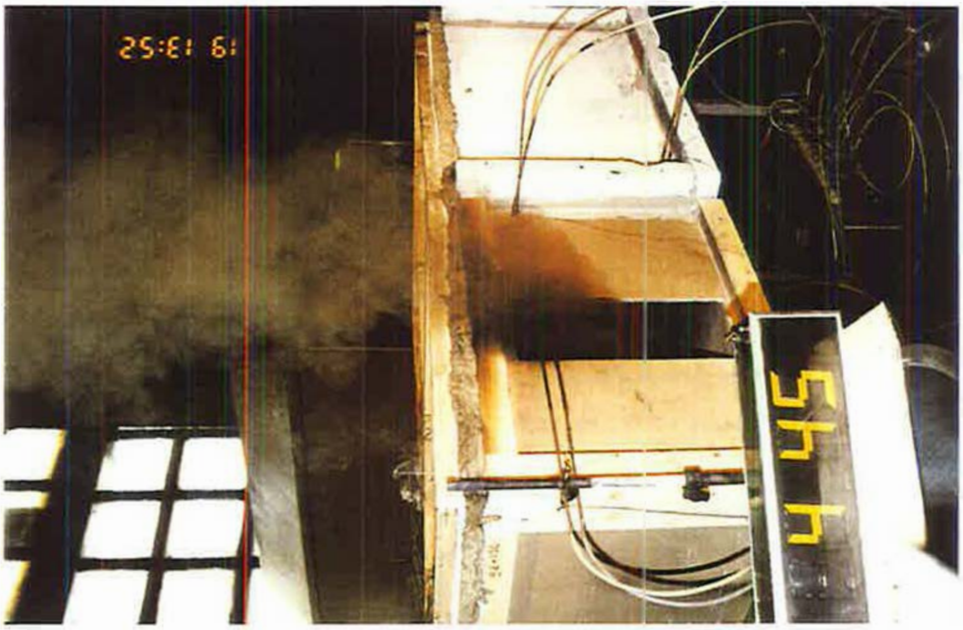
With through ventilation, part of the gases exits through the window, and the flow rate at the door is lower. Hot gases are not retained in the entrance room and the temperatures rise more slowly, only in the fully developed state of the fire do flames enter the entrance room and raise the temperatures momentarily.

Figure 7 (cont'd). Comparing two basic cases of natural ventilation: (1) no through ventilation (left) and (2) ventilation through the fire room (right).

***Thick curves:** mass flow, thin curves: temperature*

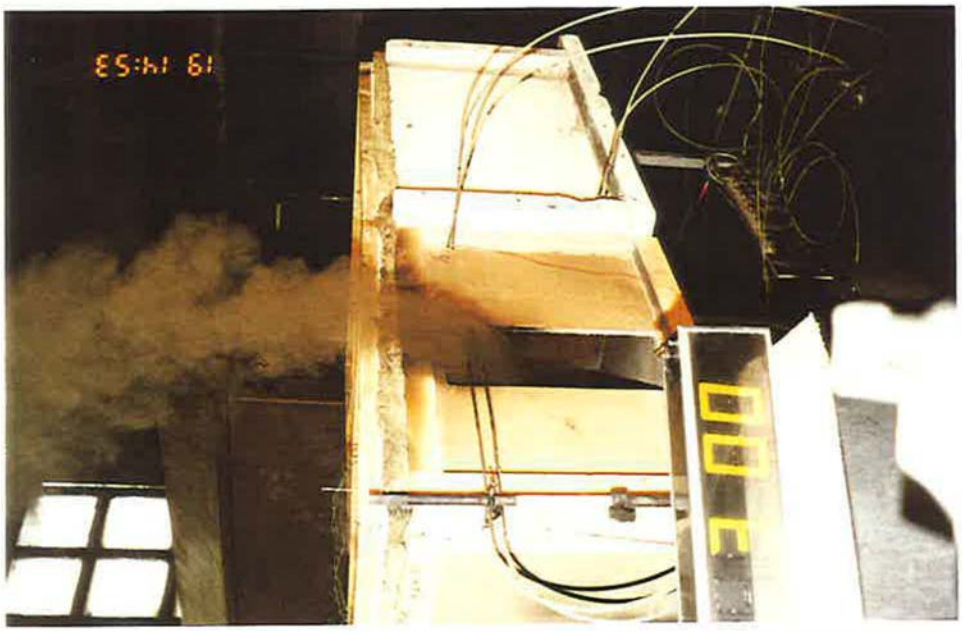


a) Heavy smoke production at 3 min.



b) Slightly reduced smoke production at 4 min 45 s.

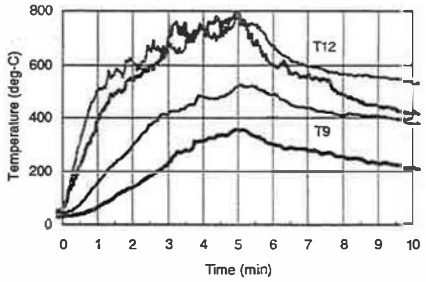
Figure 8 (← top). The door open only: relatively slow burning rate, heavy smoke production, all the smoke exits via the door, poor visibility. (ST23)



a) Heavy smoke production at 3 min, but the smoke exits via two openings.

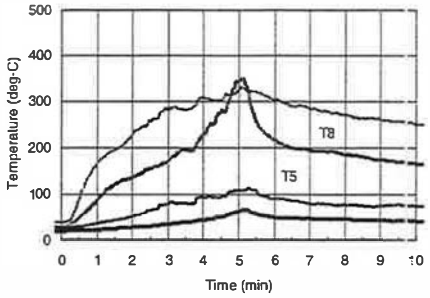
b) Momentarily the flames enter the entrance room.

Figure 9 (← top). The door and large window in the fire room open: faster burning rate, heavy smoke production but the smoke exits via two openings, improved visibility, flames may enter adjacent rooms. (ST24)



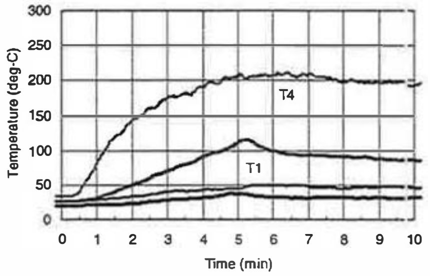
a) Fire room temperatures

With ventilation through the target room, the burning rate is about the same as with the ventilation through the fire room. The hot gas layer grows thicker and the temperatures are very high even at the midlevel without ventilation through the fire room.



b) Entrance room temperatures

Hot gases are retained more effectively in the entrance room, when the only passage out of the fire room is via the entrance room, and hence the gas temperatures are higher.



c) Target room temperatures

In the case where the hot gases exit partly via the target room, the temperatures are clearly higher at the ceiling level.

*Figure 10. Comparing two cases of through ventilation: (1) ventilation through the fire room (**thick curves**) and (2) ventilation through the target room (thin curves).*

Upper curves: close to the ceiling, at 0.55 m
Lower curves: close to midheight, at 0.25 m

4.2.2 Entering a fire compartment

When arriving at the scene of the fire, the fire fighters encounter very different circumstances. In the basic test scenario the fire was first ignited, and either all the vents were closed or a window was left open. In any case, when the fire brigade is expected to arrive, the door is closed. The following conceivable cases were studied:

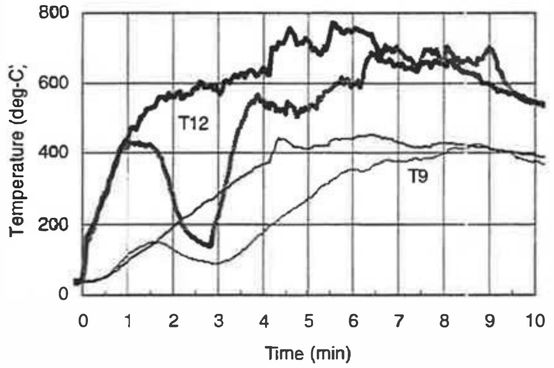
- The door is opened at an early stage of a fire, otherwise unventilated compartment (ST13).
- The door is opened at a later stage of a fire, otherwise unventilated compartment (ST14).
- The large window in the fire room is opened at a later stage of a fire, otherwise unventilated compartment (ST16).
- The door is opened at a later stage of a fire, small window open in the fire room (ST15).
- The door is opened at a later stage of a fire, small window open in the target room (ST39).

