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Positive pressure ventilation in underground systems – an experimental and modelling study

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Karel Lambert
20.04.2014

Summary/Abstract

Positive pressure ventilation (PPV) is a tactic used by the fire service. Fans are positioned at the fire ground to direct the movement of the smoke. In this work a study has been made to assess whether or not PPV fans are capable of creating a smoke-free environment in an underground system after a fire. Secondly, the study verifies whether or not ventilation can be used during extinguishment.

In tunnel research, the critical velocity is defined as the ventilation velocity which will prevent backlayering, irrespective of the size of the fire. The critical velocity has been used as a criterion of success in this work.

Over 300 FDS simulations were performed to evaluate the behaviour of the fans in different enclosures. A series of tests were carried out in a training building of the Frankfurt Fire Brigade to collect experimental data.

The main conclusion was that the tested fans have the capacity to create a smoke-free environment after a fire. In small stations/tunnels, the fans will be able to prevent or limit backlayering. This will help the fire service to deal with the fire. In bigger, more complex stations, the critical velocity is not achieved and the fans are less beneficial.

Overdrukventilatie is een tactiek die gebruikt wordt door de brandweer. Overdrukventilatoren worden gepositioneerd op de interventieplaats om de beweging van rook te beïnvloeden. In dit werk werd een studie gemaakt om te evalueren of overdrukventilatoren in staat zijn om een rookvrije omgeving te creëren na een brand in de metro. Daarnaast werd nagegaan of de ventilatie kan gebruikt worden tijdens de blussing.

In tunnel onderzoek wordt de “critical velocity” gedefinieerd als de ventilatiesnelheid die backlayering zal voorkomen, ongeacht de grootte van de brand. De critical velocity is gebruikt als performantieparameter in dit werk.

Er werden meer dan 300 FDS uitgevoerd om het gedrag van overdrukventilatoren in verschillende ruimtes te evalueren. Een reeks experimenten werd uitgevoerd in een trainingsgebouw van Brandweer Frankfurt om experimentele data te verzamelen.

De belangrijkste conclusie is dat de geteste overdrukventilatoren de capaciteit hebben om een rookvrije omgeving te creëren na een brand. In kleine stations/tunnels zullen de fans backlayering kunnen voorkomen of beperken. Dit betekent een belangrijke hulp voor de brandweer in de afhandeling van de brand. In grotere, meer complexe stations wordt de critical verlocity niet bereikt en is de meerwaarde van de ventilatoren beperkt.

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List of abbreviations

CFD	Computational fluid dynamics
CO	Carbon monoxide
FDS	Fire development simulator
FRTC	Fire Rescue Training Center (Frankfurt-am-Main)
HRR	Heat release rate
LES	Large eddy simulation
MSB	Swedish Civil Contingencies Agency
PPA	Positive pressure attack
PPV	Positive pressure ventilation
Q	Heat release rate (kW)
TIC	Thermal imaging camera

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1 Introduction & Objectives

A fire produces smoke. In an underground infrastructure such as a metro system, it will take a very long time for this smoke to disappear after a fire. This means that a fire, even a small one, may disrupt the underground system after the fire is extinguished because of the remaining smoke. As long as the concentration of airborne contaminants is too high, civilians cannot use the underground station. The (secondary) cost of such a disruption to the underground system can be very high. It is a challenge for the fire service to remove the smoke after the fire. Directing the fire through the application of tactical ventilation[1] (ventilation prior to or during extinguishment) is even more of a challenge. Traditionally, the fire service hasn't possessed the necessary means to remove smoke during the extinguishment phase in such big infrastructures. Apart from the means, the Belgian fire service doesn't have a tradition in using tactical ventilation.

A similar problem occurs with car park fires. In this instance, too, it is difficult to get rid of the smoke after the fire. The main problem is finding an outlet for the smoke and an inlet for the replacement air. Handling smoke during the fire is an even bigger challenge, just as it is in underground stations.

The French company Leader has developed positive pressure fans for use in car parks (underground structures). The idea is to put the fans at car park entrances and have them extract the smoke. The staircases of the building are then used as inlet openings. The fans are electrically powered and can be positioned in the smoke. They generate a flow of 104,000 m^3/h per fan.

In August 2012, the author had a discussion about this topic with Dr. Stefan Svensson from the Swedish Civil Contingencies Agency (MSB), now working as an associate professor at Lund University. The general idea of the discussion was to be able to use these powerful fans to remove smoke from an underground system after a fire.

The scope of this thesis is to evaluate this scenario for one of the Brussels underground stations. The first goal is to focus on ventilation after the fire. A second goal is to use the fans to prevent or limit backlayering in the event of a fire in an underground system.

This study will not cover solutions to practical problems (logistical and tactical) which will arise when the fans are used. The scope of this thesis is to check whether or not the idea is viable.

[1] Tactical ventilation is a firefighting tactic where PPV fans are used to direct the flow path of air and smoke. It can have a significant effect on the fire behaviour. When fans are used during extinguishment, the tactic is called positive pressure ventilation (PPV). When they are used prior to extinguishment, it is called positive pressure attack (PPA) [1].

2 Literature review

This thesis combines three subjects: positive pressure ventilation (PPV) by the fire service, critical velocity in tunnels, and, to a lesser degree, modelling of fans. The literature review has been divided into these three parts

2.1 Positive pressure ventilation

Positive pressure ventilation is a tactic used by the fire service in order to remove smoke, heat and other combustion products from a building during or after a fire [2]. In order to do so, portable fans are placed at inlet openings while outlet openings are created. The fans generate a flow through the building. This flow will, in turn, remove the smoke from the building (see Figure 2.1). In the past, several research projects have been undertaken to evaluate the effectiveness of PPV in different circumstances. A chronological survey is given below.

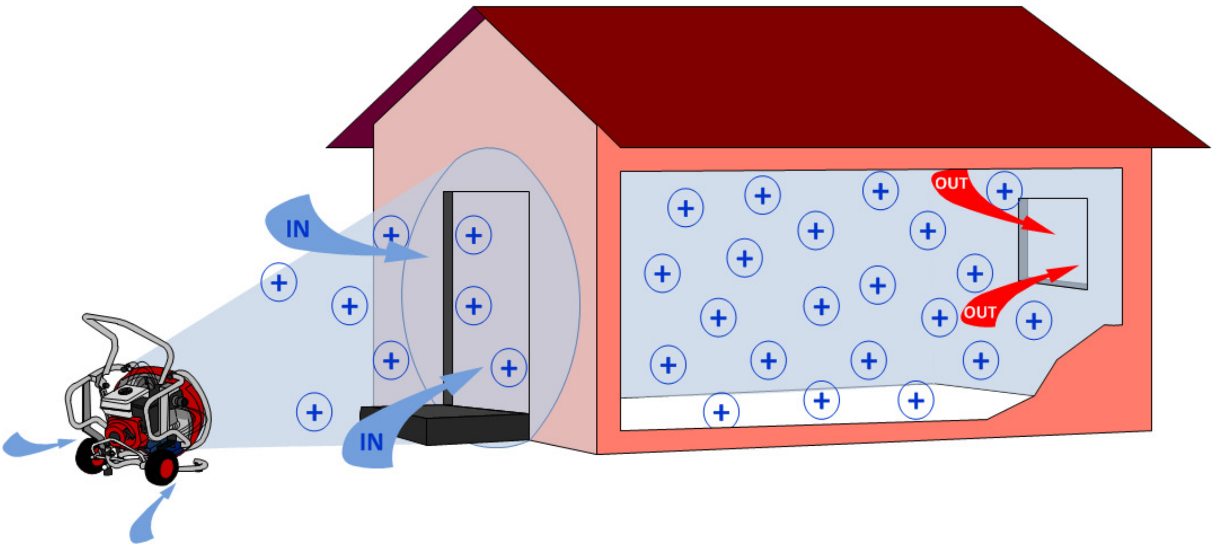

Figure 2.1 The principle of positive pressure ventilation. A fan generates a flow through the building. The smoke is removed by the generated current. Taken from Lambert [14].

Early research has been done by Ziesler *et al.* [3]. They found that temperatures and toxic gas levels are reduced, while visibility improves when PPV is applied. Tuomisaari [4] performed small-scale experiments and concluded that probability of survival increases when the flow rate is sufficiently high. Vaari and Hietaniemi [5] confirmed the findings of Ziesler *et al.,* but they also found that the HRR of the fire increases through the application of PPV. Svensson [6] found that the temperatures increased on the leeward side of the fire and decreased on the windward side. He also found that the burning rate increases through the application of PPV.

Le Corré [7] performed a study into the use of PPV fans in the Paris underground. He suggested using the escalator shafts as an outlet for the mobile ventilation system. In a previous testing programme, the usage of combustion engine driven fans has led to unacceptably high CO concentrations coming from the fan exhaust. Therefore, electric fans were used in a new series of tests.

Lougheed *et al.* [8] evaluated the use of PPV in high-rise buildings. They found that the effectiveness of a fan increases when it is placed closer to the inlet of the building. The distances tested were 2.4, 1.8, and 1.2 metres. Ezekoye *et al.* [9] looked into the effect of PPV on potential victims and found that the heat transfer to the victim can increase when PPV is applied. In a later study, Ezekoye *et al.* [10] compared natural ventilation with positive pressure ventilation and found that the latter may result in higher temperatures. Kerber *et al.* [11] confirmed a higher HRR when PPV is applied, but found slightly lower temperatures in the fire room. In a later study, Kerber *et al.* [12] considered the use of PPV in high-rise buildings and concluded that PPV is only effective up to a limited number of floors.

Ezekoye *et al.* [13] found that there is an optimum distance from the door opening for placing the fan. They also found that the effectiveness of the ventilation decreases with an increasing volume that is ventilated. Finally, they found that an increase in outlet area leads to improved effectiveness. The first finding of this work was not confirmed by Lambert *et al.* [14]. The latter found that the effectiveness increases when the distance to the door decreases as was found by Lougheed *et al.* [8]. A difference between the studies of Lougheed and Lambert on the one hand and the study by Ezekoye on the other hand is that the former evaluated multiple floors while the latter evaluated distance to the door in experiments where the inlet and outlet are on the same floor. Further conclusions of Lambert *et al.* were that two fans can be combined to generate a higher flow. The relative position of the two fans has a significant effect on the generated flow. The greatest effectiveness is achieved when two fans are positioned in a V-pattern.

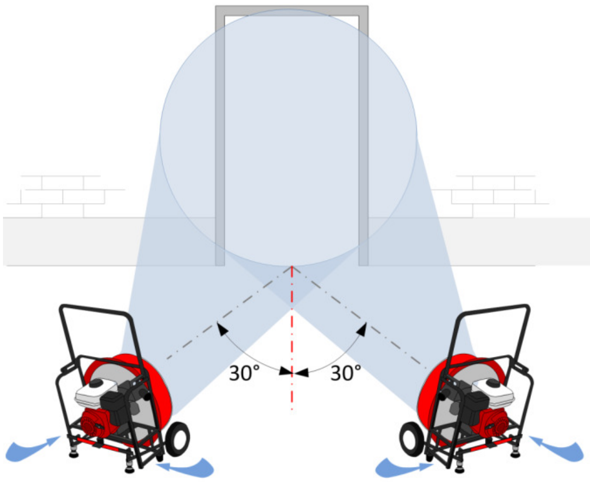

Figure 2.2 Two PPV fans positioned in a V-pattern. This combination of two fans achieves the highest flow rate when two fans are used at one inlet door. Taken from Lambert [14].

Weinschenk [15] writes in his doctoral thesis that PPV research is generally divided into two separate categories: studying the impact of flow rates through non-reacting flows and studying the impact on the thermal environment through reacting flows.

Kerber started another extensive series of experiments to study the influence of ventilation on the fire dynamics. In the first study [16], he analysed the effect of horizontal ventilation as applied by the fire service. He found that the location of an outlet opening (near the seat of the fire, or remote from it) has a significant effect on the fire dynamics. The choice between an outlet that is low or one that is high has a major influence as well. A second study [17] considered the impact of vertical ventilation. The first conclusion was that vertical ventilation should be applied in combination with interior attack. Water needs to be applied to the fire to prevent it from growing after the start of ventilation. The second conclusion was that the effectiveness of the ventilation increases if the outlet is closer to the seat of the fire. A third study to analyse the impact of PPV is being undertaken and more information is to be expected.

2.2 Critical velocity in tunnels

Ingason [18] has described stratification of smoke in tunnels (see Figure 2.3). He identifies three typical air velocity ranges:

1) Low or no forced air velocity (0-1 m/s)
2) Moderate forced air velocity (1-3 m/s)
3) High forced air velocity (> 3 m/s)

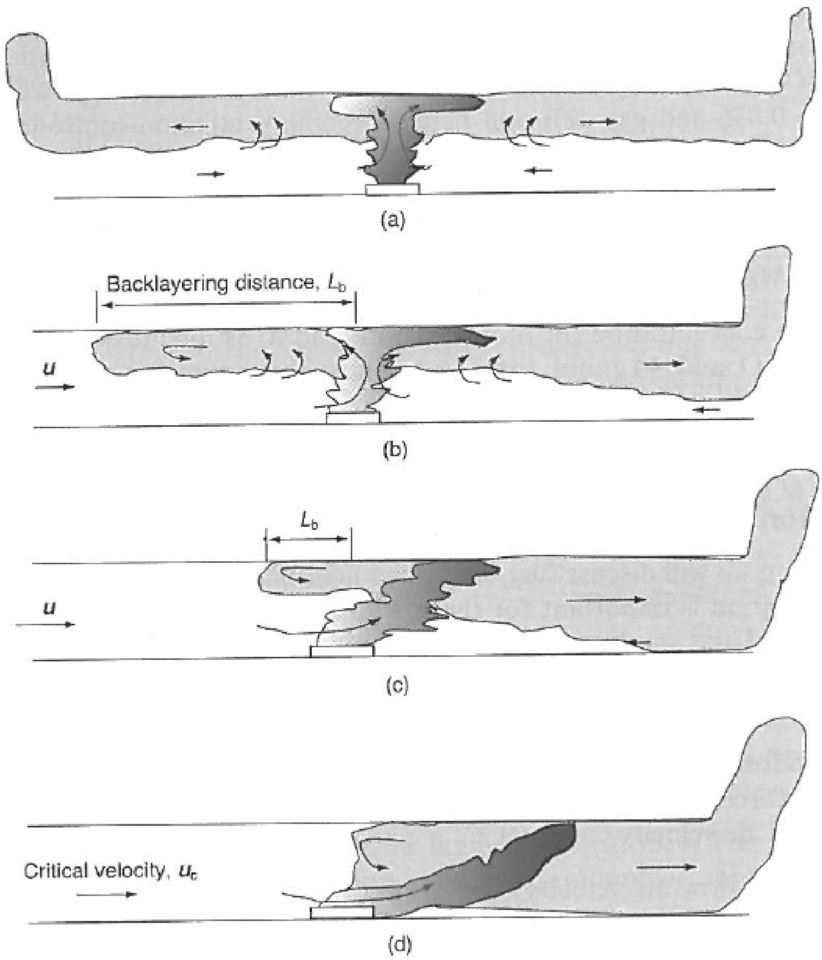

Figure 2.3 a) Smoke stratification in a tunnel with very low air velocity (0-0.3 m/s); b) smoke stratification at about u = 1 m/s; c) a typical smoke stratification for group 2; d) a typical smoke stratification for group 3; Taken from Ingason [18]

In the first velocity range, smoke can travel almost evenly in both directions (upstream and downstream) and stratification is usually high in the vicinity of the fire source. In the second velocity range, the backlayering distance is limited. It can be in the order of 17 times the height of the tunnel for a ventilation velocity of about 1 m/s. The backlayering distance will decrease when the velocity increases. Ingason mentions a correlation to estimate the backlayering distance based on the work of Thomas:

$$\frac{L_b}{H} \propto \left(\frac{g\,Q}{\rho_a c_p T_a u^3 H}\right)^{1/3}$$

where H is the tunnel height (m), Q is the HRR (kW), ρ_a is the ambient density (kg/m^3), T_a is the ambient temperature (K), u is the air velocity (m/s), g is the acceleration of gravity, and c_p is the specific heat of air at constant pressure (kJ/kg.K). The proportionality constant is found to vary between 0.6 and 2.2 following model-scale research. Ingason remarks that this is a big variation. Due to the lack of large-scale experimental date it is difficult to ascertain the validity of the proportionality constant. He suggests using the average value of 1.4 until further large-scale data is available.

The third velocity range is indicated as the range that exceeds the critical velocity. The critical velocity of the flow generated in a tunnel is the velocity at which the smoke stops travelling upstream.

Since the critical velocity is capable of preventing backlayering (see Figure 2.4), it is important for fire services. If the critical velocity is attained, it is possible to attack the fire in a smoke free environment. This reduces the risks for firefighters and increases the effectiveness of the attack. Several research projects have been undertaken because the critical velocity is such an important parameter.

Figure 2.4 Photograph of a small scale tunnel fire during the occurrence of back-layering. Taken from Colella [24] who has adapted it from Wu and Bakar [20].

Oka and Atkinson [19] found that the critical velocity was proportional to the cubic root of the heat release rate for small fires, but it becomes independent of the heat release rate for bigger fires. Wu and Bakar [20] continued this research and suggested slightly different equations to calculate the critical velocity. Li *et al* [21] showed that the critical velocity can be lower if there are any obstacles in a tunnel.

Kunsch [22] has also studied the critical velocity. His findings confirmed those of the authors mentioned above. His major conclusion was that the critical velocity converged towards a constant value for large heat release rates. He also found that the influence of the aspect ratio (W/H) was minimal, but that the tunnel height is an important factor.

More work concerning the critical velocity has been done by Tarada [23]. He found that generating velocities which are higher than the critical velocity can enhance vehicle fires and lead to loss of the smoke stratification. Colella [24] has carried out an analysis of critical velocity in his doctoral thesis. He did an extensive literature review and stated that the maximum critical velocity to be expected in any tunnel fire scenario is between 2.5 and 3 m/s. In his doctoral thesis, Colella stated that that the resulting air flow in a tunnel depends on the combination of fire-induced flows, active ventilation devices, tunnel layout, objects in the tunnel, and atmospheric conditions at the portals.

Hwang and Edwards [25] have conducted a CFD study to determine the critical velocity in two tunnels. They used a 4.9 metre tunnel to simulate experiments in a small scale test tunnel and an 853 metre tunnel to simulate experiments conducted at Memorial tunnel. They found that the critical velocity is approximately proportional to $Q^{1/3}$ for low values of Q. The critical velocity levels off for high values of Q. The second parameter which affects the value of the critical velocity is the hydraulic diameter of the tunnel. Another conclusion from their work was that the critical velocity depends on of the slope of the tunnel. A tunnel with an uphill slope requires a smaller critical velocity than a tunnel with a horizontal air flow if the longitudinal ventilation creates an upward flow.

Vaitkevicius *et al.* [26] have discussed the tendency of a fire to resist the air flow in a tunnel. This is called the throttling effect. They found that more fans are needed to achieve a constant velocity if the fire grows.

Ingason *et al*. [27] have looked into the critical ventilation concept for cross-passages. They found that the critical velocity in the cross-passage is dependent on the heat release rate of the fire, the longitudinal ventilation in the tunnel, the location of the fire, and the height of the fireproof door.

In another study, Ingason *et al.* [28] studied the influence of the ventilation on the fire. They performed tests in a 1:23 model scale tunnel with a fire load corresponding to a heavy goods vehicle. They found that the fuel mass loss rate per unit of area in a tunnel fire test is in the range of 1.4-1.55 times the value measured in a free burning test. Furthermore, they found that the fire growth rate is highly susceptible to the longitudinal velocity as well.