In Figures 11 a and b two cases are compared, where an *unventilated* fire compartment is entered at different times: the door is opened at 1 min and at 2.5 min after ignition. When the door is opened at 1 min, the fire is still at such an early stage that oxygen depletion does not affect the burning yet, and no effect of the opening is seen in the compartment circumstances. When the door is opened at a later stage, at 2.5 min, oxygen depletion has clearly affected the fire, but there is not yet any danger of a backdraft occurring. There is a clear effect on the compartment conditions at the instant of opening the door, but the situation soon relaxes back to the case of having the door open all the time. Similar behaviour is seen if – instead of the door – the large window is opened in the fire room.

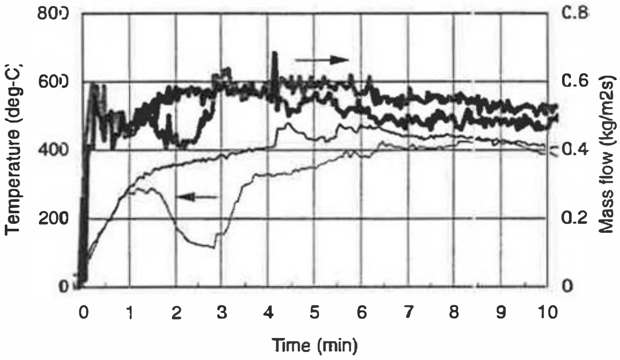
If a *ventilated* fire compartment is entered, even less dramatic effects are observed. In the case of having the small window open in the fire room, there is no observable effect on the temperatures in the compartment at the time of opening the door. If the open window is in the target room, the burning rate is affected by oxygen depletion, and opening the door is seen in the curves as in Figures 11 a and b, but in a smoother way. Thereafter, the curves approach the case where the door and target window are open all the time (see Figures 10 a - c).

Figure 12 shows the measured oxygen and CO_2 concentrations at the ceiling level in the fire room for the two cases, where (1) the small window is open in the fire room and (2) the window in the target room is open, and the door is opened at 2.5 min.

In summary, if the compartment is ventilated during the fire, no dramatic effects are caused by opening an additional door and entering the compartment. If the compartment is unventilated but there is no danger of a backdraft occurring, opening the door does affect the fire conditions momentarily, but the situation soon relaxes. Nothing dramatic is seen in the latter case either.



a) Fire room temperatures
***Thick curves:** close to the ceiling, at 0.55 m*
Thin curves: close to midheight, at 0.25 m

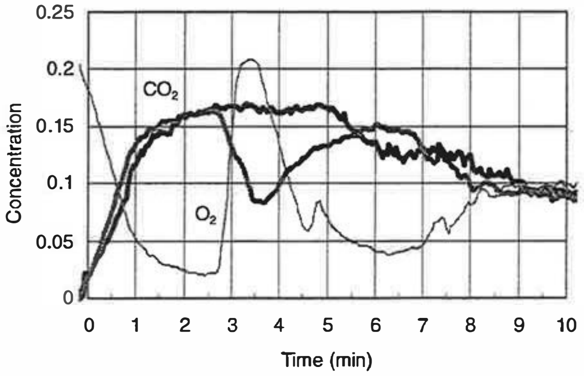


*b) Mass flow (**thick curves**) and gas temperature (thin curves) at the top of the fire room door.*

When the door is opened at 1 min, no effect of the opening is seen in the compartment circumstances. All the temperatures and flow rates behave as in the case where the door is open all the time (see Figures 7 a - e, left-hand-side).
When the door is opened at a later stage, at 2.5 min there is not yet any danger of a backdraft occurring, but the curves show a clear transition at the instant of opening the door. The curves soon approach the case of having the door open all the time.

Figure 11. Effects of timing in opening a door to an unventilated fire compartment: (1) at an early stage, and (2) at a later stage.

***Grey curves:** door opened at 2.5 min.*
***Black curves:** door opened at 1 min.*



If the window is open in the fire room, opening the door does not mix the gases in any significant way, whereas in the case of having the target room window open, opening the door abruptly provides more oxygen to the "starving" fire and initiates strong gas flows and mixing in the fire room.

*Figure 12. Gas concentrations in the fire room close to the ceiling when entering a ventilated fire compartment. The door is opened at 2.5 min and either the target room window (**grey curves**) or the small window in the fire room (**black curve**) is open. The two **thick curves** show CO_2, the thin curve shows O_2 (only one curve is shown for clarity).*

4.3 POSITIVE PRESSURE VENTILATION

The fan applied in the PPV tests was a pressure blower of type ABBA HA 219. The flow rate could be adjusted up to 8.3 m^3/min. Applying the scaling rules of Chapter 3.1 gives the corresponding full-scale value of 265 m^3/min. The PPV fans typically operate in the range 200 - 600 m^3/min, but even higher rates, over 2000 m^3/min, are available.

The fan was positioned at the floor level in front of the door. The cone of air was relatively narrow so that most of the air was blown into the compartment. Due to the narrow cone, there was an area on top of the door opening that was not completely covered by the air flow – as it should be in a real application.

In all the tests a case was simulated where the fire brigade arrives at a relatively early stage of the fire (i.e. no danger of backdraft), opens the door and one window in the fire room, and starts the fan.

4.3.1 Flow rate and direction of the fan

Several tests were conducted to study the effect of the flow rate on the results. Tests ST25, and ST27-ST33 form a systematic series where all the other conditions except for the flow rate were identical. The flow rate varied between 2 m^3/min and 8 m^3/min.

In each case, after ignition, the vents were first closed. The door and the large window were opened one minute after ignition and the fan was started. The fan was directed to midway between the doors of the fire room and the target room (direction b in Figure 15).

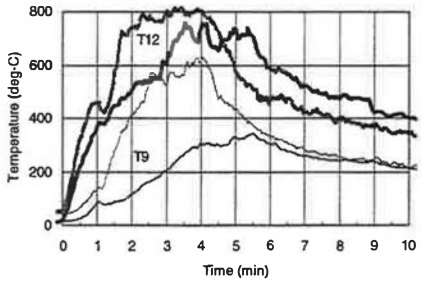
Figures 13 a - f show results for the two extreme flow rates, i.e. 2 m^3/min and 8 m^3/min. From the results, it is obvious that the lower flow rate is so low that it does not affect the conditions as compared to the corresponding natural ventilation case. The higher flow rate mixes the gases in the fire room so vigorously that almost the whole room is filled with flames. The conditions in the other parts of the compartment, however, become clearly better: the temperatures everywhere are close to the ambient temperatures and the visibility is as clear as without a fire.

An optimum flow rate would keep the conditions in the intact parts of the compartment as good as shown in Figure 13 at 8 m^3/min, but with less mixing in the fire room so that the room could be entered more safely. Figures 14 a - d show some representative results with different PPV flow rates. The results showed that the flow rate 4 m^3/min was high enough to keep the temperatures low and visibility good in those parts of the compartment that were not directly involved in the fire. In the fire room itself, the visibility was good, and the temperatures at the operational level were tolerable with protective clothing.

In summary, the PPV clearly improves the survival probability in all the parts of the fire compartment, if the flow rate is high enough: the visibility dramatically improves, and the temperatures are low everywhere else except for the fire room. On the other hand, a flow rate too high mixes the gases in the fire room so vigorously that the room may become difficult to enter. In the present case, the optimal PPV flow rate was about 4 - 6 m^3/min corresponding to 128 - 192 m^3/min full scale.

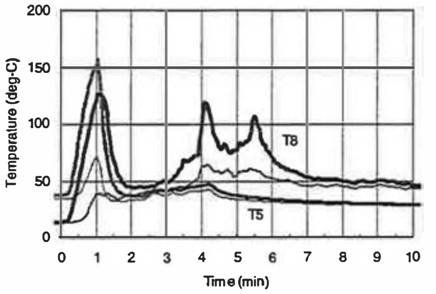
Photographs of a few principal effects of PPV are shown in Figures 16 and 17.

Similar results are obtained from tests ST17 and ST18 where PPV was initiated by pointing the fan at the main door towards the fire room door (direction c in Figure 15). Two volume flow rates were applied, i.e. 1 m^3/min and 5 m^3/min. The 1 m^3/min was such a low flow rate that conditions remained the same as with natural ventilation only. The flow rate 5 m^3/min was already high enough to have a significant effect on the circumstances in the compartment: the mixing of gas layers in the fire room was even more vigorous than with 8 m^3/min not directly pointed into the fire room, and the temperatures are the same everywhere in the fire room above the 0.25 m level. For two minutes, the overall temperature is as high as 700 °C. In the entrance and target rooms, the visibility and temperature conditions are good.



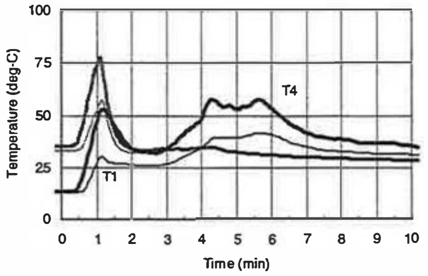
a) Fire room temperatures.

The lower flow rate does not affect the temperatures as compared to the naturally ventilated burning (see Figure 7 a, right-hand-side). The higher flow rate accelerates the burning rate as well as mixes the gases and flames in the fire room so that no clear smoke layers and/or temperature gradients are formed in the room: temperatures everywhere are high.



b) Entrance room temperatures.

Both the low and the high flow rate clearly lower the temperatures in the entrance room as compared to those with natural ventilation only (see Figure 7 b, right-hand-side). The low flow rate, however, is not quite enough to push the flames away from the room.

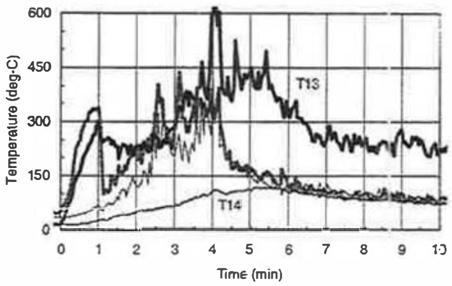


c) Target room temperatures.

Both the low and the high flow rate clearly lower the temperatures in the entrance room as compared to those with natural ventilation only (see Figure 7 c, right-hand-side).

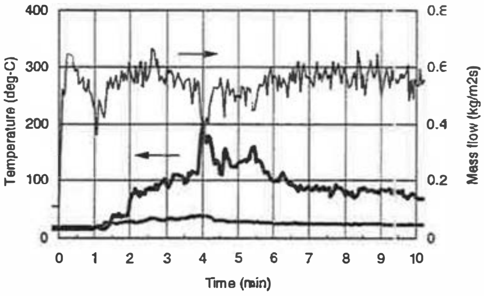
Figure 13. Comparing different PPV flow rates.

*Grey **curves**: 8 m^3/min, **black curves**: 2 m^3/min*
***Thick curves:** close to the ceiling, at 0.55 m*
Thin curves: close to midheight, at 0.25 m



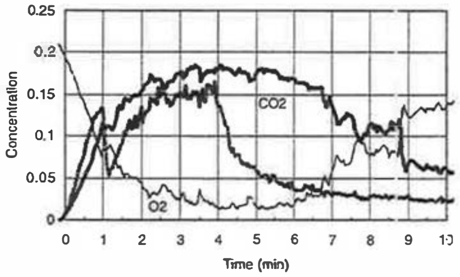
*d) Temperatures at the doorway between the fire room and the entrance room at the top (**thick curves**) and bottom levels (thin curves).*

The lower flow rate does not affect the temperatures as compared to the naturally ventilated fire (see Figure 7 d, right-hand-side). The mixing of gases in the fire room by the higher flow rate is seen as a homogeneous temperature distribution at the door.



*e) Mass flow (thin curve) and temperature (**thick curves**) at the top of the outdoor.*

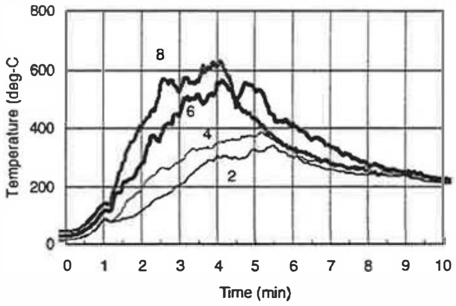
The lower flow rate just barely affects the mass flow and temperatures at the top of the outdoor (see Figure 7 e, right-hand-side). The higher flow rate naturally affects the mass flow which becomes in fact so turbulent that it is not shown in the figure. The temperatures remain very low.



f) Gas concentrations in the fire room close to the ceiling.
***Thick curves:** CO_2, thin curve: O_2 (only one curve is shown for clarity).*

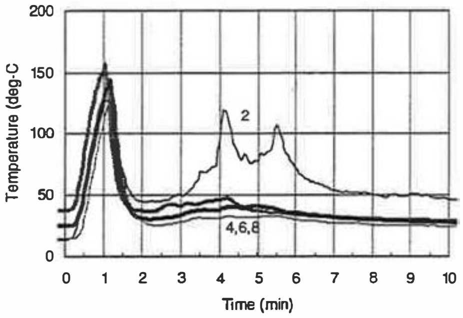
The lower flow rate does not affect the gas concentrations. The higher flow rate lowers the CO_2 concentration, and when the burning rate starts to decline, the room clears up quickly.

Figure 13 (cont'd). Comparing different PPV flow rates.
*Grey curves: 8 m^3/min, **black curves**: 2 m^3/min*



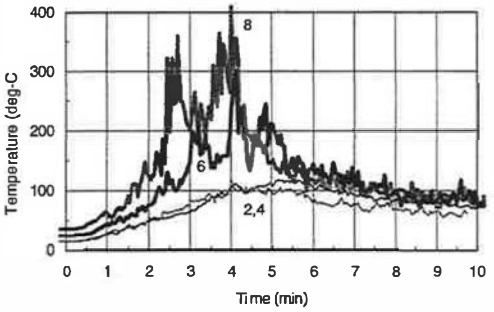
a) Fire room temperatures close to midheight (T9).

Gas mixing is strong at 6 - 8 m^3/min, clear temperature gradients are seen at lower flow rates as indicated by the clearly lower temperatures at 2 - 4 m^3/min.



b) Entrance room temperatures at the topmost level (T8).

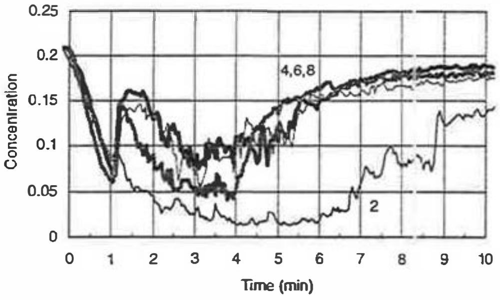
The temperatures approach ambient temperatures at any flow rate higher than or equal to 4 m^3/min. Similar situation is observed in the target room.



c) Temperatures at the doorway between the fire room and the entrance room at the bottom level (T14).

Gas mixing is strong at 6 - 8 m^3/min, clear temperature gradients form at lower flow rates as indicated by the clearly lower temperatures. At the outdoor, the temperatures at the top level approached the ambient temperatures at flow rates higher than or equal to 4 m^3/min.

Figure 14. Comparing different PPV flow rates: 2, 4, 6, and 8 m^3/min.



d) Oxygen concentrations in the fire room close to the ceiling.

The lower flow rate does not affect the oxygen concentrations. The higher flow rates increase the concentration, and when the burning rate starts to decline, the room clears up quickly.

Figure 14 (cont'd). Comparing different PPV flow rates: 2, 4, 6, and 8 m^3/min.

The effect of directing the fan was studied in more detail by tests ST29, ST34 and ST35, where everything else in the tests was identical except for the direction of the fan. The three directions are shown in Figure 15, the flow rate was 4 m^3/min. The most relevant results are shown in Figures 18 a - e.

In summary, the best overall conditions in the fire compartment are achieved when the air flow is directed so as to pressurize the room next to the fire room, and the exit opening is in the fire room. The pressurization is achieved by directing the fan at the main door so that the air is not blown directly towards the room with the exit opening. Pressurizing primarily the fire room results in vigorous turbulent flow conditions in the fire room and may cause difficulties in entering the room.