Atkinson *et al.* [29] have conducted further research on the critical velocity and studied tunnels with a downhill slope between 0 and 10 degrees. They found a correction factor for the critical velocity that is dependent on the slope:

$$V_\theta = V_0(1 + 0.014\,\theta)$$

where V_0 is the critical velocity in the corresponding horizontal tunnel, ϑ is the tunnel slope in degrees, and V_ϑ is the corrected critical velocity.

Vauquelin *et al.* [30] found that for high heat release rates in tunnels where the aspect ratio is smaller than the unit, the critical velocity increases with an increasing tunnel width. The critical velocity decreases with increasing tunnel width when the aspect ratio becomes larger than the unit.

Work by Tilley [31] on critical velocity has looked into the difference between tunnels and car parks. In car parks, more complex flow patterns can occur. Recirculation zones are often present. This is an important contrast to the unidirectional flow in tunnels. There are some recirculation zones in underground stations as well. A second difference between tunnels and car parks is the height-to-width aspect ratio. Some underground stations have a geometry that is similar to a car park, but others show more resemblance to a tunnel. Tilley found analytical formulas for the critical inlet velocity, the difference between inlet and outlet velocity, and the backlayering distance.

$$v_{cr,in} = 0.26\dot{q}_{conv}^{"1/4} A_F^{1/5} \qquad v_{out} - v_{in} = \frac{\dot{q}_{conv}^{"} A_F}{wh\rho_{in}c_pT_{in}} \qquad d = 40(v_{cr} - v)$$

where $v_{cr,in}$ is the critical velocity at the inlet, A_F is the fire source area, $\dot{q}_{conv}^{"}$ is the convective heat release rate per unit of area, v_{in} is the velocity at the inlet, v_{out} is the velocity at the outlet, *w* is the car park width, *h* is the car park height, ρ_{in} is the density of the entering air, c_p is the heat capacity, T_{in} is the temperature at the inlet, and *d* is the backlayering distance.

These formulae are only valid for car parks with one-directional smoke and flow patterns.

2.3 Modelling of the fans

The first models that were developed for PPV fans were simple, analytical models. Ingason *et al*. [32] have described such a model for a building with a door opening and an exhaust opening. Ingason has presented the following equation to calculate the volume flow through the exhaust air opening:

$$Q_F = \frac{2.44\,B\,Q_p}{\pi\sqrt{\varepsilon}D_0}\left(\frac{x}{\sqrt{1+x^2}}\right)$$

where *B* is the width of the supply opening, Q_p is the primary air flow from the fan, *x* is the ratio between the surface of outlet and inlet opening, $\mathcal{E}$ is the overall static pressure loss coefficient in the door, and D_0 is the diameter of the fan. This simple model implies several approximations. An important boundary condition is that the fan is placed outside the structure in front of the door opening. This is not always the case. Therefore, the applications for the analytical model are limited.

CFD calculations can be used to determine the generated currents in underground stations. A CFD package that is frequently used is the Fire Dynamics Simulator (FDS), version 5.5.3. FDS is a CFD code that uses a large eddy simulation (LES) approach [33]. In such an approach, the turbulent large scales are calculated. The effects of the small eddies on the flow are modelled. The Smagorinsky subgrid scale model is used to model the effect of the small eddies. An LES code provides an instantaneous flow field. FDS uses the low Mach number approach. A more complete description of FDS can be found in reference [33].

Early work concerning the modelling of PPV fans was done by Kerber [34]. He characterised an electrical fan with FDS (see Figure 2.5, left) and gave guidance on how to model a fan in FDS. Fans are tilted when they are used on the fire ground. In order to deal with the orthogonal grid of FDS, he placed the fan at 1.28 m above the floor. By doing so, the (horizontal) flow enters the building at the same height as a real fan that is placed in a tilted position 3 m from the door opening. Kerber used cells with a dimension of 25.4 mm. Later, Kerber [35] modelled the comparison of natural and mechanical ventilation. He found that the fire dynamics and the impact of positive pressure ventilation can be captured with an acceptable amount of accuracy.

Weinschenk [36] has studied analytical and CFD models of firefighting fans. He found that two parameters are important: the accurate characterisation of the fan and the characterisation of the leakage area. Weinschenk developed a rotational flow PPV fan model (see Figure 2.5) to enable a better characterisation of the PPV fan. He used a 40mm mesh size for this fan model.

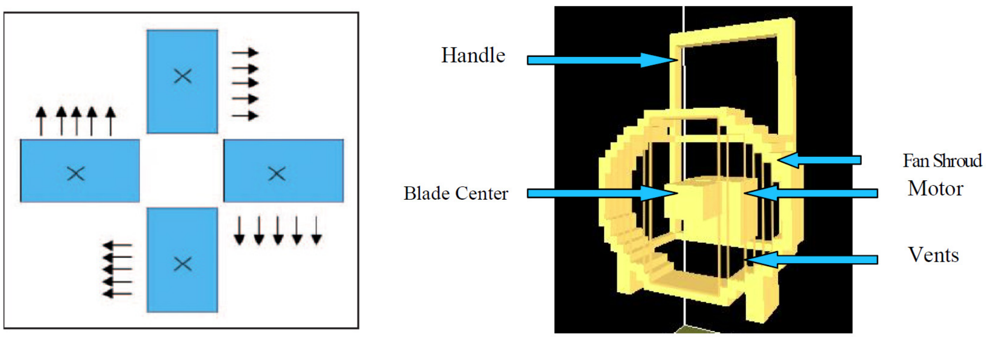

Figure 2.5 Left: Schematic of rotational flow PPV fan model. The model consists of four parts. In each part, the X indicates the normal component of the velocity and the arrows indicate the rotational component. Taken from Weinschenk [15]. Right: PPV fan model by Kerber, visualised in Smokeview. Taken from [34].

2.4 Relation between literature review and thesis

In the experimental work for this thesis, the stair shaft was used as an outlet as well, following Le Corré [7]. Since the purpose of the ventilation is to remove all smoke and toxic gases, electrical fans were used.

The findings of Lougheed *et al.* [8], Ezekoye *et al.* [13] and Lambert *et al.* [14] were used to determine the positions of the fans during the experimental work in this thesis.

The experimental work and the bulk of the simulations in this master's thesis make up a study of non-reacting flows. The critical velocity will be used as a basis for a criterion of success for this work. The work of Oka and Atkinson [19], Wu and Bakar [20], and Li *et al*. [21] is used. This is discussed in more detail in section 3.4.5.

In this thesis, the scope is a model that represents the fan in an underground geometry. The effects of the fan on the flow through the domain are important. At a certain distance downstream of the fan, the details of the fan flow are lost. When modelling an underground station, the dimensions are too big to try to capture the details of the fan. This means that it is not possible to model the fan in detail as Kerber has done (see [34]). Manufacturers have developed even more detailed fan models to optimise the fan design. Using such an approach would lead to simulations with too many cells. This is also true to a lesser degree for the Weinschenk approach (see [36]) as well. The bulk of the simulations in this work have been done with a square vent model with a 100 mm mesh to enable the computer to process the calculations with an acceptable delay. The Weinschenk model, with a 50 mm mesh, has been used to try to improve the modelling results. These results are presented in appendix C.

3 Methodology

3.1 Overview

The first step in this work was the analysis of the Brussels underground system. In this analysis all the underground stations have been divided into several categories. The determining parameter was the complexity of the geometry of the underground station. This analysis led to the selection of one underground station which was used to perform CFD calculations. The Brussels underground system can only be used for experiments during the downtime at night. This time frame is too limited for experiments. In order to obtain measured data, experiments were planned in the training infrastructure of the Frankfurt Fire Department in Germany. They have a building that simulates an underground station. The geometry of this building is quite similar to a basic underground station. In this building there were no limits regarding availability.

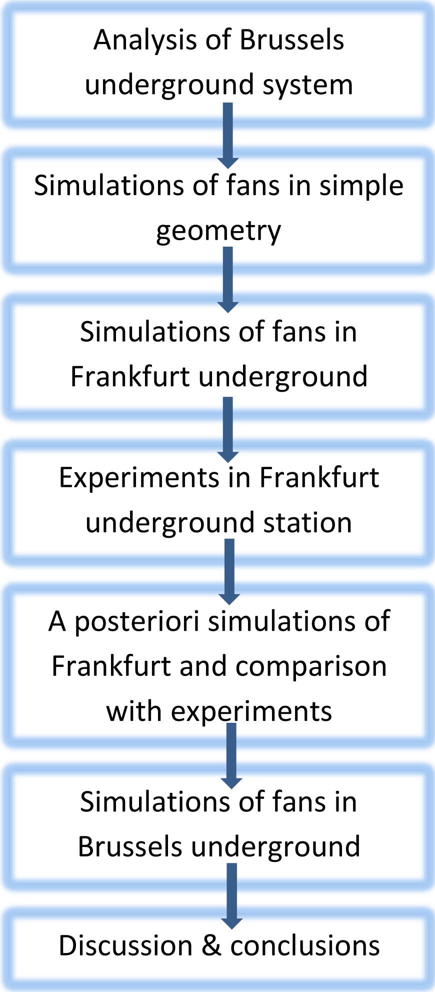

Figure 3.1 General approach for the thesis.

The next step was to develop the experiment. In order to do so the used fans were modelled into the Fire Development Simulator (FDS). The results of these simulations were used as an input for simulations in the geometry of the Frankfurt station. This approach generated an idea about the expected values in the experiment. The results of the initial FDS simulations were used to determine where the fans and measuring equipment had to be placed during the four days of full scale testing, and that was the next step.

After the results of the tests in Frankfurt had been processed, a posteriori simulations were carried out in the Frankfurt building geometry. Comparison with the experiments led to the definition of the fans in FDS for the Brussels geometry.

The selected station in the Brussels underground system was modelled in FDS as well. The fans were modelled following the results of the previous steps.

In the final step the results were discussed and conclusions were drawn.

3.2 Selecting an underground station

3.2.1 The underground station in Frankfurt

Frankfurt fire service has at its disposal a state-of-the-art training centre. All types of interventions can be performed in this training centre. A small underground station has been built to provide realistic training. The station has only one track and is not connected to a tunnel network (see Figure 3.2).

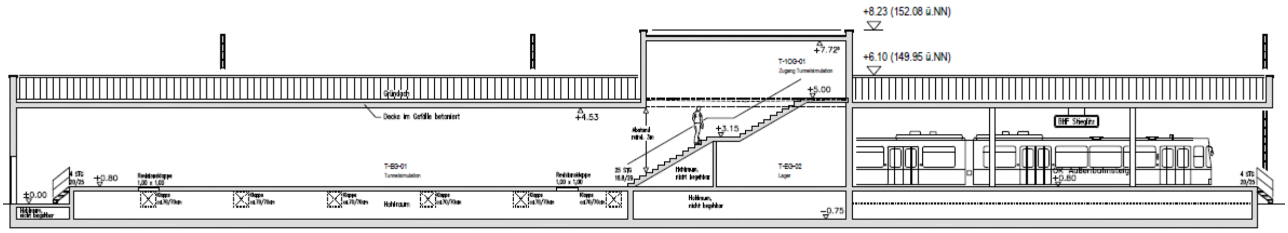

Figure 3.2 Cross section of the underground station at the Frankfurt fire academy. *(Graphic: Frankfurt Fire service)*

The underground station is 60 m long. It has only one floor. The height of the floor is 4.53m. The building is 7.15 metres wide. There is a 2.2 m wide staircase, which provides the main access to the station. This staircase leads to the only exit door. This door is 1.93 m wide and 2.47 m high. There is an entry gate for the underground trains. This opening is 3.17 m wide and 4.15 m high. The surface of the opening is 13.16 m².

The station is relatively small compared to most Brussels underground stations. However, this does limit the possibilities for placing fans. In the Brussels underground stations, there are far more possibilities for placing portable fans than in Frankfurt.

3.2.2 Analysis of the Brussels underground system

The Brussels underground system consists of two major parts. The most important part is a underground (metro) with underground railcars. This part consists of 59 stations divided into four lines. The other part consists of 11 stations used by streetcars. This part is called the "pre-metro". Some of the 59 underground stations are also used for the pre-metro system (see Figure 3.3).

The geometry of the underground stations is not consistent at all. There are stations with one level below grade, whilst others have up to four levels below grade. At the ends of the network there are stations where the underground train enters the station at ground level.

An initial analysis of the underground system has compared the number of levels below grade in all the stations. This analysis created five different groups of stations:

- One level below grade
- Two levels below grade
- Three levels below grade

- Four levels below grade
- No levels below grade (ground level or first floor)

Regarding the geometry, it must be noted that in the Brussels underground system it is very common to have duplex floors.

For every station the number of exits at ground level has been listed. A few stations have only one exit. At the other end of the spectrum some stations have up to eight exits.

This is important because the number of exits also represents the number of outlet openings. A high number of exits will increase the complexity of the flows. In order to obtain a proper understanding, only those stations with a small number of exits can be used in the simulations (see Table 3.1).

Name	Number of levels	G	-1	-2	-3	-4	Exits at ground level	Remarks
Heysel	2	X	X				5	
Houba-Brugman	2		X	X			2	
Koning Boudewijn	2		X	X			3	
Graaf van Vlaanderen	3		X	X	X		2	
Merode	3		X	X	X		6	in-between levels
Troon	2		X	X			3	
Naamsepoort	2		X	X			6	
Rogier	3		X	X	X		5	metro at -1 en premetro at -3
Schuman	3		X	X	X		5	
Park	4		X	X	X	X	1	
Weststation	2	X	X				1	
Ribaucourt	2		X	X			2	
Kunst-Wet	2		X	X			7	in-between levels, 2 levels subway
Beekkant	2	X	X				2	
Bockstael	2		X	X			5	
Kruidtuin	2		X	X			2	
De Brouckère	2		X	X			4	connection with premetro station
Erasmus	2	X	X				3	metro above grade
Simonis	2		X	X			5	2 levels subway
Eddy Merckx	1		X				2	
Centraal Station	2		X	X			8	
Het Rad	1		X				2	
Louiza	2		X	X			5	
Madou	2		X	X			4	
Ceria	2		X	X			2	

Table 3.1 Extract from the table with the underground stations. Stations suitable for the simulations are marked in green.

Appendix A gives a list of all underground stations in Brussels.

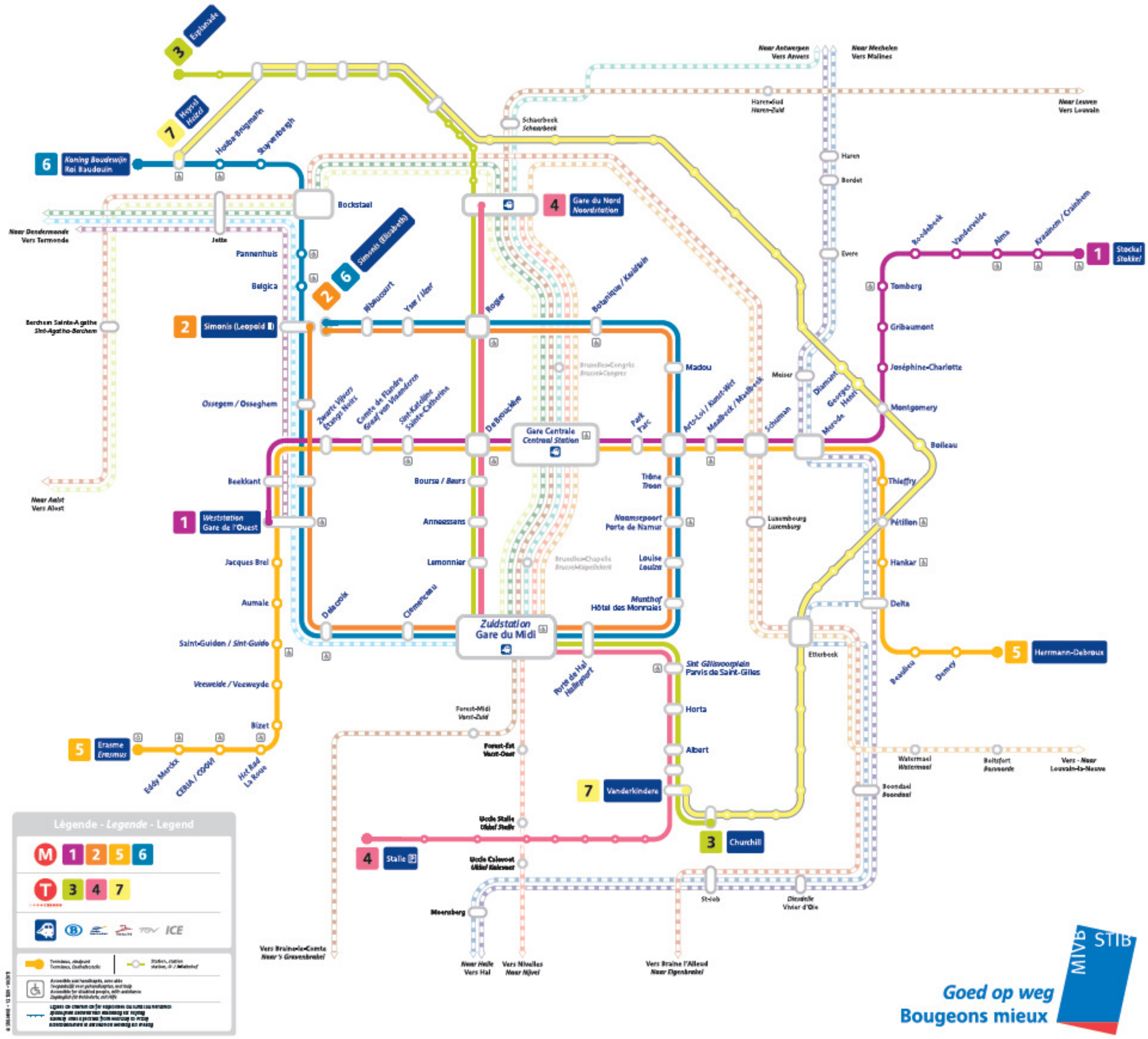

Figure 3.3 The Brussels underground system *(Graphic: MIVB)*

3.2.3 Selected underground station

3.2.3.1 Criteria for selecting a station

Several criteria have been used for the selection.

As mentioned above, the number of exits at ground level should be limited in order to avoid excessively complex flow patterns. Stations with one or two exits were considered more suitable than the others for the purposes of this study. Using such stations limited the number of locations where volume flow had to be determined.

The more complicated the geometry of the station, the more difficult it was to draw conclusions. The generated current in stations with only one level below ground will be less complicated than in stations with three or four levels below ground. In the latter, the current has to flow from level -4 to the ground floor via a complex network of stairs and escalators. For this reason it was decided to start with an underground station where there are only two levels below grade and only two exits.

3.2.3.2 Houba Brugmann

Houba Brugmann underground station is a station with two levels below grade. The two levels form a duplex, which means that they are one volume divided into two floors (see Figure 3.4). This station is almost at the end of the network. In this part of the network the underground trains travel partly in the open air. For Houba Brugmann station, the underground trains enter a tunnel in both directions before they go into open air.

Figure 3.4 Pictures taken in Houba Brugmann underground station. The picture on the left is taken at level -1 and shows the pathway used by the passengers to enter and leave the station. The picture on the right shows the platform and the two tracks at level -2. It has been taken at the end of the pathway in the picture on the left.