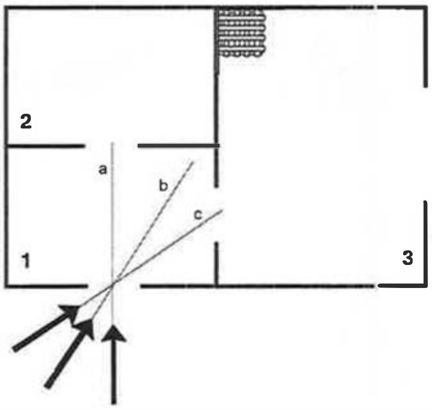
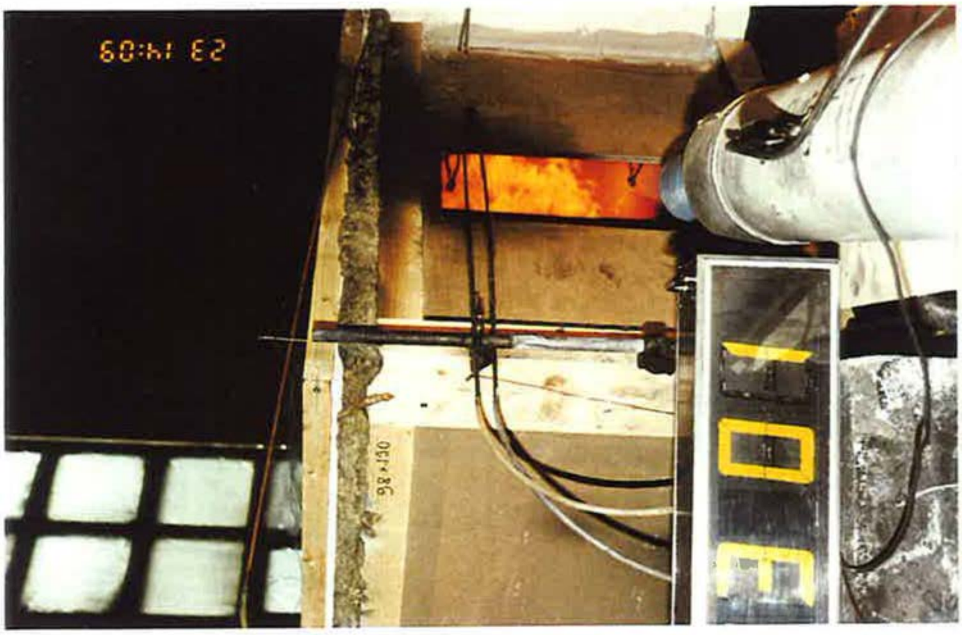
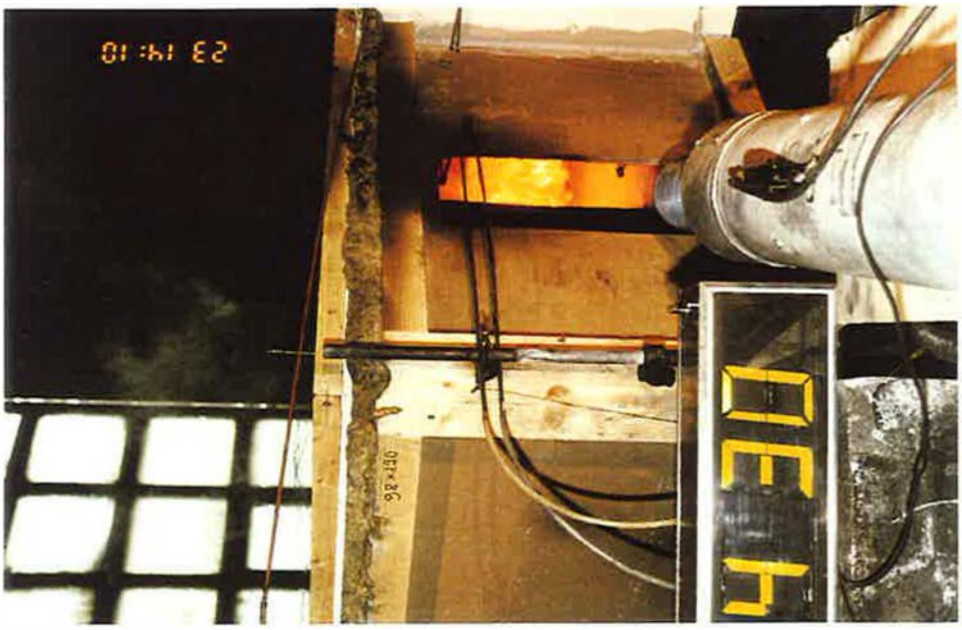


Figure 15. The three different directions of the fan.



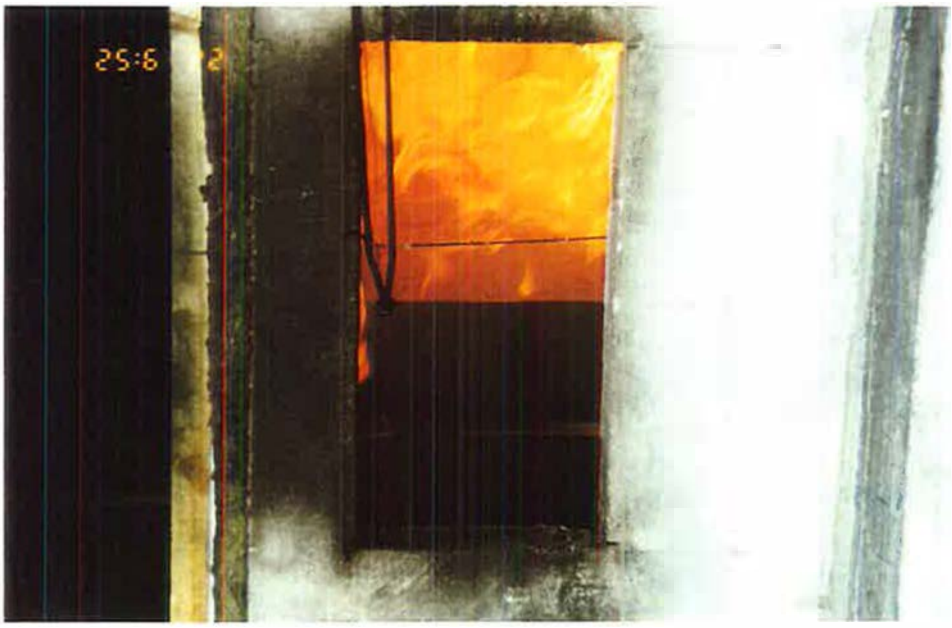
a) Hardly any smoke production at 3 min.



b) Situation remains the same throughout the intense phase of burning.

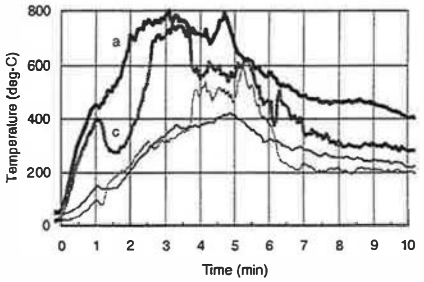
Figure 16. (← top). The door and large window in the fire room open + PPV: hardly any smoke accumulation, perfect visibility, flames fill the fire room in a turbulent fashion (Compare with Figures 8 and 9). (ST40)

a) With natural through ventilation a flashover stage is reached in the fire room: the flames cover the whole room and momentarily also enter the entrance room. Hot gas layer forms in the fire room. (ST24)



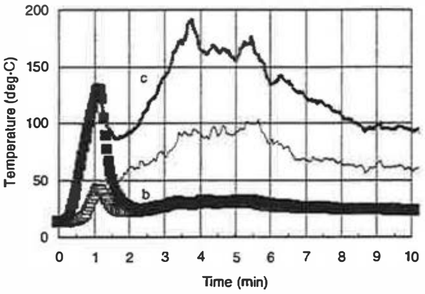
b) With PPV the gas layers and flames are mixed in the fire room. The flames are pushed away from the entrance door opening. (ST34)

Figure 17 (← top). Comparing the fire room conditions under natural through ventilation and PPV conditions.



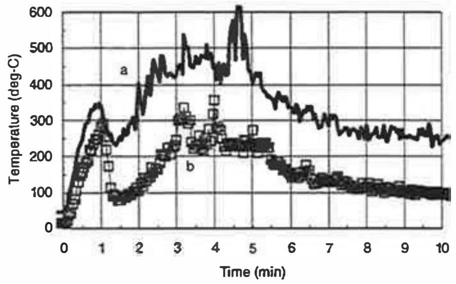
a) Fire room temperatures.
Thick curves - close to the ceiling (T12), thin curves - close to midheight (T9)
(Direction b close to direction a)

The fan pointing directly into the fire room (c) causes vigorous mixing of the flames.