3.3 FDS simulations

The CFD package FDS version 5.5.3 has been used to study the behaviour of the flows generated by the fans. FDS uses a low Mach approximation. In [33] can be found that this means Mach numbers less than 0.3. The velocities generated by the fans are in the order of 40 m/s close to the fans. This means that FDS is suitable for the study of the flows generated by these fans.

3.3.1 Mesh size

In order to select a mesh size that is fine enough simulations were run in a short tunnel (see Figure 3.5) with a fan positioned one metre above the ground. The simulations were run with meshes of 5, 10, and 20 cm. The mesh size of 10 cm was chosen as the mesh size for the remaining simulations. The loss in accuracy compared to a 5 cm mesh is limited, but the computing time increases by a 4th power when the grid size decreases.

Grid (cm)	Flow (m^3/s)	Velocity (m/s)	Variation (%)	CPU time (hr)
10	9.19	0.71	1.5	4.85
5	9.05	0.70	(-)	104.26
20	10.3	0.80	13.8	0.5

Table 3.2 Grid sensitivity study: The 10 cm grid shows a deviation of 1.5% compared to the 5 cm grid. The 20 cm grid shows a deviation of 13.8% compared to the 5 cm grid.

3.3.2 Evaluation of fan behaviour in a simple geometry

FDS is a CFD package that uses an orthogonal mesh. This means that simplifications have to be made. The fans are round. This geometry cannot be modelled in FDS. Another difficulty is modelling the inclination of the fan. Kerber (2006) approached this problem by elevating the fan in the experiments and simulations [35]. Lambert (2012) found in his research that it is not always necessary to incline the fan to obtain an optimal result [14], [37]. Therefore the influence of the variation in the height of a non-inclined fan is researched. When positive pressure ventilation is applied in underground stations, typically multiple fans are used. To gain an insight into the optimal use of multiple fans, simulations have been done with fans in series and in parallel.

A fan was simulated as a square vent. The volume flow that goes through the fan was imposed in FDS to the square vent. The imposed volume flow was extracted from the domain at the rear of the fan. This volume flow was blown into the domain at the front of the fan. This fan model was chosen in order to limit calculation time. Using the Kerber model [34] or the Weinschenk model [15] would have been too time consuming.

In total 112 simulations have been performed with one fan or multiple fans in a simple geometry (see Figure 3.5).

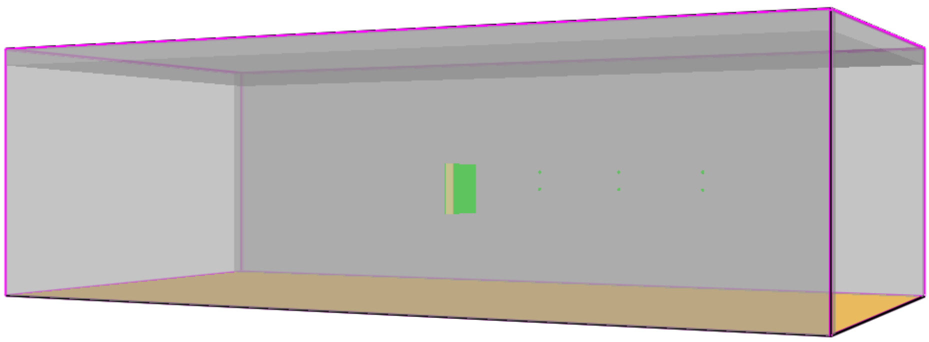

Figure 3.5 Geometry of a short piece of tunnel with one fan.

The behaviour of one fan in a short tunnel was simulated (see Figure 3.5). The tunnel was 10 metres long and 3 metres high. The width varied. Values of 4, 5, and 8 metres have been used. This resulted in simulations with 120,000, 150,000, and 240,000 cells respectively.

The distance between the fan and the floor varied. The behaviour of two fans in series and in parallel was evaluated as well. The distance between the two fans varied.

3.3.3 Evaluation of fan behaviour in the Frankfurt underground station

The goal of this series of simulations was to determine the set-up of the experiments and to gain an insight into the influence of the different factors that play a part in the effectiveness of the ventilation.

The premises have been modelled in FDS (see Figure 3.6). Important items were the entrance for underground trains, the stairway to ground level and the exit at ground level. The dimensions of the domain were 64, 7.2, and 8.1 metres. This resulted in a domain of approximately 3.7 million cells.

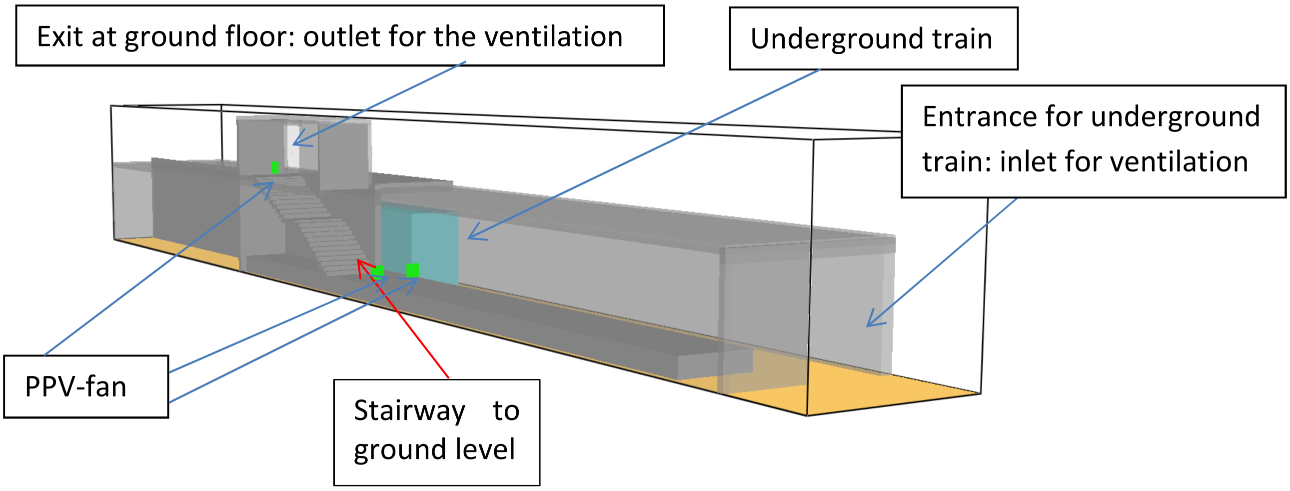

Figure 3.6 Geometry of the Frankfurt underground station

207 scenarios were simulated in this enclosure. Scenarios included one fan in front of the exit. The distance to this exit varied from 90 to 170 cm. Two fans were added to the staircase on the landing, resulting in a scenario with three fans. The distance to the door from the top fan varied. The capacity of the fans varied from 8.33 m^3/s to 16.67 m^3/s (30,000 m^3/h to 60,000 m^3/h). The position of the two fans on the landing has been varied.

Two fans were positioned at the bottom of the staircase, resulting in a scenario with three fans as shown in Figure 3.6. The distance between the fans and the first step of the stairs has been varied between 1 and 9 metres. The fans on the platform have been inclined to study the influence of the inclination on the results. The inclination used in the *a priori* simulations was 10°.

3.3.4 Boundary conditions

In order to limit the amount of cells a study was performed to evaluate the influence of the boundary conditions on the simulation. In a first series of simulations, the inlet for ventilation was at the limit of the domain. In a second series, the length of the domain was extended by 2.5 metres as in Figure 3.6. This meant that the currents in the space in front of the inlet opening were simulated as well. In a third series of simulations, the domain was extended by 4 metres. The simulations with a domain that is extended 2.5 metres past the inlet showed volume flow differences of up to 3.5% compared to the cases where the ventilation inlet is the domain boundary. When the domain was extended by 4 metres, the differences compared with the 2.5 metres cases were limited to 1%.

Qualitatively, there was a difference in the flow pattern between the simulations (see Figure 3.7). In the simulations where the inlet opening was the limit of the domain, the flow was uniform over the height of the station. This is the flow pattern that is expected when a tunnel would be attached to the station. This is not the case in reality (see Figure 3.8). In the other two simulations, the top of the opening created important eddies. These eddies altered the flow pattern. These flow patterns were to be expected in the Frankfurt training building.

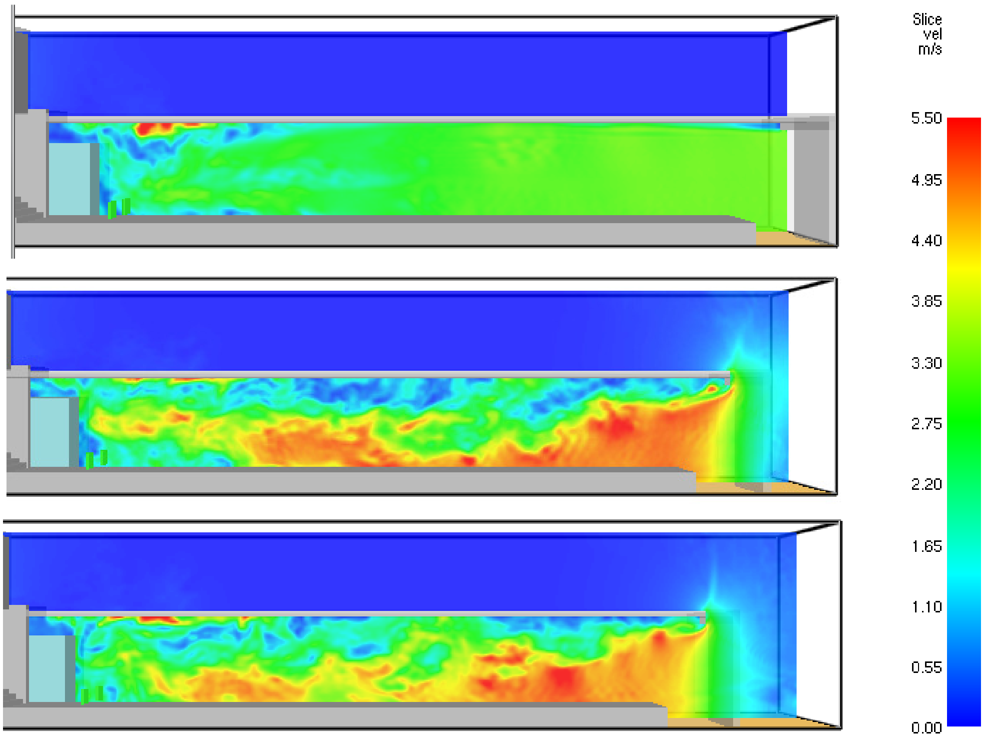

Figure 3.7 Simulations with three different boundary conditions. The top image shows a simulation where the inlet is at the limit of the domain. In the middle image, the inlet is 2.5 metres away from the limit of the domain. In the bottom image, the inlet is 4 metres away from the limit of the domain. All slices were taken 60 seconds into the simulation.

The width of the domain was extended as well. Simulations were run with a 0.9 and a 1.8 metre extension. Deviations were limited to 0.36%.

The remainder of the simulations were performed in the geometry shown in Figure 3.6: an extension of 2.5 metres of the length of the domain but no extension in the width direction.

3.4 Experiments in Frankfurt

The city of Frankfurt has an underground system. The Frankfurt fire brigade has developed a strategy to tackle a fire in the underground. To be able to train the procedures, they can use a platform from one of the subway stations as well as a dead end tunnel that has never been used. Since this infrastructure is in a real underground station, they cannot do exercises with hot smoke. In order to have a higher degree of realism, a building simulating an underground station (see 3.2.1) has been built onto the training site of the Frankfurt fire academy. The Frankfurt Fire Department made this infrastructure available for the tests necessary for this thesis.

3.4.1 The fans used

In the experiments, two types of fans were used: the car park fan and the ESV 280. Both fans are electrically powered and have been developed by the company Leader in France.

The Car Park Fan weighs 72 kg. In the open air it can generate a flow of 104,000 m^3/h. The fan possesses an electrical engine of 17.3 kW. The engine has three phases (400 V) and needs to be fed with a 6 mm^2 cable of 32A. Its dimensions are L x D x H: 710 x 670 x 720 mm [38].

Figure 3.8 The summary of all the materials used during the tests. The underground building is in the background. The five fans are in the middle. The 156 kVA generator is on the right. It is connected to the fans by means of several cables and a distributor cabinet (64A→2x32A). The cabinet with the pressure transducers, voltmeters, and laptop is on the left. The bidirectional probes are positioned in the entry opening for the underground trains.

The ESV 280 weighs 80.5 kg. In the open air it can generate 87,500 m^3/h. The fan possesses an electrical engine of 11.4 kW. The engine has three phases (400 V) and needs to be fed with a 6 mm^2 cable of 32A. Its dimensions are L x D x H: 720 x 720 x 680 mm [38].

Both fans have a standard vertical inclination of 10°. This can be altered within the range 10° - 18°. In the experiments, the angles of 10° and 18° were used.

Both fans can be operated by one firefighter as long as there are no stairs to be passed. When the fan has to be carried on the stairs, experience during the experiments showed that this can be done easily with three firefighters.

These fans can be used to create both positive and negative pressure. In the experiments the fans were used at remote positions. In the underground station a fan was used at the exit. To “feed” this extraction fan, other fans were placed on the platform.

For the experiments, the Frankfurt fire department used their 156 kVA generator. All the equipment that was used in the experiments can be seen in Figure 3.8.

3.4.2 Measuring equipment

In order to measure the flows generated by the fans, a measurement system was put in place to measure the air velocities going through the entry opening of the underground trains (see Figure 3.8). The system consisted of nine bidirectional probes, nine pressure transducers and a data logging system. In order to evaluate ambient weather conditions a weather station was used.

3.4.2.1 Bidirectional probes

In order to do the measurements a grid with bidirectional velocity probes was installed. The probe described by McCaffrey and Heskestad [39] in 1976 was used. This probe consists of a steel tube with a length/diameter ratio of 2 (see Figure 3.9).

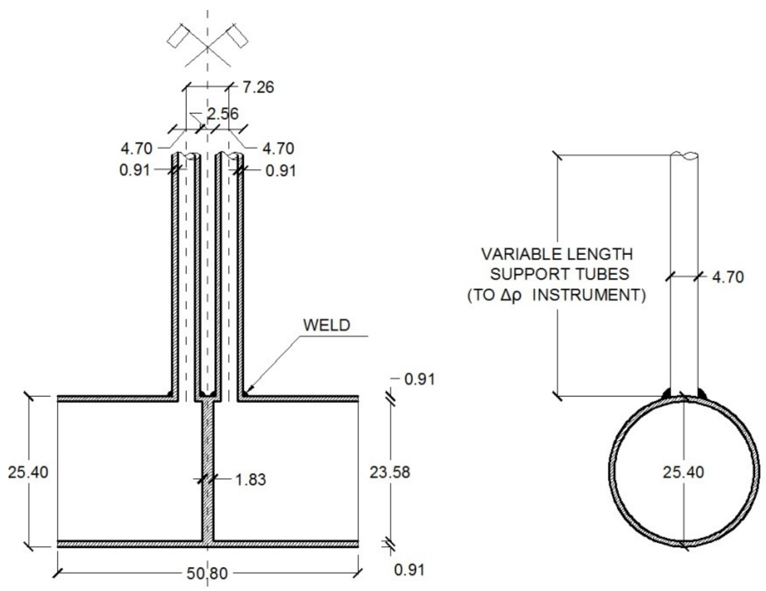

Figure 3.9 The bi-directional probe used in the experiments (Graphic: adapted after Heskestad and McCaffrey [39])

In their paper, Heskestad and McCaffrey described the procedure for calculating the velocity starting with the differential pressure and the density. Sette [40] has performed more in-depth research on the calibration constant. Appendix B gives a more detailed explanation of both papers.

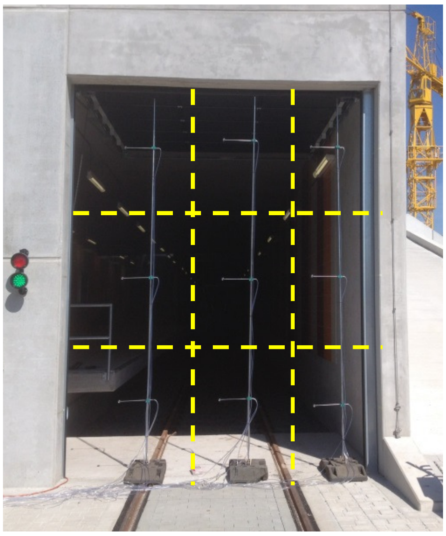

Figure 3.10 The opening of subway station is divided in 9 rectangles. A bidirectional probe is positioned in the middle of every

The entry opening for the underground trains was used as a location for the measurements. The flow going through this opening was ascertained by multiplying the average velocity by the surface of the opening. The opening was divided into nine parts (rectangles). Both the height and the width of the opening were divided into three parts (see Figure 3.10).

A system with steel tubes was designed and manufactured to be able to fix the bidirectional probes in the exact positions. Bidirectional probes were attached to the vertical columns so that there was a probe in the middle of each rectangle. The rows of bidirectional probes were positioned at respectively 0.70, 2.08, and 3.45 m above the ground level. This corresponded to $1/6^{th}$, 1/2 and $5/6^{th}$ of the height of the opening. The columns of bidirectional probes were positioned at 0.53, 1.59, and 2.64 m from the left side of the opening respectively. This corresponded to $1/6^{th}$, 1/2 and $5/6^{th}$ of the width of the opening.

3.4.2.2 Pressure transducer

The probes were connected to a differential pressure transducer (see Figure 3.11). The pressure transducers used in the experiment were LP 1000 type pressure sensors, manufactured by GE. The range of the transducers was +/- 25 Pa. The accuracy was 0.25% of the full scale.

The transducers required a supply of 15-30 Volts. The output was a Volt signal within the range 0 to 10 Volt [41].

Figure 3.11 The pressure transducers of the type LP 1000

3.4.2.3 Data logging system

A data logging system was used to save the data. The Volt output signal from the pressure transducers was read by two voltmeters, which continually scanned the nine pressure transducers. The two voltmeters were of the Keithley 2000-10 type. The signal from the voltmeters was recorded by dedicated software that was installed on a laptop.

The data logging system recorded the Volt output every three seconds.

3.4.2.4 Weather station

The weather station used during the tests was the Primus, manufactured by TFA. It was used to measure the wind velocity and the ambient temperature. The wind velocity meter has a range of 0 – 50 m/s with a resolution of 0.1 m/s. The thermometer has a range of -40 °C to +59.9 °C with a resolution of 0.1 °C [42].

The measure values were transmitted via a wireless connection to a receiver. During the experiments, the wind speed and direction were recorded every minute. The ambient temperature was registered as well. Since the variation in the ambient temperature was minor throughout the day, only one value was registered per day of measurements.

3.4.3 Experimental procedure

Before starting with experiments, all the planned positions of the fans were marked with tape. The distance between to position of the fan and the staircase or the exit door was measured, marked with tape and the distance was written on the tape (see Figure 3.12).

This had to be done for two reasons: Firstly, it was necessary to be able to repeat tests and to make sure that the fans were in exactly the same position. Furthermore, the exact position of the fans in underground building had to be known to be able to compare the results of the experiments with the results of a priori modelling and to perform a posteriori modelling.

Figure 3.12 The possible positions of the fans are measured, marked with tape and the distances are written down on the tape.