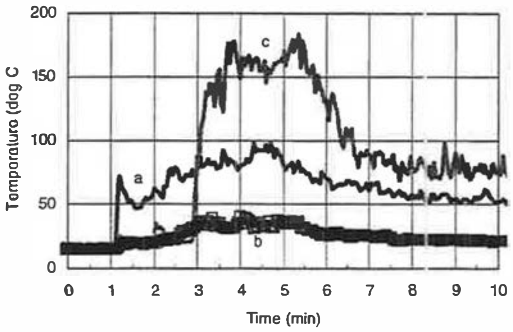
b) Entrance room temperatures.
Thick grey curve and filled squares - close to the ceiling (T8),
thin grey curve and empty squares - close to midheight (T5)
(Direction a between directions b and c)

Blowing air directly into the fire room (c) causes a vigorous turbulent movement of the flames and gases in the fire room, and hot gases partly enter the entrance room, too. Direction b is the best one in preventing the hot gases from entering the entrance room. The same trends are seen also in the target room, but there the temperatures remain under 50 °C in each case.



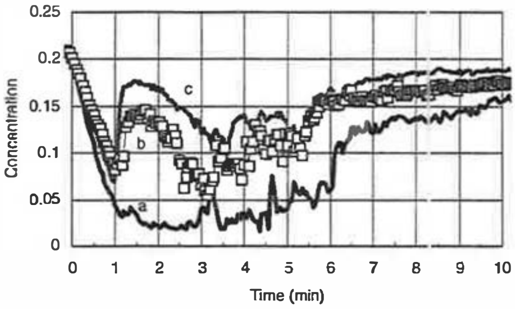
c) Temperatures at the top of the fire room and the entrance room doorway (T13).
(Direction c close to direction a.)

Figure 18. Comparing different directions of the PPV fan.



d) Temperatures at the top of the outdoor.

(In direction c the sensor was positioned at the door only at around 3 min.) Since the cone of the fan does not cover the total door area, hot gases from the entrance room escape also from the main door. The situation is worst with direction c.



e) Oxygen concentrations in the fire room close to the ceiling.

Blowing air through the target room (a) does not mix the gases in the fire room; mixing is strongest when the air flow takes place via the fire room.

Figure 18 (cont'd). Comparing different directions of the PPV fan.

4.3.2 Size and location of the exit opening

Three tests were conducted to study the effect of the size and location of the exit opening. The opening was always in the fire room, which is the case worth studying as indicated by the natural ventilation and PPV tests presented above. In each test, the door was opened at 1 min after ignition. The window was opened and the fan (4 m^3/min) started immediately afterwards. The fan was directed towards the righthand corner of the entrance room, i.e. direction b in Figure 15.

The following exit opening cases were studied:

- the large window open (ST29, exit opening area 1.25 times the inlet opening area)

- half of the large window open (ST36, exit opening area 0.625 times the inlet opening area)
- the small window open (ST37)

Cutting the size of the exit window to half barely affected the results: only the hot gas layer was thinner in the fire room with the larger window, and hence also the temperatures at the midlevel were lower. Otherwise, no significant differences were observed.

In the present case, the location of the opening was not critical either: when the opening was closer to the fire, hot gases escaped the room more easily and they did not accumulate close to the ceiling as much as in the case were the exhaust opening was further away. Hence, the temperatures at the ceiling level were lower.

In summary, slight improvements in the fire room conditions were observed with a larger exit opening, closer to the seat of the fire. The effect might be more significant in a different room geometry. It should be realized, though, that when the opening is very close to the seat of the fire, flames may extend far out of the room through the opening. The situation is shown in the photographs in Figure 19.

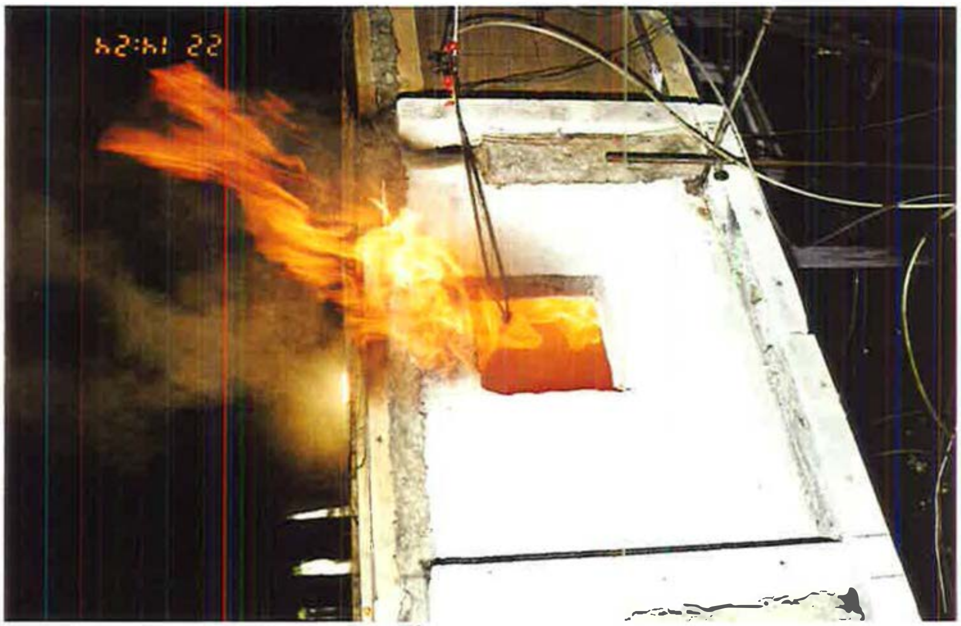
4.4 BACKDRAFT EXPERIMENTS

In a few tests (ST22, ST26. ST27) the objective was to achieve the conditions of a backdraft. The fire was first ignited, all the vents were closed, and after differing periods of time (3 min, 3 min 15 s, and 3 min 45 s) the main door was opened. Figures 20 a - c show some relevant results of the tests.

The most significant observation of all the tests is that the fuel load as applied in the tests did not generate a sufficient amount of pyrolysis products for a real backdraft to occur. (If all the vents had been originally open to reach a high pyrolyzation rate and high temperatures, closing the vents and opening them again at a later stage would probably have generated a real backdraft. Within the limitations of the present project, the issue was not studied any further.)

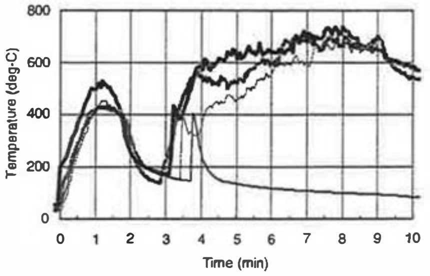
In two tests a "mild" backdraft was observed, i.e. in the tests where the door was opened at 3 min and 3 min 15 s: after opening the door, there was first a 10 s delay when fresh air entered the fire room. Since the fire load was still smouldering, it acted as an ignition source and ignited the fuel-air mixture, which was seen as flashing flames momentarily reaching out of the fire room. No "fire ball" was observed, though, as descibed in Refs. 7 and 8. When the door was opened at 3 min 45 s, the room cooled down so much that the smouldering fuel could only ignite the propane that had been accumulating in the room. The propane burned out instantaneously but was not enough to ignite the extinguished fuel load in the corner.

a) With the ventilation opening futher away from the seat of the fire the flames extend outside as random, thin flames – if any. (ST36)

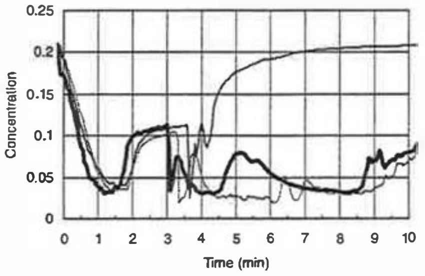


b) With the opening close to the seat of the fire, flames may extend far out of the room. (ST37)

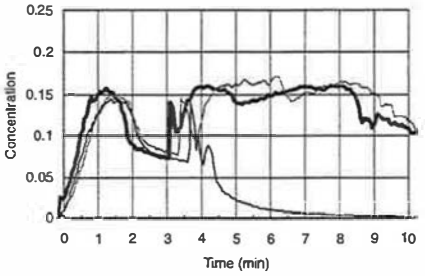
Figure 19 (← top). Comparing two locations of the exit opening.



a) Fire room temperatures close to the ceiling (T12).



b) Oxygen concentration close to the ceiling level in the fire room.



c) CO_2 concentration close to the ceiling level in the fire room.

In each case the fire first evolves freely until (at ~1 min) oxygen depletion starts to restrict the burning rate, and temperatures go down. The door is opened at different times:

- *At 2 min 30 s (**grey thick curve**, no gas measurements): the burning rate gradually increases and temperatures start to rise smoothly some 20 s after opening the door.*
- *At 3 min (**black thick curve**): 11 s after opening the door a thin flame at the ceiling level is seen to flash into the entrance room. The flame disappears abruptly and the situation soon relaxes to normal.*
- *At 3 min 15 s (grey thin curve): 12 s after opening the door a thin flame at the ceiling level is seen to flash into the entrance room. The flame disappears abruptly and the situation gradually relaxes to normal.*
- *At 3 min 45 s (black thin curve): immediately after opening the door, a flame at the ceiling level is seen to flash into the entrance room and even outside. The flame disappears abruptly and the fire has been extinguished.*

Figure 20. Results of the backdraft experiments.

Figure 21 shows the methane and propane concentrations (the primary hydrocarbons in the tests) in two tests measured close to the ceiling level. When the door was opened at 1 min, i.e. at a time when no oxygen depletion was affecting the burning yet, all the propane was burning and hence is not seen in the analysis. Methane concentration, on the other hand, is increasing at the ceiling level and is consumed only when the hot layer is mixed so that the methane comes into contact with oxygen. When the door is opened at 2.5 min, propane has started to accumulate in the room due to lack of oxygen. When it is able to burn again, it is not seen in the gas analysis any more, but instead, a lot of methane is formed in the upper gas layer.

For a real backdraft to occur, a lot more hydrocarbons would have been required: over 10 % is needed according to Refs. 7 and 8.

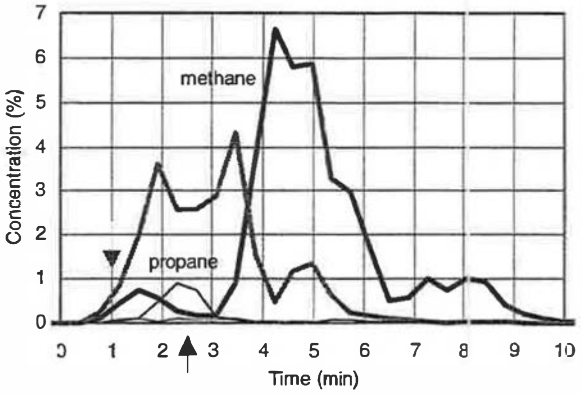


*Figure 21. Hydrocarbon concentrations close to the ceiling in the fire room. The arrows show the time of opening the door, i.e at 1 min (grey curves) and at 2.5 min (**black curves**).*
*(**Thick curves** - methane, thin curves - propane)*

In summary, the present tests confirmed the previous experience that if backdraft conditions prevail, the most dramatic moments occur only after a delay after opening a vent. Hence, whenever there is a fear that backdraft may occur, after opening any vent, the fire fighters should back out and wait for a while before entering the building.

5 COMPUTER SIMULATIONS

A few basic ventilation cases were studied by computer simulations. The difficulty in any fire simulation model at present is that they do not contain a feedback between the ventilation conditions and the heat release rate. The heat release rate typically must be given as input, and hence the effect of changing ventilation conditions should be known already prior to running the simulation. *Predicting* the fire behaviour in a compartment under varying ventilation conditions is highly unreliable if the heat release rate is known only for certain conditions but is applied to other conditions, too.

In the present project, the heat release rate was measured for three ventilation cases (see Figures 5 and 6). These rates were applied in the simulations to give a qualitative idea of what the simulations are capable of.

Simulations were carried out using the zone model code BRI2 (Version July 1992), that applies the Japanese Building Institute's multi-room, multi-floor zone fire model /13, 14/. In zone models, a compartment is divided into two horizontal layers, each of which is at the same average temperature throughout. The models are especially suitable for predictions of smoke fillings and the development of a fire room including time to flashover.

In the present simulations, the ventilation conditions were not changed during the fire. The following basic ventilation cases were simulated:

- the door is open
- the door and the large window are open
- air is blown into the compartment through the door at a rate of 6 m^3/min, with the large window open.

Based on the measured heat release rates and estimated delays in the measurements, the heat release rates and burning areas shown in Figure 22 were given as input for the three cases.

Figures 23 - 25 a - f show the relevant results of the simulations. Experimental temperature curves measured close to the ceiling and at midheight are included for comparison. When making any quantitative comparisons, however, it should be noted that the measured upper layer temperatures are the maximum values in the room, whereas the calculation gives an average temperature of the whole hot layer. Also, it should be remembered that the lower layer temperature is measured close to the midheight, which – in many cases – belongs to the hot layer in the calculations. The actual temperature close to the floor level is considerably lower than at the midheight.

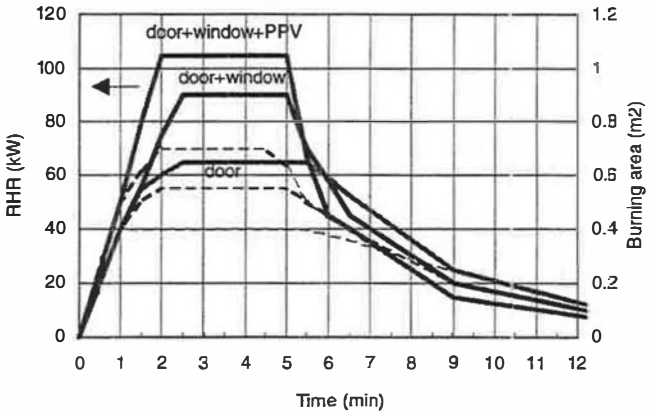
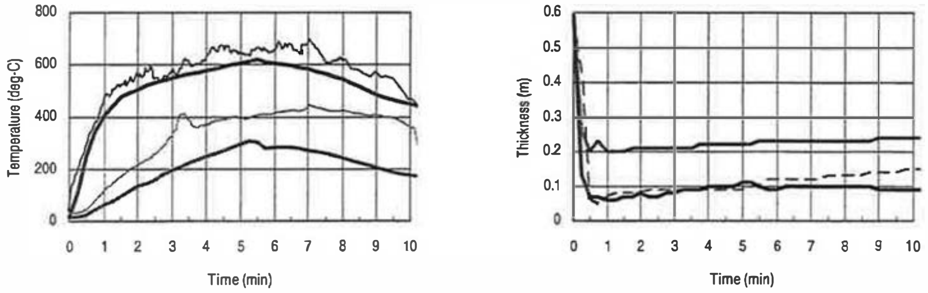


*Figure 22. The heat release rates (**thick continuous lines**) and burning areas (thin dashed lines) used as input in the simulation code.*

Even so, a few major conclusions can be drawn:

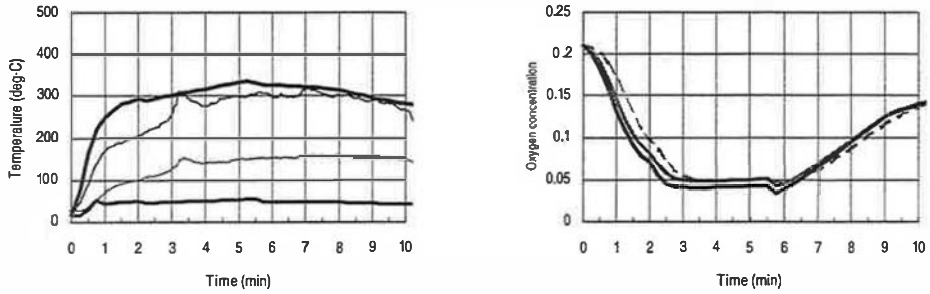
1. The two-layer model works naturally best when there is barely any mixing of the gas layers in the compartment, i.e in the door open case of the present examples. The overall agreement between experiment and theory is very good.
2. In the model, natural through ventilation affects the thicknesses of the hot and cool layers as well as the oxygen concentrations in the compartment. The net effect, however, does not bring about the experimentally observed overall cooling in the entrance and target rooms. The overall agreement between experiment and theory is still satisfactory.
3. PPV causes vigorous turbulent mixing in the compartment and no visible gas layers are formed. In this case the model has most difficulties: the layer thicknesses and oxygen concentrations in the compartment are adjusted by the model from those of the natural ventilation case, but the upper layer temperatures remain high - in contrast to the experimentally observed, dramatic cooling.