At the beginning of every testing day the measurement equipment was put in the correct position. A plumb line was used to make sure that the three bidirectional probes were positioned correctly. The bidirectional probes were set up in such a way that they measured the velocity normal to the opening for the subway cars (see Figure 3.10). The weather station was positioned outside the underground station. The same position was used every day. The connection with the receiving unit was checked. The generator was switched on and a check was performed to verify that the fans were working properly. The cabinet with the pressure transducers, the voltmeters, and the laptop were put in place. The laptop and the voltmeters were switched on.

The experimental procedure consisted of several steps to guarantee consistency.

- The first step consisted of placing the fans in the selected positions for the test at hand.
- The dedicated software was activated.
- The name of the test was used as input for the test.
- The test started with the recording of a 60 second baseline (t= -60 s till t= 0s). The software recorded the signal every three seconds.
- The wind velocity and direction were recorded.
- At t = 0s, the fans were started. The wind velocity and direction were recorded.
- The software recorded the signal every three seconds.
- Every 60 seconds, the wind velocity and direction were recorded. (at t = 60s, 120s, 180s, 240s and 300s)
- The fans were stopped at t = 300 s.
- The file with raw data (.rw1 file) was copied.
- The measurement was stopped.
- The dedicated software was shut down.

At the end of every day the results of the day were copied from the laptop on a USB stick to secure the data. All the measuring equipment was shut down and stored in the underground building.

3.4.4 Data processing

The datalogging software generated a comma separated file. The values of the volt meter were recorded in this file. An Excel file was created in order to copy and paste the data from the comma separated file. In the Excel file, the first step in the processing was to copy the data from the 60 seconds prior to the experiment. The average voltage was determined for each of the 9 bidirectional probes during the 60 second period. These 9 values were used as a basis of comparison for the other values. All the values that were negative compared to the basic value indicated a flow leaving the underground building whilst all the positive values indicated a flow entering the underground building.

In the second step, the data from the 300 seconds of processing was pasted into the Excel file. The Excel file performed the following calculations for every time step and for each of the probes:

- The difference between the volt signal and the baseline value was calculated.
- The difference in Volt was converted into a pressure difference in Pascal using the characteristics of the pressure transducer (see 3.4.2.2).
- The pressure difference was converted into a velocity. A calibration constant of 1.046 was used when the Reynolds number of the flow was above 2 500.

In a number of experiments this led to a good result. The values for the instantaneous velocities were put into a graph. Figure 3.13 (Left) shows that the flow needed almost 30 seconds to achieve a steady state. The flow was relatively constant until late in the experiment. At the end of the experiment, some fluctuations were observed. In the case of experiment 24, three pressure transducers indicated a Volt value below the baseline value. Physically, this means a flow that was exiting the building. The six other pressure transducers didn't show any such value. Moreover, the three pressure transducers with a negative value only showed this reading once. For each of the transducers there was one negative value out of 301 values.

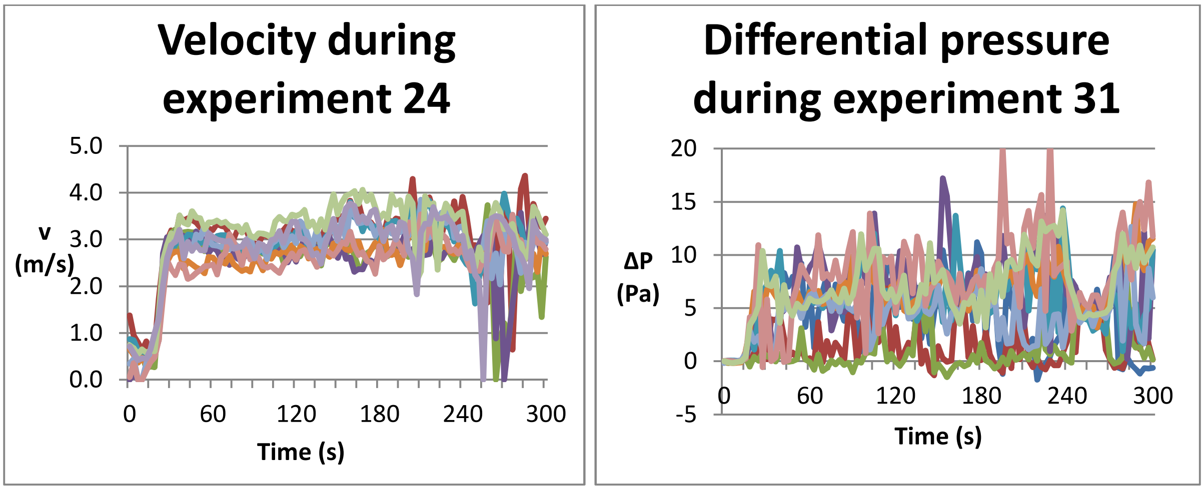

Figure 3.13 Left: the evolution of the velocity measured during experiment 24. Right: the evolution of the pressure difference measured during experiment 31. The different colours correspond to the 9 different probes.

In order to compare the different experiments, an average velocity was determined. This was done by time averaging the velocity from t = 60 until t = 180 s. This led to nine average velocities which corresponded with each of the bidirectional probes. The mathematical average of the nine values was calculated. This lead to the average velocity over the opening during 120 seconds of the test. This velocity was multiplied by the surface of the opening. The result was the average flow in m^3/s going into the underground station. This value was used to compare the different experiments.

When the results of several experiments were processed, it was noticed that some of the probes showed irregular results. This led to negative pressure differences. Since the results were being processed on an Excel sheet, this created a problem. In order to calculate the velocity, the square root of the pressure difference was calculated. If the pressure difference was negative, an error was created. Figure 3.13 (Right) shows the evolution of the differential pressure during experiment 31. Four pressure transducers show values that were below the calculated baseline. Other than in experiment 24, these values appeared more than once. The other five pressure transducers behaved as in experiment 24. In several experiments, probes two and three (red and green in Figure 3.13, right) showed results that indicated that there was very little pressure difference. Probes two and three were the middle and bottom probes of the column next to the side wall of the underground building (right column in Figure 3.10). A possible explanation can be found in the presence of the side wall. The flow tries to create an eddy (as happens on the left side of the opening) but the presence of the wall makes this impossible. A second possible explanation can be the presence of the slope next to the building (see Figure 3.8). The combination of the slope, the ground effect, and the presence of the side wall can explain why probes two and three were influenced by turbulence while probe one was not influenced.

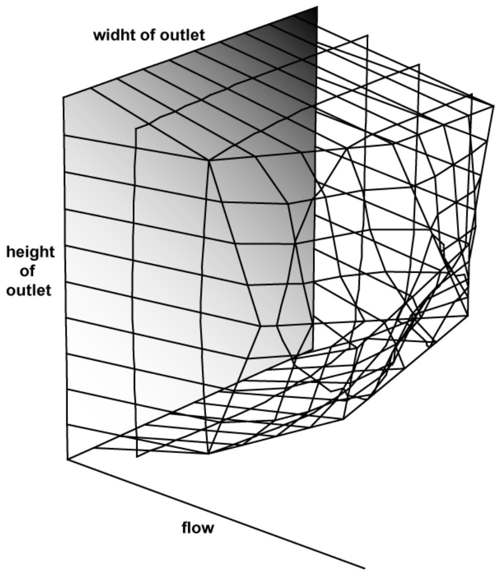

Figure 3.14 The flowfield of the flow going through an outlet. Close to the borders, the velocity is reduced to zero. *(Graphic: Stefan Svensson)*

To be able to process the data the average value of the pressure difference was determined for every probe from t = 60 to t = 180 s. In the case of probes which showed negative values, this led to a lower average pressure difference. The average pressure difference from every probe was then used to calculate an average velocity for that probe. The mathematical average of the nine velocities was determined. It was multiplied by the surface of the opening and this once again led to the average flow through the opening for the experiment.

A closing remark about this way of processing can be made about the implicit assumption that the velocity is evenly distributed over the surface of each of the nine rectangles. This, of course, is not the case. At the edges of the opening, the velocity will reduce drastically because of the influence of the walls (see Figure 3.14).

At ground level, there will be an effect caused by the ground as well. The flow will experience the presence of the ground and there will be a boundary layer. Therefore, lower velocities will be found close to the ground.

Due to the size of the opening (4.15 x 3.17m), the effect of both the phenomena (ground and border) will be limited. The choice has been made to consider this effect as negligible. The effect of this choice is a slight overestimation of the flow. In reality, the flow will be a little lower due to the effects described above, but it was impossible to quantify this deviation with the measurement equipment available.

3.4.5 Criterion for success

In order to evaluate whether or not the experiments are successful, a criterion for success needed to be formulated. In literature, very little is found about removing smoke after a fire. Lots of research about the design of fixed installations in tunnels has been done, though. These applications deal with controlling smoke during the fire. This demands an air flow that is superior to the one needed for removing smoke after a fire, since the fire source acts as a resistance [26]. The buoyant fire gases will move up and then they will spread in different directions and the generated flow will have to overcome that movement. The longitudinal ventilation is considered to be successful when backlayering is avoided. The absence of backlayering was used as a criterion for success in this work. Moreover, using such a criterion of success will immediately give an indication about the possibility of using the same solution prior to or during extinguishment.

In several works [19],[20],[43] the critical velocity is used. The critical velocity is the velocity needed to prevent the smoke from flowing upstream. This critical velocity was the parameter that was used to determine if experiments or simulations were successful. Oka & Atkinson [19] performed experiments in a model tunnel. The shape of the section of the tunnel was the BS 227 colliery arch. They defined two dimensionless variables:

$$Q^* = \frac{Q}{\rho_0 c_p T_0 g^{1/2} H^{5/2}} \qquad\qquad V^* = \frac{V_{cr}}{\sqrt{gH}}$$

Oka & Atkinson showed that the critical velocity is proportional to the cubic root of the heat release rate for small fires but becomes independent of the heat release rate for bigger fires. They have suggested the following equations:

$V^* = 0.35\ (0.124)^{-1/3} Q^{*1/3}$ for V* < 0.124

$V^* = 0.35$ for V* > 0.124

Wu & Bakar [20] continued this research and assessed the influence of the geometry of the tunnel. They tested five different cross-sections and found that the height of the tunnel is not the ideal parameter to describe the critical velocity. In their work, they proposed to use the hydraulic diameter $\overline{H}$: the ratio of four times the section to the perimeter of the tunnel. They defined two alternative dimensionless variables:

$$Q^{"} = \frac{Q}{\rho_0 c_p T_0 g^{1/2} \overline{H}^{5/2}} \qquad\qquad V^{"} = \frac{V_{cr}}{\sqrt{g\overline{H}}}$$

This led to two equations for the dimensionless velocity:

$V^{"} = 0.40\ (0.20)^{-1/3} Q^{"1/3}$ for Q” ≤ 0.2

$V^{"} = 0.40$ for Q” > 0.2

To evaluate the success of the experiments, the theory developed by Wu and Bakar [20] was used. Firstly, the heat release rate that will lead to a dimensionless heat release rate of 0.2 was determined. Since the used underground station in Frankfurt is a training building, there is no tunnel attached to it. The calculations were done for a virtual tunnel that would be arriving in the subway station. The dimensions of the tunnel would then be those of the opening: 3.15 x 4.17 m (W x H).

$$Q = Q^{"}\rho_0 c_p T_0 g^{1/2} \overline{H}^{5/2} = 0.2 \times 1.2 \times 1.0 \times 293 \times 9.81^{1/2} \times 3.59^{5/2} = 5395\ kW$$

Next, the corresponding critical velocity was calculated:

$$V_{cr} = V^{"}\sqrt{g\overline{H}} = 2.37\ m/s$$

If the velocity generated by the fans through the opening underground system is higher than 2.37 m/s, there should be no backlayering in the event of a fire in the tunnel arriving in the station. Knowing the dimensions of the opening, this leads to a flow rate of 31.2 m^3/s as a criterion of success for the Frankfurt underground station.

To be able to assess whether or not the generated flow can prevent backlayering with a fire in the subway station itself, the calculation above is repeated with the dimensions of the subway station: 6.35 x 4.6 m (W x H). This leads to a heat release rate of 14.488 MW. The critical velocity is calculated to be 2.89 m/s. This value represents a flow rate of 84.52 m^3/s.

Li *et al* [21] showed that the critical velocity can be reduced when there are obstacles in a tunnel. Typically, an obstacle to the flow will be present in the tunnel when a fire with a high heat release rate occurs. The train in the tunnel is the only object that can generate a high heat release rate. They suggested a conservative rule of thumb: The reduction rate ε is the ratio of the cross-sectional area of the obstructions to the cross-sectional area of the tunnel. In the tunnel of the Frankfurt underground station, the reduction factor would be 73%. This is a high reduction factor. Li *et al.* used a model train that occupied 20% of the tunnel. In the station itself, the reduction would be 33%. This value is closer to the value used in the research by Li *et al*.

When comparing the reduction rates to the situation in Brussels, it can be seen that the reduction rates are even lower. The reduction rate in the tunnel is 13% and only 7% in the station.

3.4.6 Position of the fans

A total of 106 experiments were performed in the underground building during the four-day measurement campaign.

In the first series of experiments, the position of the fans was determined by the results of the *a priori simulations* (see 3.3). The test results of the first two test days were used to determine positions that lead to greater effectiveness. During the last two days, extra markings were made with tape to test new fan positions which hadn't been simulated.

3.5 Comparison of the Frankfurt test results with simulations: a priori and a posteriori

The position of the fans during the experiments were based on 83 simulations of fans in a simple geometry and 88 simulations that were performed in the simulated underground building.

The simulations were compared with the experimental results. During a posteriori simulations, the generated flow in FDS was matched to the measured flow during the experiments. Afterwards, a virtual tunnel was attached in FDS and several fires were simulated in order to check the effect of the fire on the flow. The occurrence of backlayering could be verified visually in these final simulations.

3.6 FDS simulations: Evaluation of Fan behaviour in the Brussels underground station

The results of the full scale experiments and simulations of the building in Frankfurt were used to model the fans in the Brussels underground station.

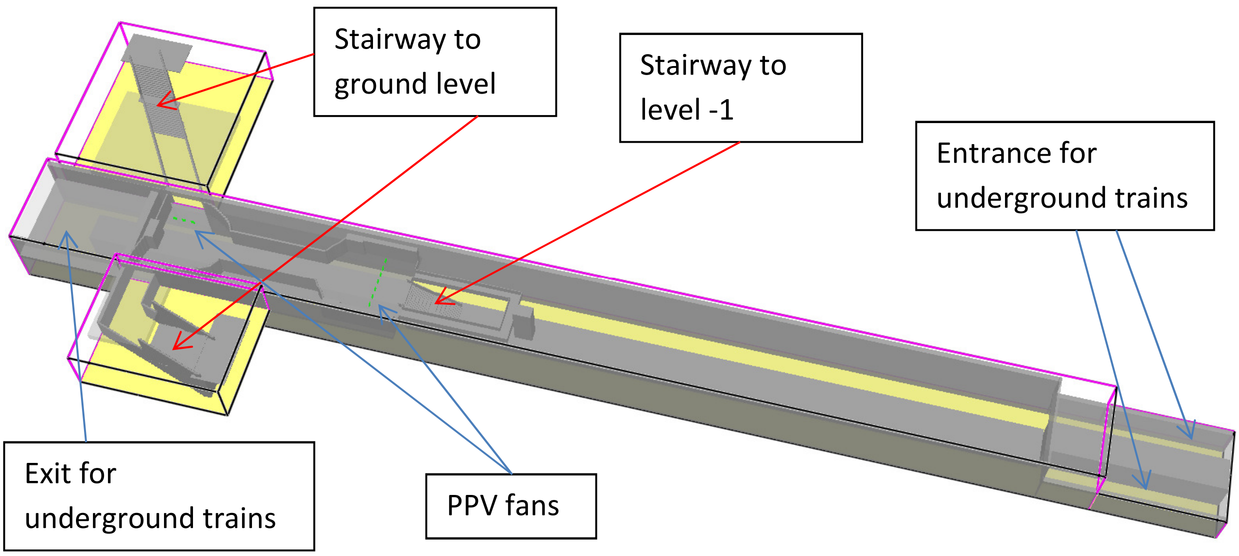

Figure 3.15 The geometry of the Brussels Houba Destrooper underground station. The PPV fans are the green dots in the geometry.

The station has been modelled in FDS (see Figure 3.15, Figure 3.4). Important items were the entrance and exit for subway cars at level -2, the stairway at level -1, and the two stairways to ground level. The dimensions of the main part of the geometry were 200, 16, and 12 metres. This resulted in a domain that consisted of four meshes and of approximately 46 million cells.

A placement with 14 fans was simulated in FDS. The generated velocities were evaluated to determine whether the use of PPV's is useful for the fire service in interventions in this underground station. The flow rate of each fan was varied to evaluate the effect on the flow.

The baseline value was 15 m^3/s per fan. The effect of a 10% higher and lower flow rate was simulated.

4 Results

4.1 FDS simulations: Evaluation of fan behaviour in a simple geometry

4.1.1 Influence of the variation in height

A fan with a nominal flow of 8.33 m^3/s was simulated in a short hallway. Its distance to the floor was varied.

It can be observed that the flow generated by the fan decreases when the fan is placed closer to the ground. This is due to a worsening entrainment. The modelling of the fan at a height of 20 cm corresponds to the placement in reality. In this case the generated flow is 89% of the capacity of the fan.

Distance (cm)	Flow (m^3/s)	Velocity (m/s)	Percentage (%)	Effectiveness (%)	No.
100	9.19	0.71	100	110	F12
80	9.08	0.70	99	109	F14
60	8.18	0.64	89	98	F15
40	7.26	0.56	79	87	F16
20	7.45	0.58	81	89	F17

Table 4.1 The results of simulations with a fan that flows 8.33 m^3/s in a small tunnel. The height of the fan is varied. The percentage is the comparison with the result of one fan which is 100 cm above the ground. The effectiveness is the comparison of the flow with the nominal flow of the fan.

4.1.2 Using two fans in parallel

To study the effect of two fans in parallel, a hallway was simulated. The width of the hallway was set at three different values: 4, 5, and 8 m. Two fans with a nominal flow of 8.33 m^3/s were simulated. The distance between the two fans was the major variable. All the fans were placed at a height of one metre above the floor.

4.1.2.1 Hallway of four metres wide

Two fans in parallel have a flow that is higher than the combined capacity of the fans. Table 4.2 and Figure 4.1 show that there was an entrainment effect of up to 40%. The maximum effectiveness attained was 140%. Another observation is that there was only a little variation between the different distances.

Distance (cm)	Flow (m^3/s)	Velocity (m/s)	Percentage (%)	Effectiveness (%)	No.
80	22.3	2.21	100	134	F47
100	23.1	2.29	104	139	F48
120	23.2	2.30	104	139	F49
140	23.3	2.31	104	140	F50
160	22.2	2.20	100	133	F51
180	21.1	2.09	95	127	F52
200	20.1	1.99	90	121	F53

Table 4.2 The flow and the velocity generated by two fans in a 4 metre wide hallway. The percentage is the comparison with the result of two fans which are 80 cm apart. The effectiveness is the comparison of the flow with the combined nominal flow of the two fans.