In summary, zone models are best in situations where no vigorous turbulent mixing of the gas layers is expected. No model, however, can be applied in truly *predicting* the effects of varying ventilation conditions. Due to these limitations, the available models are not suitable for PPV applications but can be used in many natural ventilation cases – provided that proper input data are available.



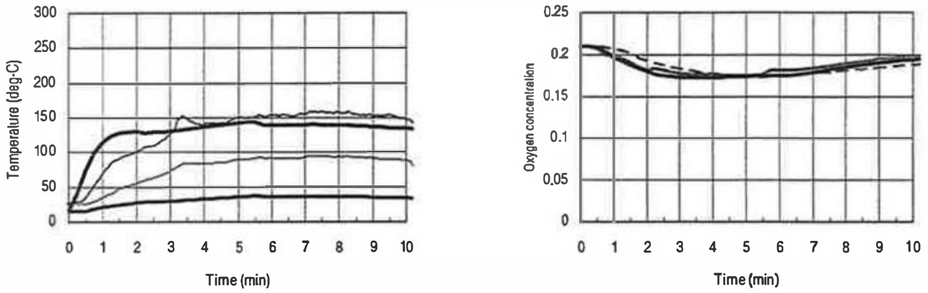
a) Upper and lower layer temperatures in the fire room.

d) Lower layer thickness in the compartment.



b) Upper and lower layer temperatures in the entrance room.

e) Oxygen concentration in the upper layer in the three rooms of the compartment

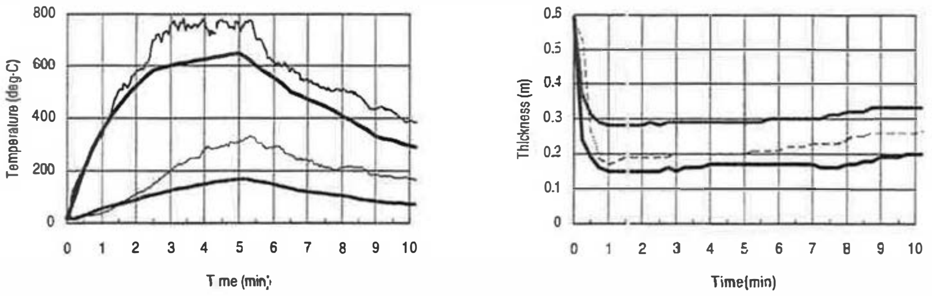


c) Upper and lower layer temperatures in the target room.

f) Oxygen concentration in the lower layer in the three rooms of the compartment

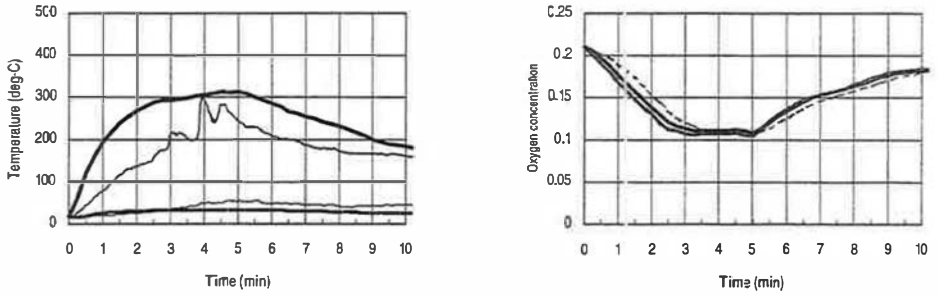
Figure 23. Simulation results for the case with the door open. Experimental temperatures are included for comparison (thin curves in a) - c), for making quantitative comparisons, see text). The overall agreement between experiments and calculations is very good.

***Grey curves** in d) - f): entrance room (solid line), target room (dashed line)*
***Black curves** in d) - f): fire room*



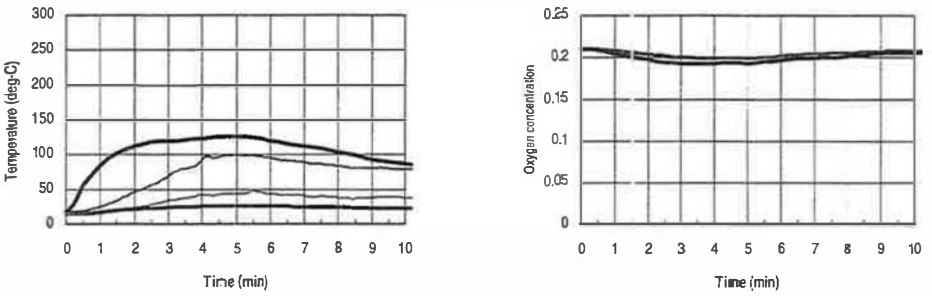
a) Upper and lower layer temperatures in the fire room.

d) Lower layer thickness in the compartment.



b) Upper and lower layer temperatures in the entrance room.

e) Oxygen concentration in the upper layer in the three rooms of the compartment

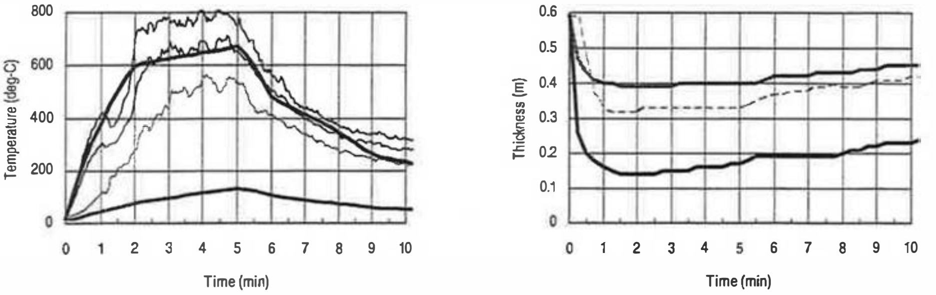


c) Upper and lower layer temperatures in the target room.

f) Oxygen concentration in the lower layer in the three rooms of the compartment

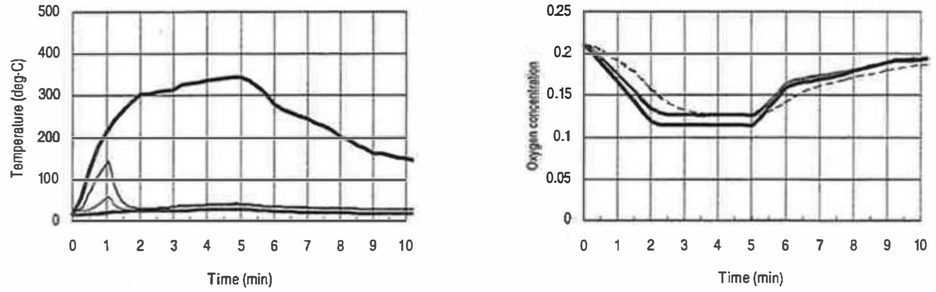
Figure 24. Simulation results for the case with the door and large windows open. Experimental temperatures are included for comparison (thin curves in a) - c), for making quantitative comparisons, see text). The through-flow is seen rather in a thinner hot layer and higher oxygen concentrations than in overall cooling of the entrance and target rooms as was experimentally measured.

***Grey curves** in d) - f): entrance room (solid line), target room (dashed line)*
***Black curves** in d) - f): fire room*



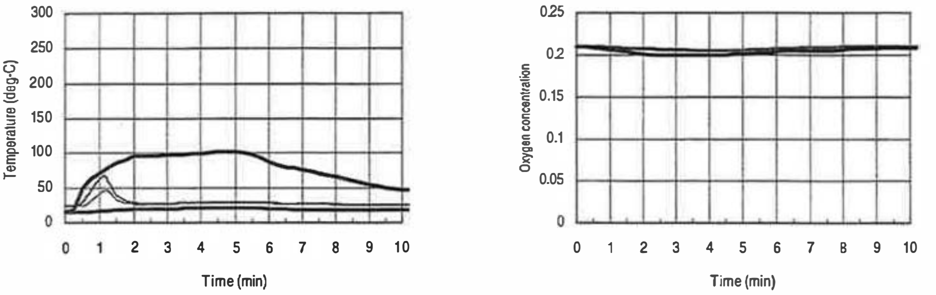
a) Upper and lower layer temperatures in the fire room.

d) Lower layer thickness in the compartment.



b) Upper and lower layer temperatures in the entrance room.

e) Oxygen concentration in the upper layer in the three rooms of the compartment



c) Upper and lower layer temperatures in the target room.

f) Oxygen concentration in the lower layer in the three rooms of the compartment

Figure 25. Simulation results for the case with the door and large window open + PPV 6m^3/min. Experimental temperatures are included for comparison (thin curves in a) - c), in the tests venting was started at 1 min, for making quantitative comparisons, see text.) The PPV is seen rather in a thinner hot layer than in overall cooling of the entrance and target rooms as was experimentally measured.