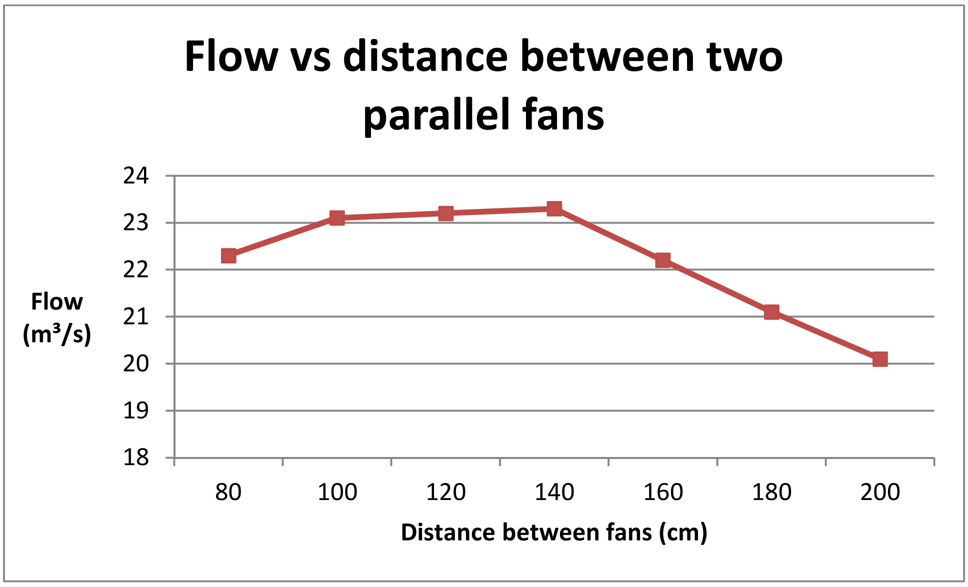

Figure 4.1 The influence of the distance between two fans on the flow generated in a four-metre wide hallway. Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

4.1.2.2 Hallway of five metres wide

In the five metre wide hallway it was possible to increase the distance between the fans on the one hand and between the fans and the walls on the other hand. Table 4.3 and Figure 4.2 show that there was an entrainment effect of up to 36% extra. The effectiveness is 4% lower than in the hallway that was four metres wide.

Distance (cm)	Flow (m^3/s)	Velocity (m/s)	Percentage (%)	Effectiveness (%)	No.
80	20.5	1.59	100	123	F18
100	21.1	1.64	103	127	F19
120	21.9	1.70	107	131	F20
140	22.4	1.74	109	134	F21
160	22.7	1.76	111	136	F22
180	22.6	1.75	110	136	F23
200	22.7	1.76	111	136	F24
220	22.2	1.72	108	133	F25
240	21.2	1.65	103	127	F26
260	20.6	1.60	100	124	F27
280	19.8	1.54	97	119	F28

Table 4.3 The flow and the velocity generated by two fans in a five-metre wide hallway. The percentage is the comparison with the result of two fans which are 80 cm apart. The effectiveness is the comparison of the flow with the combined nominal flow of the two fans.

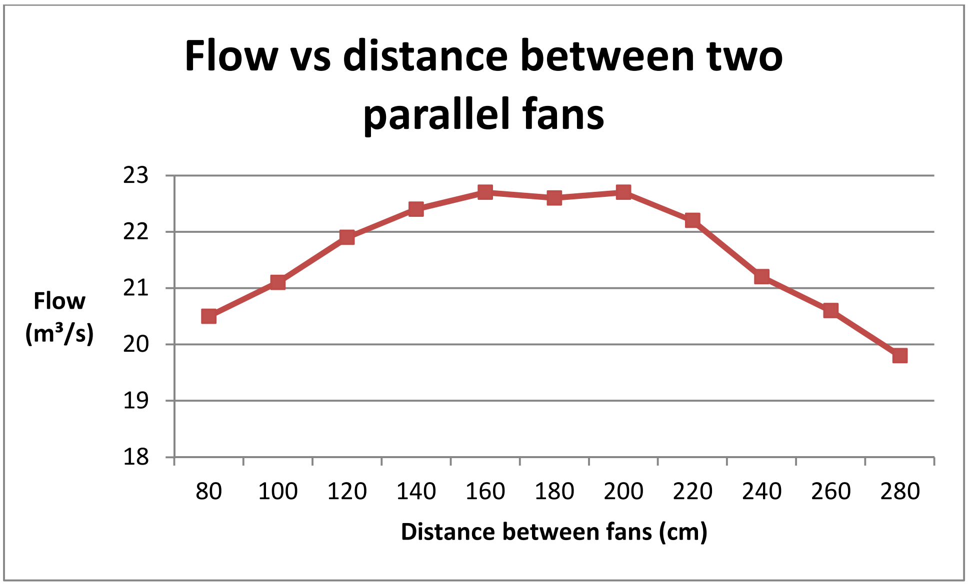

Figure 4.2 The influence of the distance between two fans on the flow generated in a five-metre wide hallway. Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

4.1.2.3 Hallway of eight metres wide

In order to evaluate the placement of two fans in a hallway that has big dimensions as in underground stations, a hallway with a width of eight metres was simulated (see Figure 4.3). It can be seen from Table 4.4 and Figure 4.4 that the entrainment has decreased. The entrainment was limited to 26% in the best performing case. In the poorest performing cases, the generated flow was less than the combined nominal flow of the fans.

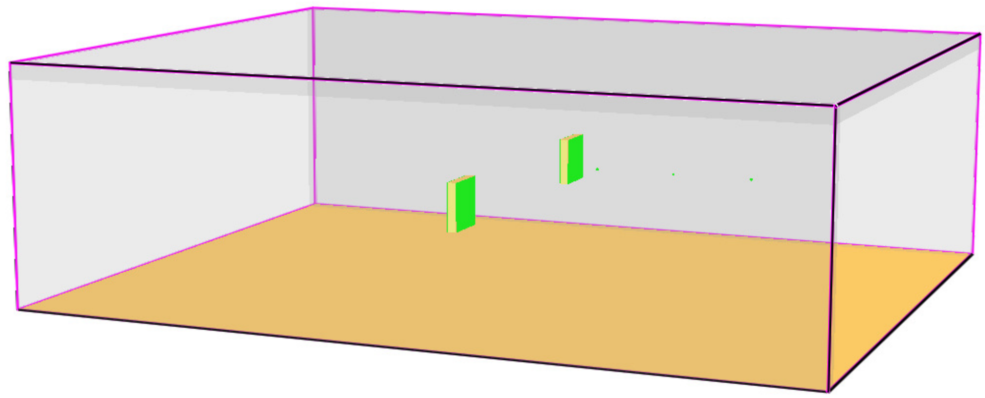

Figure 4.3 A Smokeview visualisation of simulation F38. Two fans are positioned 3.2 metres apart in a hallway that is eight metres wide.

Distance (cm)	Flow (m^3/s)	Velocity (m/s)	Percentage (%)	Effectiveness (%)	No.
80	14.0	0.66	100	84	F32
120	15.7	0.74	112	94	F33
160	18.0	0.85	129	108	F34
200	19.6	0.92	140	118	F35
240	20.4	0.96	146	122	F36
280	20.6	0.97	147	124	F37
320	20.4	0.96	146	122	F38
360	21.0	0.99	150	126	F39
400	20.4	0.96	146	122	F40
440	21.0	0.99	150	126	F41
480	18.0	0.85	129	108	F42
520	17.1	0.80	122	103	F43
560	13.6	0.64	97	82	F44
600	15.5	0.73	111	93	F45

Table 4.4 The flow and the velocity generated by two fans in a eight-metre wide hallway. The percentage is the comparison with the result of two fans which are 80 cm apart. The effectiveness is the comparison of the flow with the combined nominal flow of the two fans.

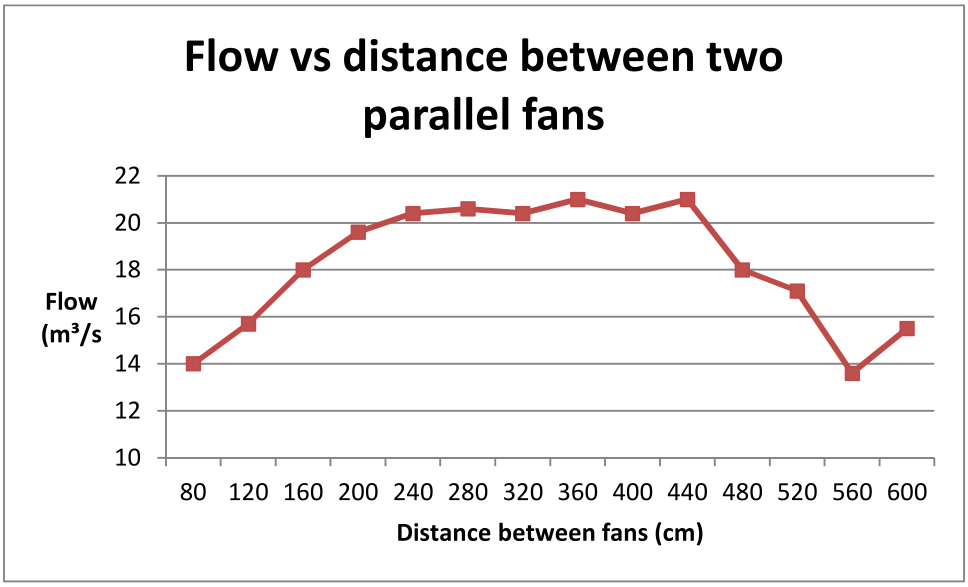

Figure 4.4 The influence of the distance between two fans on the flow generated in a eight-metre wide hallway. Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

4.1.3 Using two fans in series

Two fans were simulated in series at 23 different distances in a hallway that was five metres wide and ten metres long. It can be seen from the results that the flow increases as the distance between the fans increases. These simulations should be repeated in a longer hallway with longer distances between the fans.

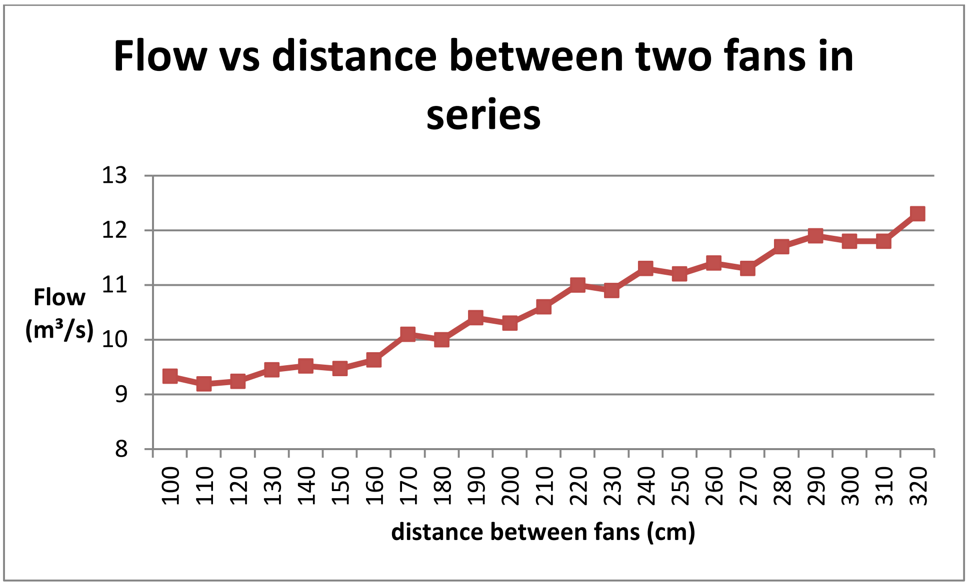

Figure 4.5 The results of the flow generated by two fans in series. The distance between the fans is varied. Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

4.2 FDS simulations: Evaluation of fan behaviour in the Frankfurt underground station

4.2.1 Using one fan at ground level

The distance of the fan to the door opening was the first variable to be evaluated. This distance varied between 90 and 170 cm. The capacity of the fan was set at 30,000 m^3/h or 8.33 m^3/s. Variation of the position of the fan didn't have a big influence. An important observation is that the geometry of the underground system causes ca. 30% losses. The effectiveness of one fan is maximum 72%.

Distance (cm)	Flow (m^3/s)	Velocity (m/s)	Percentage (%)	Effectiveness (%)	No.
90	5.66	0.39	100	68	FF4
100	5.74	0.40	101	69	FF5
110	5.81	0.40	103	70	FF6
120	5.91	0.41	104	71	FF7
130	5.93	0.41	105	71	FF8
140	5.97	0.41	105	72	FF9
150	5.95	0.41	105	71	FF10
160	5.93	0.41	105	71	FF11
170	5.95	0.41	105	71	FF12

Table 4.5 Simulations with a fan that has a nominal flow of 8.33m^3/s. The distance to the door is the variable. The percentage is the comparison with the result from a fan that is positioned 90cm from the door. The effectiveness is the comparison of the flow with the nominal flow of the fan.

4.2.2 Combining one fan at ground level and two fans at the stairs

The second possibility that was evaluated was the combination of two fans on the landing of the stairs with one fan at ground level. Again, it was the distance to the door that varied. Each of the fans had a capacity of 30,000m^3/h. The distance to the door had little influence in the range from 90-160 cm. The effectiveness of the fans dropped to 60% but the absolute result increased compared to the simulations with only one fan at ground level.

Distance (cm)	Flow (m^3/s)	Velocity (m/s)	Effectiveness PPV (%)	No.
90	14.7	1.02	59	FF21
100	14.7	1.02	59	FF20
110	14.8	1.03	59	FF19
120	14.9	1.03	60	FF18
130	15.0	1.04	60	FF17
140	14.9	1.03	60	FF16
150	15.0	1.04	60	FF15
160	14.9	1.03	60	FF13

Table 4.6 Simulations with three fans that have a nominal flow of 8.33m^3/s. The distance to the door is the variable. The percentage is the comparison with the result from a fan that is positioned

90cm from the door. The effectiveness is the comparison of the flow with the combined nominal flow of the fans.

4.2.3 Influence of more powerful fans

It was not clear what flow the used portable fans would generate in the underground system. Therefore the above simulations have been repeated with simulated fans which had a capacity of 11.11 m^3/s (40,000 m^3/h), 13.89 m^3/s (50,000 m^3/h) and 16.67 m^3/s (60,000 m^3/h). The result of these simulations were used as a basis for the a posteriori simulations.

Overall, it can be concluded that the distance to the exit door doesn't have a big influence. The effectiveness of the placement with three fans was in the order of magnitude of 60%.

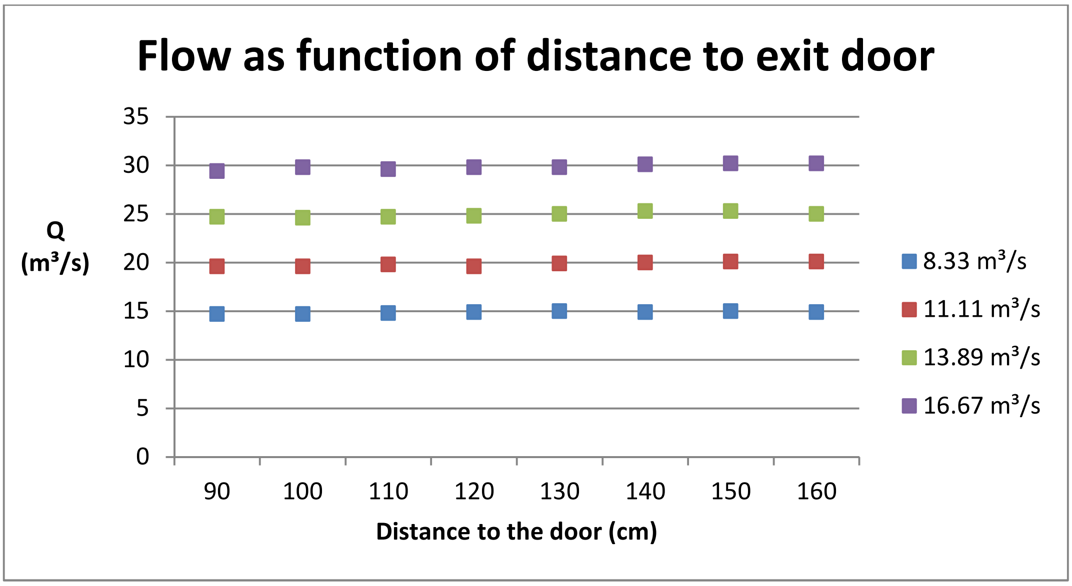

Figure 4.6 Four flowrates are used in simulations where two fans are at the bottom of the staircase and one fan is at the top of the staircase. The distance of this last fan to the door is varied.

4.2.4 Combining one fan at ground level with two fans on the platform

Several scenarios with three fans were tested. The distance from the edge of the stairs to the fans varied from 1 to 20 m with a one-metre interval (see Figure 4.7). The angle of inclination of the fan varied as well: values of 0°, 10°, and 18° were compared. It can be seen that the flow produced by the fans increases as the distance to the stairs increases with the fans with zero inclination. The flow rate generated by the fans with a 10° angle reaches an optimum at 10 metres from the stairs. The series of simulations with a 18° angle reaches the maximum flow at 12 metres. It can be seen, though, that with the latter, there is an optimum "zone" that starts at 7 metres and stops at 14 metres. Within this zone, the flow rate varies between 36.8 and 37.7 m^3/s.

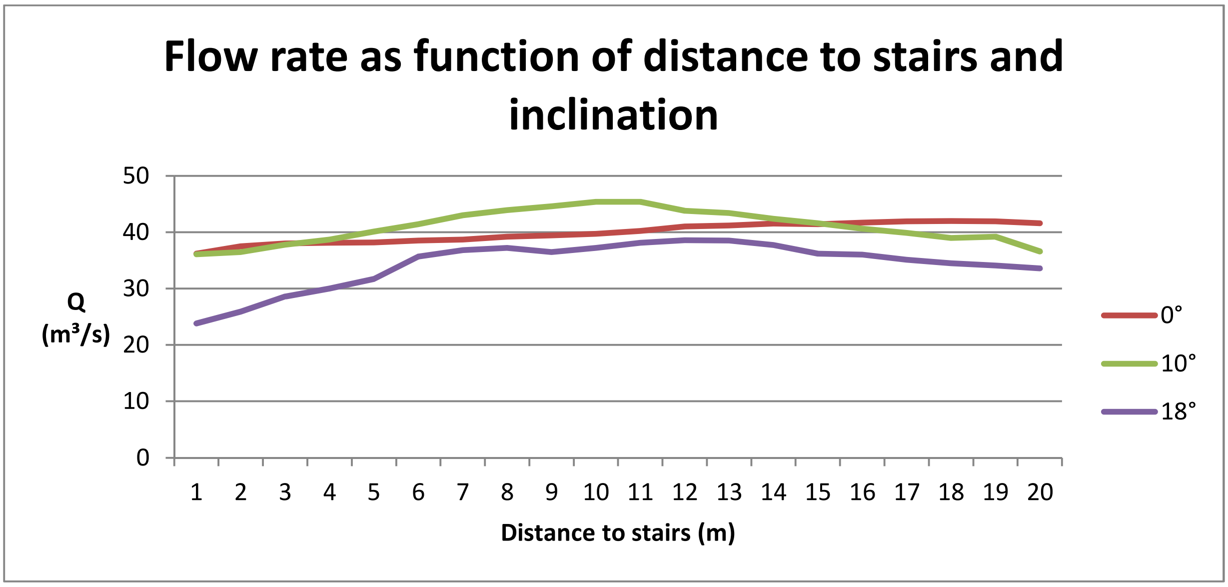

Figure 4.7 Results of simulations with one fan at the exit and two fans on the platform. The distance between the fans on the platform and the stairs varied.

4.3 Full scale experiments in Frankfurt

In the first week of August 2013 four days of experiments took place in the FRTC in Frankfurt. In total 106 full scale experiments were performed:

- 5 August 2013: 24 tests
- 6 August 2013: 33 tests
- 7 August 2013: 21 tests
- 8 August 2013: 28 tests

4.3.1 Repeatability

To evaluate the repeatability of the experiments between different days, eight tests from the third day were repeated on the fourth day. While the temperature had been constant 30 °C on the first three days of the measurement campaign, it was only 20 °C on the last day. The average wind velocity during the eight tests on the third day was 1.34 m/s whilst it was only 0.45 m/s during the experiments on the fourth day. The difference between the measurements of the tests on the third day and the respective tests on the fourth day was in the range from 96-103% (see Figure 4.8). Only test 95 showed a bigger deviation: 87% of the value of test 74. It is not clear what caused this deviation. Wind gusts could provide an explanation.

These results show that the experiments have a good repeatability. This means that it is possible to compare results from these days.

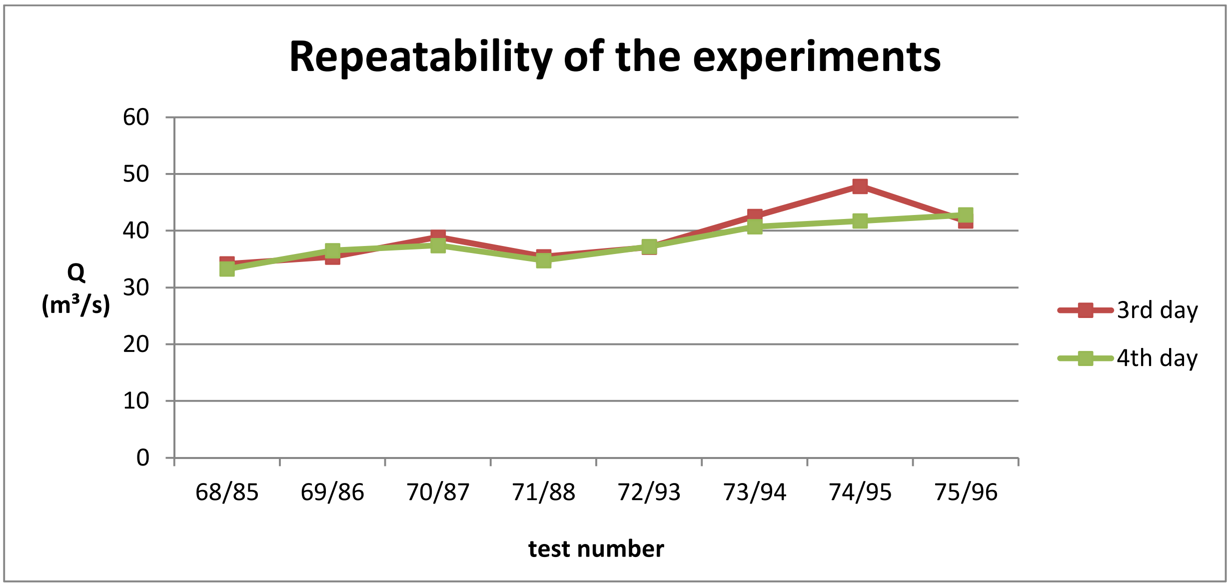

Figure 4.8 Eight experiments from the thrid day were repeated on the fourth day. The deviation between the results is limited (-4% to 3%). Only experiment 74 showed a deviation of 13% compared to experiment 95. Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

4.3.2 Position of the fans (3 fans)

In total 36 tests were performed with three fans. Several set-ups were used. Parameters as the position of the fan at the top of the staircase and the placement of the fans on the platform were varied.

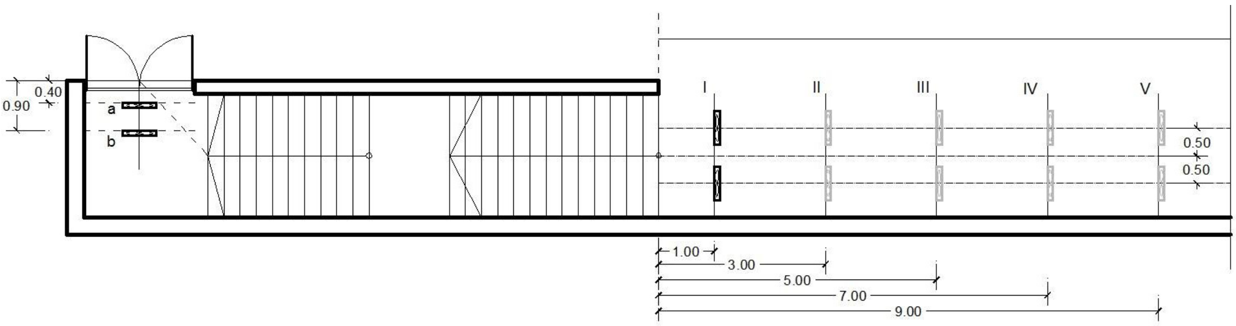

Figure 4.9 Position of the three fans. Two positions were used at the top of the staircase. The fan in position a was placed 40 cm from the exit. Position b is 90 cm from the exit. These positions were combined with five positions on the platform, ranging from one to nine metres from the stairs. (Drawing: Ruxandra Darmon)

Figure 4.10 shows the results of a first series of ten tests with three ESV 280 fans as set up in Figure 4.9. All fans had an inclination of 10°. Two fans were positioned on the platform with reference to the middle line of the stairs (-50 cm and +50 cm). Both fans were placed so that their axis was parallel to the middle line of the stairs. Their distance to the stairs varied from one to nine meters with a two metre interval. The fan at the top of the staircase was placed on the centreline of the exit opening. The distance from the fan to the door was 40 cm during the first five tests and 90 cm for the five remaining tests.

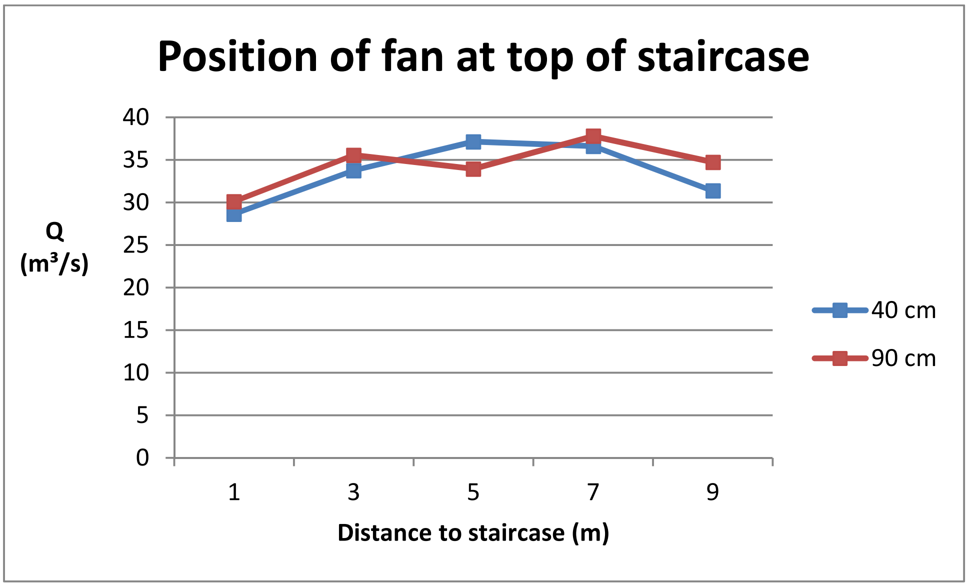

Figure 4.10 Results of 10 tests with three fans ESV 280. Two fans on the platform were combined with one fan at the top of the staircase. The distance of this last fan to the exit varied. The distance between the fans on the platform and the stairs also varied. Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

There is a trend in Figure 4.10 which shows that the better position of the fan at the top of the staircase is 90 cm from the door. The difference varies between 5 and 11%. These differences are rather small. Therefore it is not possible to state that the one position is better than the other. The test data from the set-up with two fans five metres from the stairs and 90 cm from the door shows an anomaly. This test doesn't follow the trend. There is no known explanation for this. A second important observation is that the flow for a set-up one metre from the staircase is 15% less than three metres. A final observation is that the optimal placements can generate the critical velocity in a tunnel that would be attached to the station (Flow rate > 31.2 m^3/s, see 3.4.5).

In a second series of experiments with three ESV 280 fans, four different placements for the top fan were compared (see Figure 4.11). This was done to determine the position of the fan that would be used in the tests with four fans. All the fans had an inclination of 10°. Two fans were positioned on the platform at a distance of three metres from the stairs. These two fans were positioned with reference to the middle line of the stairs (-25 cm and +150 cm). The leftmost fan had its axis parallel with the middle line of the stairs whilst the rightmost fan had its axis oriented on the middle of the stairs. This meant that it was turned 27° horizontally.

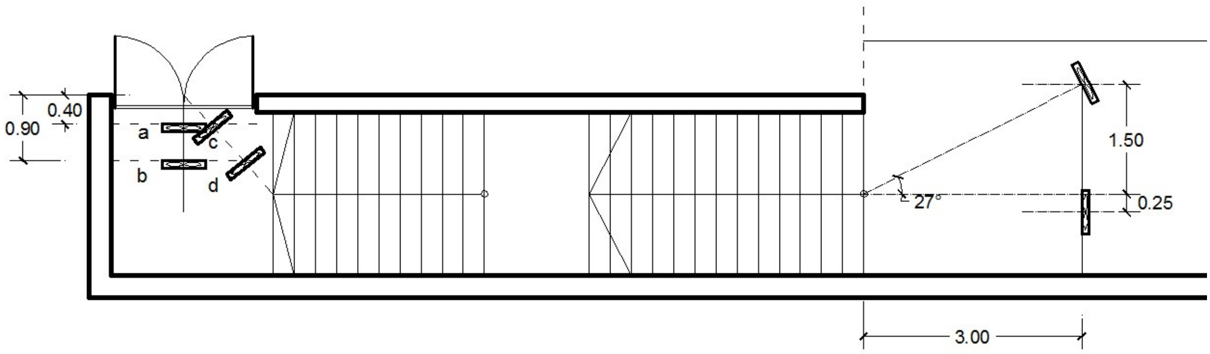

Figure 4.11 Four different fan positions at the top of the staircase. Position a: 40 cm from the door. Position b: 90 cm from the door. Position c: 40 cm from the door on the line that connects the middle of the door with the middle of the stairs ('turn close'). Position d: 90 cm from the door on the line ('turn far'). Two additional fans were placed on the platform. (Drawing: Ruxandra Darmon).

The fan at the top of the staircase was placed first of all on the middle line of the exit 40 cm from the door. The distance was then changed to 90cm. The two final positions were set-ups where the axis of the fan was on the line which connected the middle of the stairs to the middle of the door. Firstly, the fan was placed close to the exit door ('turn close') and, finally, it was placed close to the stairs and further away from the exit door ('turn far').

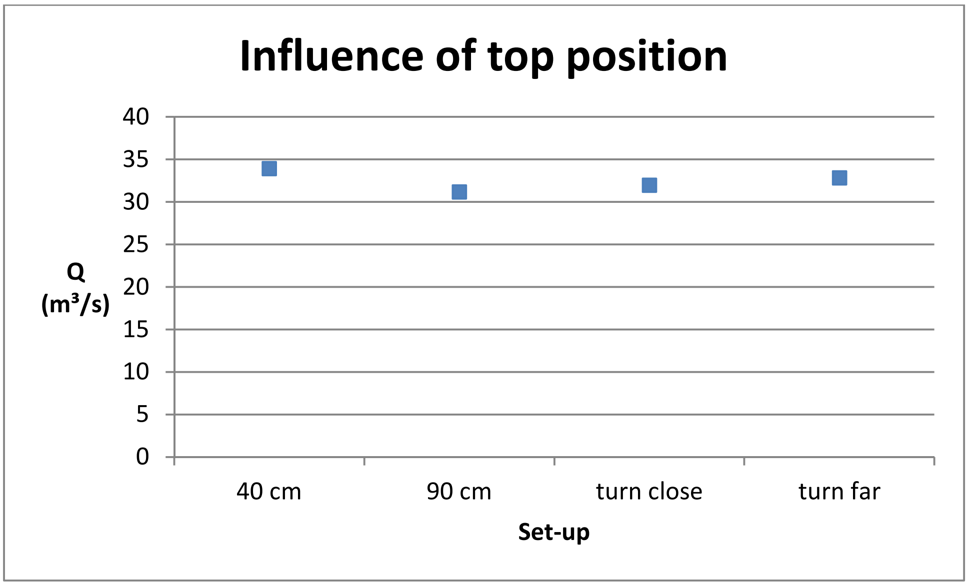

Figure 4.12 The comparison of four positions at the top of the staircase.

Figure 4.12 shows that the influence of the top position is limited. The best position is 9% better than the worst position.

4.3.3 Four fans vs three fans

The FDS study of the fans in parallel (see 4.1.2) showed that it was necessary to position the fans so that there was sufficient space between them. In the subway building in Frankfurt, the geometry of the building didn't allow to position three fans on the platform with sufficient space between the fans.

Figure 4.13 Three fans placed on the platform in the Frankfurt subway building. The fans are positioned with reference to the middle line of the stairs. From right to left: -25cm, +67cm and +150cm. The stairs are behind the photographer. The fan which is right in the picture is addressed as 'left' in the text and vice versa.

Therefore, it was interesting to check whether or not adding a third fan on the platform had any extra benefit. To evaluate this, 16 tests were performed. In eight tests, two fans on the platform were combined with one fan at the top of the staircase. In the other eight tests, a third fan was added on the platform. In all the tests, the fan at the top of the staircase was positioned in such a manner so that the axis of the fan was on the line that connected the middle of the stairs with the middle of the exit door.

In the tests with two fans on the platform, two ESV280 fans were placed as described above (-25cm and +150cm). The distance to the first step of the stairs varied from three to nine metres with a two metre interval. The fan at the top of the staircase was an ESV280 as well.

In the tests with three fans on the platform, the third ESV280 fan was placed in between the two other fans (see Figure 4.13). The distance to the middle line was +67cm and axis of the fan was parallel with the middle line of the stairs. The distance to the first step of the stairs varied from three to nine metres with a two metre interval. A park fan was placed at the top of the staircase.

All the tests were performed twice. In the first series, the angle of inclination for all the fans was 10°. In the second series, the angle of the fans on the platform was 18° while the inclination of the park fan at the exit remained 10°.

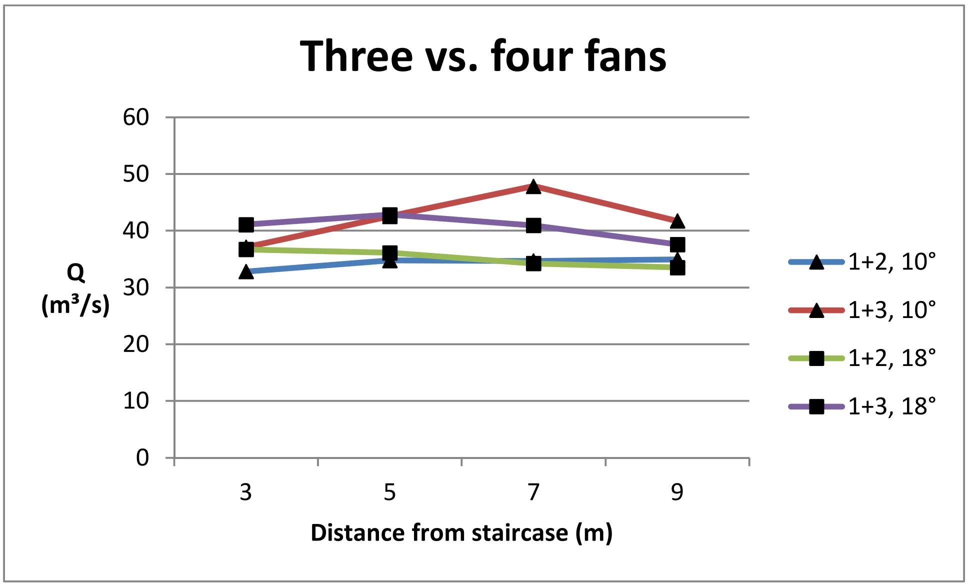

Figure 4.14 Comparison of placements with two and three fans. The triangles refer to fans with an inclination of 10°, the squares to an inclination of 18°. Note that measurements have only been made where a symbol is depicted in the figure. The lines, connecting the symbols, have been added for clarity.

It can be seen from Figure 4.14 that the combinations with three fans on the platform are better than the combinations with only two fans on the platform. The difference between the set-ups varies from 12 to 38%. The difference between the two set-ups was limited but it would probably increase if the platform were wider. In that case the distance between the three fans would be greater and the generated flow would be increase as outlined in 4.1.2.

The flow rate generated by the set-ups with four fans varies from 37.11 m^3/s to 47.85 m^3/s. The flow rate generated by three fans varies from 32.81 m^3/s to 36.97 m^3/s. All set-ups were capable of preventing backlayering in a tunnel connected to the Frankfurt station.

4.3.4 Position of the fans (four fans)

In total 29 tests were performed with four fans in the underground station. In every experiment, one car park fan was positioned at the exit of the subway building on the upper floor (various positions). In 12 of the experiments one ESV280 fan was placed on the landing of the staircase. This fan was always positioned on the middle line of the landing with the back of the fan at the edge of the landing. The other two ESV280 fans were placed on the platform at four different distances from the staircase: 3, 5, 7, and 9 m (see Figure 4.15). The two fans on the platform were positioned with reference to the middle line of the stairs (-25 cm and +150 cm). The fan furthest to the left had its axis parallel with the middle line of the stairs while the fan furthest to the right had its axis oriented on the middle of the stairs. This meant that it was turned 9-27° horizontally, depending on the distance to the stairs.

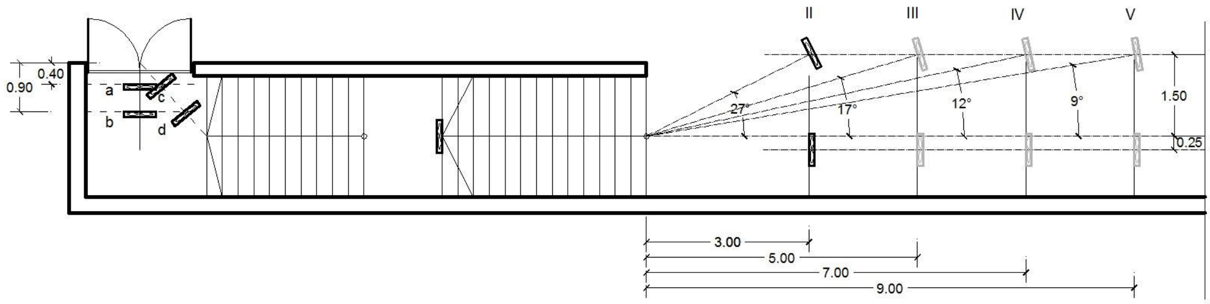

Figure 4.15 Positions of the fans in the experiments. At the top of the staircase, the four different positions are indicated by a, b, c and d. On the landing, there was only one position. The two fans on the platform were placed at four different distances. (Drawing: Ruxandra Darmon)

In the 17 other experiments, there was no fan on the landing. The fourth fan (ESV280) was also placed on the platform at a distance of +67 cm with reference to the middle of the stairs.