***Grey curves** in d) - f): entrance room (solid line), target room (dashed line)*

***Black curves** in d) - f): fire room*

6 DISCUSSION

There are five principal ventilation techniques applied in fire fighting, i.e.

1. Natural vertical ventilation
2. Natural horizontal ventilation
3. Positive pressure ventilation (PPV)
4. Negative pressure ventilation (NPV)
5. Water spray assisted ventilation

The present study concentrated on the horizontal ventilation, accomplished both naturally and with external fans (PPV). Ventilation in the pre-attack stage was specifically focussed on.

Contradictory feelings are expressed among fire fighters about horizontal ventilation as a part of active fire fighting attack: intentionally forcing fresh air into a burning building is not very popular since the fire fighters have traditionally been taught to *prevent* the access of air to the burning materials. Hence there are, on the one hand, obvious reasons for fearing the consequences of active ventilation. But on the other hand, overwhelmingly praising statements of the benefits of the method have been expressed first in Finland as early as in the 40's and – after a 50-year delay – in the US, where the method is becoming a common practice for many fire brigades.

There seems to be a clear trend: those ones in favour of forced ventilation have experience of it, and the ones against it have not seen it working in practice (or have applied it wrongly). The categorically negative attitude, however, seems to be changing rather to curiosity, which is one of the reasons the present study was initiated in the first place. *The objective of the study was to provide systematic and neutral information on smoke ventilation as a part of active fire fighting procedures.*

Smoke ventilation was studied experimentally in a single-storey, three-room laboratory-scale (1:4) test compartment. In total, 40 fire tests with varying horizontal ventilation conditions were conducted. Due to the limitations of the available computational simulation codes, zone models were found to be unsuitable for studying the present PPV applications. (Field models might provide a suitable research tool for the purpose, but being so time-consuming and hence expensive they were outside the scope of this project.)

After the first tests with PPV, the qualitative impression of its effects was negative: it is true that feeding fresh air into the fire accelerates the burning rate, and vigorous turbulent mixing may occur in the fire room. After a few more tests and quantitative inspection, it was realized that the conditions in the fire room always *seem* to become clearly worse because of the perfect visibility gained with PPV. The only matter that does deteriorate in the fire room is that – due to the turbulent mixing – the motion of flames is unpredictable. Yet a visible fire is easier to fight than a fire that cannot even be located. Outside the fire room, the conditions improve dramatically, i.e. the visibility becomes as good as without a fire and temperatures decrease close to the ambient temperatures.

The key issue in a successful attack is of course that the ventilation is implemented *properly*. Factors affecting the "proper" attack were studied, and the following conclusions were drawn:

- Natural horizontal ventilation improves the conditions in the compartment as compared to the case where only one vent is open – provided that the gas flow is directed through the fire room.
- PPV clearly improves the survival probability in the compartment: the visibility dramatically improves, and the temperatures are low everywhere else except for the fire room.
- The best overall conditions in the fire compartment are achieved when the air flow is directed so as to pressurize the room next to the fire room, and the exit opening is in the fire room.
- Optimal flow rate depends on the room geometry, the location of the fire etc. The flow rate has to be high enough to push the flames back to the fire room but low enough not to mix the gases so vigorously that the fire room becomes too difficult to enter. In the present case, the optimal PPV flow rate was 4 - 6 m^3/min corresponding to 128 - 192 m^3/min full scale for a compartment of about 80 m^3 total volume.
- Slight improvements in the fire room conditions were observed with a larger exit opening, closer to the seat of the fire. The effect might be more significant in a different room geometry.
- If the compartment is ventilated (e.g. open window) during the fire, no dramatic effects are caused by opening an additional door. If the compartment is unventilated (but there is no danger of a backdraft occurring), opening the door does affect the fire conditions momentarily, but the situation soon relaxes.
- If backdraft conditions prevail, the most dramatic moments occur only after a delay after opening a vent.

Based on the results above and the experience on full scale fires published in the US, the following is recommended for proper application of PPV in a pre-attack mode:

1. After opening any vent, the fire fighters should back out and wait for a while, say around 30 s, before starting the attack.
   If there is no danger of backdraft, the delay is long enough to let the conditions stabilize.
   If there is a danger of backdraft, vertical ventilation should be considered as it allows smoke and heat to rise naturally thereby eliminating the conditions for a backdraft. But if opening a vent in the ceiling is not possible, the delay is long enough to let the backdraft occur without having the fire fighters trapped inside.
2. Before initiating PPV, the location of the fire should be known.
3. Also before initiating PPV, there must be a discharge opening in the compartment.
   The closer the opening is to the seat of the fire, the better. Some consideration must be given to the outside, however: flames may extend far out of the room through the opening.
   It must be confirmed that there are no obstructions disturbing the flow between the entrance and exhaust openings.
   The opening must provide an exit wide enough for the free flow. The present study did not reveal any recommendations, but ¾ - 1¾ of the area of the inlet opening has been suggested in the literature /10/.
4. The entrance door must be pressurized so that the air blowing from the fans covers the whole opening. The objective is to pressurize the room next to the fire so as to force the flames to be contained in the fire room only.
5. If possible, PPV should be started at a lower flow rate and increased gradually to see the positive effect.
6. When the fire fighters have advanced close to the seat of the fire, it might be helpful to turn off the fan to ease entering the fire room. (This, however, was not specifically studied, and in practice it would require functional communications between the inside and outside of the building.)
7. If anything goes wrong at any stage of the attack, just turn off the fan.

PPV should not be applied if the recommendations above cannot be followed, for example if the building has too many natural ventilation openings preventing a directed and controlled flow, or in a potentially explosive situation or in a flammable atmosphere, or when people could be endangered in any way. And, as always, it is easy to write recommendations, but to implement them in practice requires efficient training!

The present study concentrated in one basic fire scenario, i.e. fire in a single-storey compartment. Other important scenarios are fires in multi-storey compartments and in high rise buildings. These two scenarios remain to be studied, and they are included in a proposed continuation to the project.

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Title

Smoke ventilation in operational fire fighting

Abstract

Ventilating a fire compartment during operational fire fighting procedures may have unpredictable consequences. In some cases the ventilation is advantageous: the hot gases are removed from the fire enclosure, the visibility improves and the enclosure cools down. In some cases the opposite happens: with the accelerated burning rate, more smoke is spread around, and the temperatures rise. The most dramatic consequence is the initiation of a backdraft, where the pyrolyzed gases ignite instantaneously, in the worst case causing a severe explosion.

The effect of ventilating the fire compartment was studied systematically by quarter scale laboratory tests. The fire was initiated in a one-storey three-room compartment subject to different horizontal ventilation conditions. Both natural and positive pressure ventilation (PPV) were applied. The tests revealed many critical factors affecting the success of the attack. When properly used, PPV clearly improves the survival probability in the compartment: the visibility dramatically improves, and the temperatures are low everywhere outside the fire room.

A fire spread zone model code (BRI2T) was applied to a few principal test scenarios. The model simulates well scenarios with no vigorous turbulent mixing of the gas layers, but predicting dependences between different parameters is tedious because the model (like all zone models) does not contain a feedback between varying ventilation conditions and the heat release rate. Due to these limitations, the available zone models are not suitable for PPV applications.

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A fire spread zone model code (BRI2T) was applied to a few principal test scenarios. The model simulates well scenarios with no vigorous turbulent mixing of the gas layers, but predicting dependences between different parameters is tedious because the model (like all zone models) does not contain a feedback between varying ventilation conditions and the heat release rate. Due to these limitations, the available zone models are not suitable for PPV applications.

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