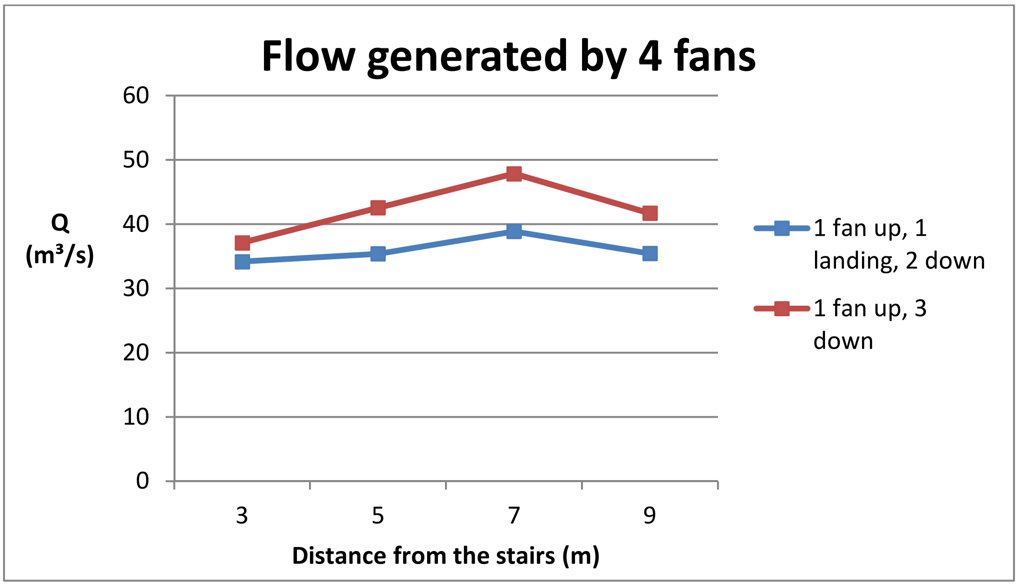

Figure 4.16 Comparison of two different types of set ups. One car park fan was placed at the exit door of the building. Two ESV280 fans were placed on the platform. The third ESV280 fan was placed on the landing (blue line) or on the platform between the two other fans (red). Note that measurements have only been made where a symbol is depicted in the figure. The lines, connecting the symbols have been added for clarity.

The results in Figure 4.16 show that the set-ups with three fans on the platform and one at the building exit generate a higher flow at any distance from the staircase than the set-ups with two fans on the platform, one on the landing and one at the building exit. The extra flow generated varies from 9 to 23%. There seems to be an optimum at 7 m distance from the stairs.

4.3.5 The vertical inclination of the fans

The fans used in the experiments can be given a vertical inclination. The minimum inclination is 10°, whilst the maximum inclination is 18° [38]. Both extremes were tested during the 22 tests. The results of three series of tests are shown in Figure 4.17. In all tests, the fan upstairs was positioned intuitively (see 4.3.2: 'turn far'). In the tests with three fans, this was an ESV280 fan. In the tests with four fans, it was a car park fan. In the first series of tests ("1+2"), two ESV 280 fans were placed on the platform. The two fans were placed with reference to the middle line of the stairs (-25cm and +150cm) The distance to the stairs for the two fans on the platform varied from three to nine metres with an interval of two metres. The test was done twice. The first time, all the fans had an inclination of 10°. The second time, the two fans on the platform had an inclination of 18°. In a second series of tests ("1+3"), a third fan was placed on the platform as described above. At first, all fans had an inclination of 10°, then all the fans on the platform had an angle of 18°. In a third series of tests ("1+1+2") the third fan was placed on the landing instead of on the platform as described above. The first time, all the fans had an angle of 10°. After these tests, the angle of the fans on the platform and landing was altered to 18°.

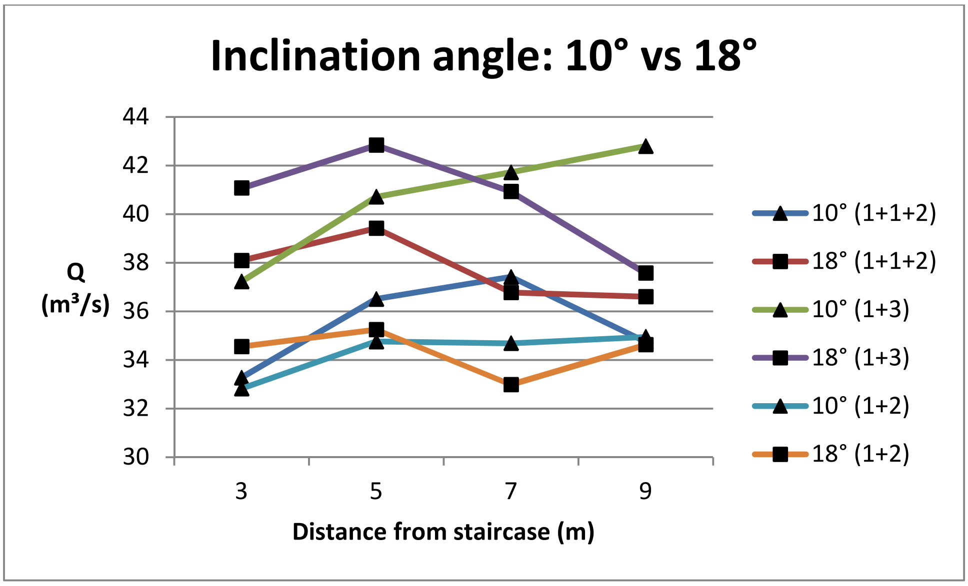

Figure 4.17 Comparison of three series of tests where set-ups with an inclination of 10° (triangles) were is compared with set-ups with an inclination of 18° (squares). Note that measurements have only been made where a symbol is depicted in the figure. The lines connecting the symbols have been added for clarity.

Figure 4.17 shows that the set-ups with an inclination of 18° generated a higher flow then the set-ups with 10° when they were placed closer to the staircase. At a distance of five metres from the first staircase step, the fans which were tilted at 18° generated the highest flow in every configuration. The optimum for fans with an inclination of 18° seemed to be five metres. This is logical because the 18° tilted fan will generate a flow directed at a height of 1.9 m. This is more or less the middle of the height of the opening towards the staircase.

4.4 Comparison of the Frankfurt test results with the FDS simulations (a priori and a posteriori)

4.4.1 Qualitative comparison

In experiments, it was found that there is an optimal distance for the position of the fans on the platform. This distance was seven metres for fans with an inclination of 10° (see Figure 4.16) and 5 metres for the fans with a 18° inclination (see Figure 4.17).

These optima are not found at the same distance in the *a priori* simulations. In Figure 4.7, it can be seen that there is no optimum for fans with zero inclination. The optimum for fans with 10° inclination is at 10 metres while the optimum zone for 18° fans begins at seven metres.

The geometry was composed starting with the building plans of the underground station. Small modifications to the building were made during the building process.

4.4.2 A posteriori modelling

A series of experiments was modelled in FDS. In experiments 72-75, three ESV fans on the platform were combined with one park fan at the exit. The distance to the staircase varied from three to nine metres with a two-metre interval. In order to match the experiment with the simulation, the flow rate of the fans had to be adapted. Since two different types of fans were used, the ratio between the flow rates of the fans was kept constant. The results are shown below:

No.	Experiment (m^3/s)	Simulation (m^3/s)	No.	Flow park fan (m^3/s)	Flow ESV280 (m^3/s)
E72	37.1	37.1	FF129	15.03	12.65
E73	42.5	42.5	FF132	16.53	13.91
E74	47.8	47.8	FF131	18.59	15.64
E75	41.7	41.5	FF130	16.27	13.68

Table 4.7 A posteriori modelling of experiments. The nominal flow of the fans varied to become the measured value from the experiments.

It can be seen that the modelled flow rate has a variation of 23% between the highest and the lowest flow. The value of 15 m^3/s for the park fan has been used as an input value for the simulations of the Brussels underground station.

Experiments 72-75 were simulated again with a flow rate of 14 m^3/s for the ESV280 and 16.64m^3/s for the park fan. This led to the following results.

No.	Experiment (m^3/s)	Simulatie (m^3/s)	No.	Deviation (%)
E72	37.11	41.5	FF188	+11.86
E73	42.54	43.1	FF189	+1.41
E74	47.8	42.8	FF190	-10.46
E75	41.7	42.3	FF191	+1.44

Table 4.8 Simulation of experiments 72 to 75 with a square vent model. The ESV280 fan has an imposed flow rate of 14 m^3/s. This is 16.64 m^3/s for the park fan.

The deviation between the simulations and the experiments were limited to 11.86%.

4.4.3 FDS simulations of a tunnel with and without a burning underground train

The generated flows during the experiments reached a maximum of 47.8 m^3/s. This would generate a velocity of 3.63 m/s in a virtual tunnel attached to the Frankfurt subway underground. The presence of the tunnel itself will generate friction losses and reduce the flow rate. Simulations were performed with tunnel lengths up to 480 metres. This length is representative for the tunnel lengths in Brussels. The reduction of the flow was limited to 5%.

No.	Length (m)	Flow (m^3/s)	Velocity (m/s)	Effectiveness (%)
FF97	0	33.1	2.52	100
FF103	24	32.9	2.51	99.40
FF104	64	32.8	2.50	99.09
FF105	204	32.4	2.47	97.89
FF112	480	31.2	2.38	94.26

Table 4.9 Simulation of experiment 59 (FF97). A virtual tunnel was added to the underground building with an increasing length. The generated flow decreased with an increasing tunnel length.

In reality, the tunnel will have larger dimensions since all tunnels have two tracks. The presence of a train in the tunnel will generate higher velocities locally around the train since the train reduces the section of the tunnel. Simulations were performed with a 6.4 metre wide tunnel.

In the case of a fire in the tunnel, the fire will have an influence on the generated velocities. In order to evaluate what the used fans were capable of, simulations with a burning train in the tunnel have been performed. A simulation was performed in the wider tunnel with the placement of the fans that generated the maximum flow during the experiments. A train generating an 8 MW fire was simulated in the tunnel.

$$Q^{"} = \frac{Q}{\rho_0 c_p T_0 g^{1/2} \bar{H}^{5/2}} = \frac{8000}{1.2 \times 1.0 \times 293 \times \sqrt{9.81} \times 5.04^{5/2}} = 0.1277$$

$$V^{"} = 0.40\,(0.20)^{-1/3} Q^{"1/3} = 0.40\,(0.20)^{-1/3} 0.1277^{1/3} = 0.344$$

$$V^{"} = \frac{V_{cr}}{\sqrt{g\bar{H}}} \rightarrow V_{cr} = V^{"} \times \sqrt{g\bar{H}} = 0.34 \times \sqrt{9.81 \times 5.04} = 2.42\ m/s$$

A critical velocity of 2.42 m/s was calculated with the Wu & Bakar formula [20]. By applying the work of Li [21], this value could be reduced by 34%. By doing so, the required critical velocity became 1.60 m/s. In the simulation a velocity of 1.84 m/s was found and backlayering was prevented. Backlayering was also prevented with a 10 MW fire. In the case of a 12 MW fire, the corrected critical velocity became 1.83 m/s. In this simulation backlayering occurred over a distance of 12 metres. (see Figure 4.18)

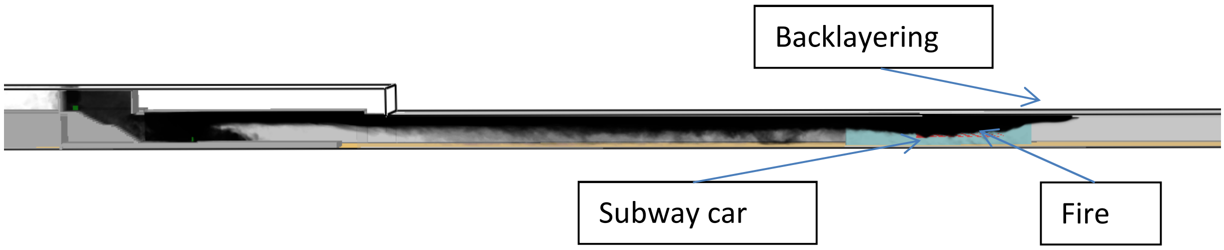

Figure 4.18 A underground train is burning in the tunnel. The heat release rate is 12 MW. The ventilation flow rate is 48.9 m³/s. The backlayering length is limited.

4.5 FDS simulations: Evaluation of fan behaviour in the Brussels underground station

The results of the full scale experiments and simulations of the building in Frankfurt were used to model the fans in the Brussels underground station. Due to the size of the domain the simulations took up to 30 days. Therefore the number of simulations in this station was limited.

4.5.1 Ventilation velocities

When the fans were simulated with a square vent that flows 15 m^3/s, the total generated flow in the station was 165 m^3/s. This led to a velocity of 1.55 m/s on the tracks at the station entrances.

When the flow rate of the fans increased by 10%, the total generated flow reached 180 m^3/s. The velocity on the tracks became 1.69 m/s.

When the flow rate of the fans decreased by 10%, the total generated flow reached 148 m^3/s. The velocity on the tracks became 1.40 m/s.

4.5.2 Maximum heat release rate without backlayering

The two tracks are separated by technical rooms in the station. They have a joint section of 9.6 x 5.4 m (W x H). The formula of Wu and Bakar [20] was used to calculate the maximum heat release rate of the fire that would not lead to backlayering on the tracks. The ventilation velocity was created by 14 fans that deliver a flow rate of 15 m^3/s, which leads to a velocity of 1.55 m/s on the tracks.

$$V^{"} = \frac{V_{cr}}{\sqrt{g\bar{H}}} = \frac{1.55}{\sqrt{9.81 \ \times 6.91}} = 0.188$$

$$V^{"} = 0.40\ (0.20)^{-1/3} Q^{"1/3} \rightarrow \ Q^{"} = (\frac{V^{"}}{0.4\ (0.20)^{-1/3}})^3 = (\frac{0.188}{0.684})^3 = 0.0208$$

$$Q = Q^{"} \rho_0 c_p T_0 g^{1/2} \bar{H}^{5/2} = 0.0208 \times 1.2 \ \times 1.0 \ \times 293 \ \times \ 9.81^{1/2} \times \ 6.91^{5/2} = 2882\ kW$$

A fire on the tracks can develop up to 2.8 MW before backlayering occurs.

Outside the station the tracks join in the tunnel tube. The dimensions of the tunnel are 14.4 x 5.4 m (W x H). This is a larger section than the combined section of the two tracks that enter the station. A velocity of 1.55 m/s on the tracks would lead to a velocity of 1.04 m/s. When the calculation procedure is repeated with these values, the maximum heat release rate without backlayering is 992 kW.

For the fire service it is important to estimate the backlayering distance in the case of a fire. A 12 MW fire led to a backlayering distance of 12 metres in the simulations of the Frankfurt underground station with a 6.4 m wide tunnel. The same HRR was used to calculate the backlayering distance in the Brussels underground tunnel using the formula given by Ingason [18].

$$L_b = 1.4 \left(\frac{g\ Q}{\rho_a c_p T_a u^3 H} \right)^{1/3} H = 1.4 \left(\frac{9.81 \times 12000}{1.2 \times 1.0 \times 293 \times 1.04^3 \times 5.4} \right)^{1/3} 5.4 = 28.73\ m$$

5 Discussion

5.1 FDS simulations in a simple geometry

The model that has been used in the bulk of the simulations is the square vent. It is shown that modelling the fan close to the ground leads to a reduction of the flow. This is what can be expected.

An important observation is that the effect an optimal distance between two fans in parallel increases with an increasing hallway width. This is important in underground stations where wide hallways are present. In an eight-metre wide hallway, the best position generates a flow that is 50% higher than the case where there is only 80 cm between the fans.

When fans are placed in parallel, there is a major influence if the fans are placed close to the wall or close to each other. When the fans are positioned too close to the wall, the generated flow rate decreases compared to the situation where the available space is used to create the ideal position for both fans. The same goes for two fans which are positioned too close to each other. The main conclusion of this part of the study is that the correct placement of the fans becomes more important as the hallway gets wider. If there is sufficient room, it is necessary to space the fans. This corresponds to information received from the manufacturer [38].

When these data are studied in detail, we can conclude that two fans obtain the best results if they are positioned at 1/4th of the width of the hallway. Intuitively one would position the fans at 1/3rd. It turns out that it is better to put them closer to the walls to compensate for the wall friction.

Finally, it can be seen from the results that the flow is increasing with increasing distance between fans that are positioned in series.

5.2 Experiments and FDS simulations in Frankfurt underground station

In both the simulations and the experiments, it is shown that the position of the fan at the top of the staircase doesn't have a big influence. Whether the fan is positioned close or far from the door, perpendicular to the outlet opening or turned, the influence remains limited.

For the tests with four fans, the choice was made to work with the position 'turn far' (see Figure 4.11 and Figure 4.12). This position corresponds to an intuitive position. The flow coming from the stairs has to make a turn to go through the opening. For firefighters, it feels intuitive to place a fan at this position. Besides finding the optimal position of a fan for this building, it is important to think about how to formulate general rules for positioning fans in underground stations. With this factor in mind, the choice for the turned position far from the door is the best.

It must be pointed out that a major influence of the wall will occur when a fan is too close to it. In this case the flow towards the fan will be hindered by the wall. The manufacturer [38] has issued a warning about this and it is the effect was measured by Lambert [37]. The fan model that is used in FDS in this study doesn't represent this. This is the case because the fan is simulated by an obstacle which is introducing air through the front side and which is extracting air at the rear. There is no coupling between these two flows in the model. In reality, the air that is leaving the front side of the fan is the same volume flow that entered the fan at the rear. The model in FDS represents the flow but not the fan (characteristic) itself. There is no correlation between the flow rate and the pressure field in the proximity of the fan. The extract side of the fan will cause a relative negative pressure in reality. This negative pressure tends to decrease the flow rate going into the fan. This is not taken into account in the fan model adopted.

The experiments showed that the position of the fans on the platform has a major influence on the generated flow rate. An optimal flow is generated when the fans are placed five to seven metres from the staircase. When the inclination angle of the fan is 18°, the optimum placement will be closer to the staircase (5m) than with a 10° inclination (7m). The fans cannot be placed too close to the stairs. This will cause the effectiveness to drop. This can be important in realistic set-ups where the available space to set up the fans is limited.

When a fourth fan is added, it generates a better result when it is added on the platform (in parallel) rather than when it is placed on the landing (in series). Even though the fans are positioned too close to each other, a third fan on the platform generates a higher flow than combining one fan on the landing with two fans on the platform. This is important for placement of fans in reality. In real stations, the platform might be wider. The fans can be placed with more space in-between. This will tend to to even higher flow rates.

During the experiments, several placements with three and four fans achieved a flow superior to 31.2 m³/s. This flow rate would create a velocity superior to the critical velocity in a tunnel that would be connected to the Frankfurt station.

The flow rate measured in the experiments varied between 36-50% of the flow rate in open air as given by the manufacturer. The ratio decreased when four fans are used instead of three. The average ratio for placements with three fans was 46%. This became 40% for the placements with four fans. In the *a posteriori* simulations of the experiments, a ratio of 58% was found. This shows that a certain loss in effectiveness is not modelled in FDS.

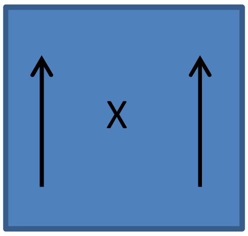

Figure 5.1 Square vent model. The normal component is represented by the "X". The arrows indicate the tangential component.

In the simulations, the optimum distance to the stairs was found to be a different value than in the experiments. Typically, the optimal distance was further away from the staircase in the simulations. The difference between the experiments and the simulations must be found in the way the fans are modelled in FDS. In the simulations, the fans are modelled as a square vent with a normal and a tangential velocity (see Figure 5.1). The vector sum of these components has to form the flow. In reality, the flow pattern is more complex. There is a rotational component of the fan that is not simulated. In the middle of the fan there is a hub where there is no flow going through the fan. Moreover, there is an area with a lower effectiveness since the presence of the engine of the fan blocks the flow of air to the fan. This leads to an annular flow leaving the fan. This is not modelled. The combination of the annular flow and the rotational component will lead to a higher entrainment of air in the flow in reality than is modelled. During experiments, the flows of the fans will interact. Since the complex flow pattern of one fan is not modelled correctly, the interaction will not be modelled correctly either. Other effects which are not taken into consideration are the furniture on the platform and small differences between the simulated station and the real building. A last item that influences the difference between the simulations and the experiments is the experimental uncertainty. Weinschenk [15] mentions the accurate quantification of the leakage area as an important factor. The influence of leakage area was checked with 12 simulations and showed to be minor.

The optimal placement of the fans was capable of creating good conditions for firefighters for a fire up to 10 MW in a 6.4 metre wide virtual tunnel connected to the Frankfurt station. When the heat release rate of the fire reaches 12 MW, limited backlayering occurs. Backlayering lengths of less than 15 metres are acceptable for the fire service [44]. This means that the tested setting with the best result enables the fire service to launch an attack from the upstream side of the fire with a considerable amount of success.

In reality, a wider tunnel with two tracks will result in two platforms or in a wider platform. This means that fans can be placed with more space in between or more fans can be placed. A higher flow rate can then be achieved.

5.3 FDS simulations in Brussels underground station

The experiments in Frankfurt were modelled *a posteriori* in section 4.4.2. A flow rate of 15 m^3/s was found to be a conservative value for a park fan. For the simulations in the Brussels station, this flow rate was used as a basis.

The velocity obtained in the tunnel was in excess of 1 m/s. This means that the ventilation would be sufficient to limit the backlayering length in the case of a major fire. Moreover, stratification would be enforced. This will allow the fire service to attack the fire in easier conditions than the situation without PPV. The backlayering length could be very long since the velocity obtained is at the lower end of the moderate forced air velocity as defined by Ingason [18]. In the case of a minor fire, backlayering can be avoided. This leads to the conclusion that the PPV fans will be capable of creating a smoke-free environment when the fire is extinguished.

It should be noted that the fire will create a throttling effect [26]. This will have an impact on the flow created by the fans.

Another effect that has not been studied in this work is the effect of the wind on the ventilation. The wind will have an impact on the portals of the tunnels and on the station entrances. In the underground system, there is a current present due to pressure differentials at the different openings. The flow generated by the PPV will be impacted by this current. Another important transient effect is when an underground train drives through the tunnel. This has not been taken into account because the assumption is made that traffic is stopped during a fire in the subway.

6 Conclusions and future work

The general conclusion of this thesis is that the tested fans are capable of removing the smoke after a fire in a basic underground station to create a smoke-free environment. After a fire a smoke-free environment needs to be created in order to restart the underground system.

In the small Frankfurt station, the fans were capable of realizing a flow above the critical velocity in the small tunnel. This means that the tested fans are capable of preventing backlayering in a tunnel that would be attached to such a underground station. This is very important for firefighters because they can attack the fire coming from a smoke-free environment. The PPV fans could be used successfully for tactical ventilation in a small underground tunnel.

In the bigger Brussels station, the achieved velocity was lower than the critical velocity and backlayering will not be prevented. In the event of a major fire the PPV fans will not be able to limit backlayering length below 15 metres [44]. Therefore the added value of PPV prior and during extinguishment is limited.

In more complex stations, the obtained result will depend on the geometry of the station (number of exits and floors), the locations of the fans and the location of the fire.

The flow rate measured in the experiments varies between 36-50% of the flow rate in the open air as given by the manufacturer for the Frankfurt building.

In this thesis, it was shown that the tested fans have the capability of generating a significant flow. Further work is needed to turn this knowledge into practical application. Tactics need to be developed considering the manpower needed to place the fans. An important factor will be the positioning of the fans in a smoke-filled environment. The smoke temperatures could present a problem. The thermal imaging camera (TIC) will be an important aid to evaluate this and to navigate inside the building. Training will be needed, both for the firefighters that have to position the fans and for the (chief) officers who will command the operation.

Seeing as the fans need an significant electrical supply, work needs to be done to create a logistical part that consists of one or more trucks, fans, electrical generators and several sets of long cables.

A lot of time was spent in doing FDS simulations. Future work could consist of developing a "library" with fan models of commercial available fans. Such a model should allow to incline the fans at a given angle and to turn them horizontally as is done in reality. In these applications, the swirling effect that is present in the Weinschenk model [36] should be conserved. Moreover a study could be performed to implement the fan characteristic (pressure vs flow rate). This development would be very challenging but if this would be available, real life situations could be simulated in order to prepare ventilation plans for fires in all kinds of buildings.

In this thesis, all the fans were positioned in one (small) underground station. Situations where fans are positioned in several adjacent stations are very interesting as well. This has not been done since doing experiments is not possible and since the computing capacity for such an approach is very demanding. To a lesser degree, the same goes for ventilation scenarios in bigger underground stations where up to four levels below grade are connected with 8 escalator blocks. Further research could look into ventilation methods which are possible in such stations.

The experiments were limited to four fans. It was seen that the ratio of effectiveness of four fans is lower than for three fans even though the total generated flow was higher. Experiments with more fans could provide more insight into the usage of more fans.

Further simulations should be performed to evaluate the effect of the fire on the obtained velocity. More fans will have to be added depending on the heat release rate of the fire to cope with the throttling effect.

Finally, a study could be performed to evaluate the wind effects on the usage of PPV. Data on the current present in the underground stations could be collected. Moreover, the effect of the wind direction and velocity on the exits could be estimated.

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During this programme I found my classmates to be a group of interesting people. We had a good time and I learnt a lot from them.

Last but not least, I would like to thank my family: my parents, my son and his mother. All of them made sacrifices so I could participate in this programme.

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Appendices

A. The subway stations in Brussels

Stations with one level below grade

Heysel	Maalbeek	Hankar
Weststation	Sint-Guido	Petillion
Beekkant	Beaulieu	Pannenhuis
Eddy Merckx	Kraainem	Sint-Katelijne
Het Rad	Alma	Delacroix

Stations with two levels below grade

Houba-Brugmann	Louiza	Aumale
Koning Boudewijn	Madou	Bizet
Troon	Ceria	Clemenceau
Naamsepoort	Roodebeek	Zwarte Vijvers
Ribaucourt	Delta	Munthof
Kunst-Wet	Gribeaumont	Jacques Brel
Bockstael	Herreman-Debroux	Stuyvenbergh
Kruidtuin	Thieffry	Veeweide
De Brouckère	Tomberg	IJzer
Simonis	Vandervelde	
Centraal Station	Josephine-Charlotte	

Stations with three levels below grade

Graaf Van Vlaanderen	Schuman	Montgommery
Merode	Zuidstation	
Rogier	Hallepoort	

Stations with four levels below grade

Park

Stations above grade

Erasmus	Osseghem
Demey	
Stockel	

B. Bidirectional probes

In order to do the measurements a grid with bidirectional velocity probes will be installed. The probe described by McCaffrey and Heskestad [39] in 1976 will be used. This probe consists of a steel tube with length/diameter ratio of 2 (see Figure 3.9).

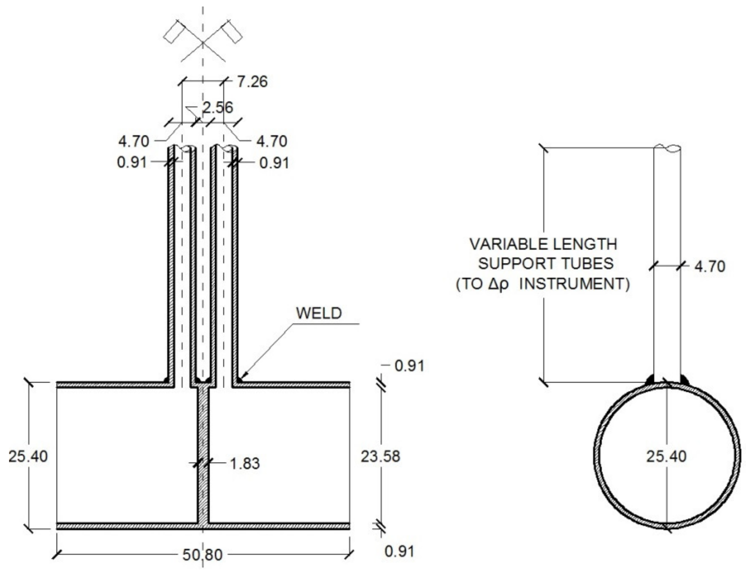

Figure 0.1 The bi-directional probe used in the experiments (Graphic: adapted after Heskestad and McCaffrey [39])

The following formula will be used to convert the pressure difference in a velocity:

$$V = \frac{\sqrt{\frac{2\Delta p}{\rho}}}{k_p} \qquad (Eq\ 3.1)$$

k_p is the calibration constant.

In their paper, Heskestad and McCaffrey state that there is no significant influence of the diameter on the calibration if the diameter is between 12.7 and 25.4 mm. Further, they suggest to use a value of k_p of 1.08 if the Reynolds number of the flow is higher than 3800. In the interval 40 to 3800, they suggest an equation to determine the calibration factor:

$$k_p = 1.533 - 1.366\ \times 10^{-3} Re + 1.688\ \times 10^{-6} Re^6 - 9.706 \times 10^{-9} Re^3 + 2.555 \times 10^{-13} Re^4 - 2.484 \times 10^{-17} Re^5 \qquad (Eq\ 3.2)$$

In order to use the above equation, the velocity is first calculated with equation 3.1. The result is used to calculate the Reynolds number. If the Reynolds number is lower than 3800, equation

3.2 is used to calculate a value for k_p. With the new value of k_p a new value for the velocity can be determined. This is iterated until the velocity converges to a value.

With Reynolds numbers higher than 500, the value of k_p is fairly constant. The value of k_p varies from 1.48 to 1.17 when the Reynolds number varies in the range 40-500. When the above calculation procedure is applied, it can be seen that the influence of the calibration factor is significant in this range. By using a 25.4 mm diameter probe, the Reynolds number doubles and it is less likely to obtain a higher value for Re. Further, it is mentioned in the paper that it is reasonable to take a 25.4 mm diameter probe in full scale tests. That is why this diameter has been chosen for these experiments.

Lastly, McCaffrey and Heskestad suggest to pay attention with velocities that are much lower than 0.3 m/s. At low velocities, problems might arise with the resolution of the pressure transducer.

Sette [40] performed more in-depth research on the constant k_p. He found a value of 1.046 for k_p when the Reynolds number of the flow is in the interval 2 500 -18 000. A Reynolds number of 2500 corresponds with a flow velocity of 1.49 m/s. A Reynolds number of 18 000 corresponds with a flow velocity of 10.71 m/s. In section 3.4.5 a criterion of success is suggested. In order for the experiments to show that the used fans are effective, the velocity should be 2.37 m/s or higher. The velocity of the flow generated by the fans in positions that are useful for the fire service will probably have a Reynolds number higher than 2 500. This will be checked when the experimental data are processed.

Since the experiments were performed without a fire source, the ambient temperature can be used to determine the density of the air. This density is used in equation 3.1 to calculate the velocity.

C. Results with the Weinschenk model

The fan model that was developed by Weinschenk consists of four parts [15]. The generated current by each part has a normal component and a tangential component (see Figure 0.2). The four tangential components generate a swirling effect. For this reason, the model is also called "the rotational flow model".

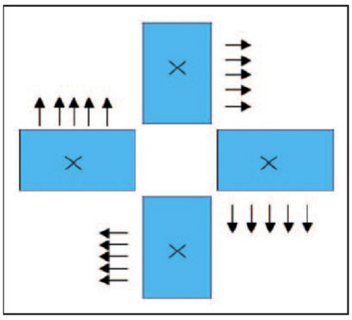

Figure 0.2 Schematic of rotational flow PPV fan model. The model consists of four parts. In each part, the X indicates the normal component of the velocity and the arrows indicate the rotational component. Taken from Weinschenk [15].

Simulations were performed in a small tunnel section with the model in order to determine the flow rate of the components. The manufacturer provided two important numbers: the generated flow rate in open air and the flow rate going through the shroud [38]. These numbers were 104,000 and 30,000 m^3/h respectively. This means that a large quantity of air is entrained in the flow.

When the vectors of the two components are added, a new vector appears. This new vector makes an angle with the normal direction. The magnitude of this angle is dependent on the ratio between the two components. Simulations were performed in a short tunnel section (4.6 X 2.8 X 10 m) with the angle as variable. It's influence on the entrainment was verified.

To do so a rotational flow model was modelled where the combined flow rate of the normal and the tangential component was 30,000 m^3/h (8.33 m^3/s).

The results of the simulations can be found in Table 0.1. The column "Flow" indicates the flow rate that was generated. The velocity was the generated velocity normal to the section of the tunnel. The column percentage compares the result to a simulation with an angle of 35°. The column effectiveness represents the ratio between the imposed flow (8.33 m^3/s) and the generated flow. It is a measure of the entrainment.

It can be observed that the entrainment can be modelled correctly. With an angle of 17.5°, the entrainment corresponds with the data given by the manufacturer. The effectiveness is 349 %

for this angle. The effectiveness for the square vent model can be found in Table 4.1. With the square vent model, the entrainment is not well represented.

Angle (°)	Flow (m^3/s)	Velocity (m/s)	Percentage (%)	Effectiveness (%)	Nr
35	27.4	2.13	100	329	F98
30	38.7	3.00	141	465	F99
25	38.2	2.97	139	459	F100
20	33.6	2.61	123	403	F101
15	23.0	1.79	84	276	F102
10	16.3	1.27	59	196	F103
17.5	29.1	2.26	106	349	F104
16	25.0	1.94	91	300	F107

Table 0.1 Simulation with the rotational flow model in a short tunnel section.

The rotational flow model was also used in simulations of experiments in the Frankfurt subway station (see Figure 0.3). Three fans were modelled into the subway geometry. The components of the rotational flow model had to be adapted since the fans were tilted (vertically) and turned horizontally in the experiments.

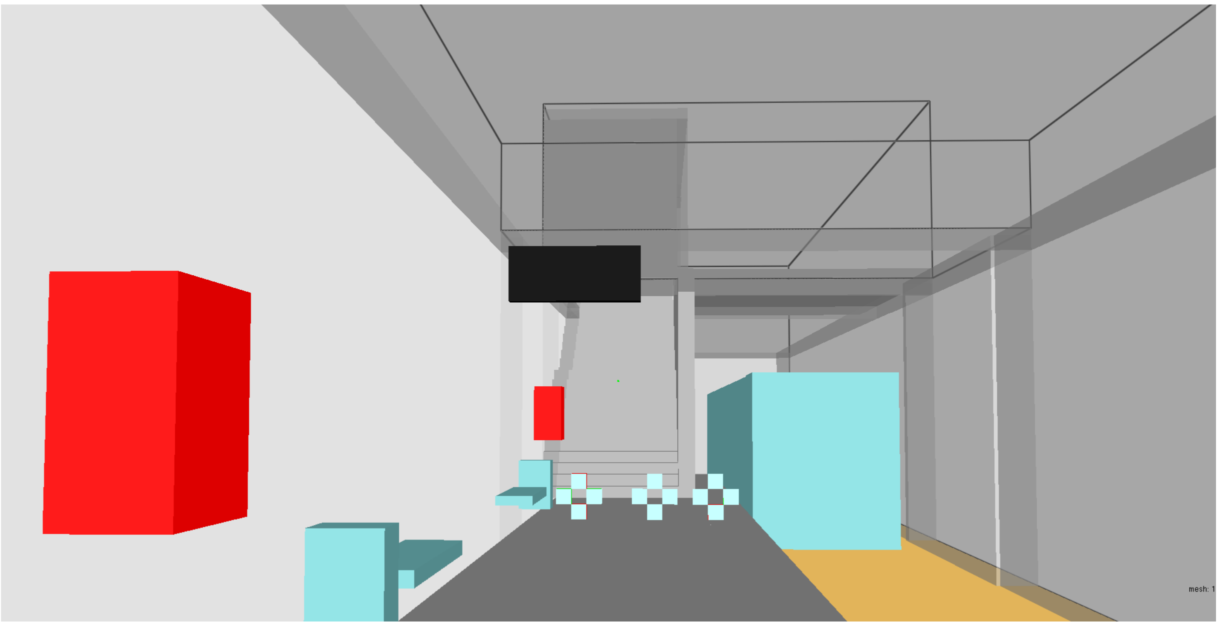

Figure 0.3 Three fans using the Weinschenk model in the Frankfurt subway station.

All fans were tilted 10°. This leads to an extra component for the upper and lower block in Figure 0.2. These two blocks had two tangential components, one in the z-direction and one in the y-direction. The angle between the two components of the two side blocks was changed into 27.5° (left) and 7.5° (right). By doing so both side blocks have a vector sum that had an upward direction. The rotational effect was lost.

When the fan was tilted 10° and turned 18°, all the four blocks had three components. This had a detrimental effect on the rotational effect. A comparison between both models and the experiment can be found in Table 0.2. Both models were simulated with a 5 cm mesh in the zone where the fans were simulated. It can be seen in the column "V/Exp" that the simulations with the square vent model are in a range of -2% till +17% compared to the experimental values.

Square vent model	Flow (m^3/s)	V/Exp (%)	Weinschenk model	Flow (m^3/s)	W/Exp (%)	Experiment (m^3/s)	Nr
FF192	43.4	116.98	**FF202**	35.0	94.34	37.1	**E72**
FF193	45.6	107.29	**FF203**	31.8	74.82	42.5	**E73**
FF194	47.2	98.74	**FF204**	17.8	37.24	47.8	**E74**
FF195	44.8	107.43	**FF205**	17.9	42.93	41.7	**E75**

Table 0.2 Comparison of the square vent model and the Weinschenk model with experiments

The ratio between the simulated flow with the Weinschenk model and the experimental values is shown in the column "W/Exp". It can be seen that the correlation between both is not acceptable. This is because of the loss of the rotational element. A solution to this problem has not been found during the work of this thesis.

D. Full scale experiments

N°	Fan N°	distance to stairs	position Fan 1	position Fan 2	position Fan 3	position Fan 4	Flow rate (m^3/s)
1	3		40cm				
2	3		90cm				
3	1		40cm				18.99
4	1		90cm				16.88
5	1		O: 0cm				15.11
6	1		O: 50cm				5.64
7	4		O: 0cm				10.40
8	4		O: 50cm				11.74
9	1	1					10.82
10	1	3					13.78
11	1	5					21.26
12	1	7					18.55
13	1	9					16.81
14	4	1					9.57
15	4	3					15.91
16	4	5					15.56
17	4	7					19.62
18	4	9					19.60
19	4+5	1	-50	+50			15.25
20	4+5	3	-50	+50			25.70
21	4+5	5	-50	+50			33.80
22	4+5	7	-50	+50			29.43
23	4+5	9	-50	+50			27.24
24	4+5+3	7					40.36
24A	4+5+3						38.44
24B	4+5+3						38.11
25	4+5	L: 0 cm	-50cm	+50cm			19.62
26	4+5	L: 50 cm	-50cm	+50cm			19.92
27	(3+5)+4	L: 0 cm	-50cm	+50cm	40cm		26.63
28	(3+5)+4	L: 0 cm	-50cm	+50cm	90cm		28.12
29	(3+5)+4	1	-50cm	+50cm	40cm		28.63
30	(3+5)+4	3	-50cm	+50cm	40cm		33.74
31	(3+5)+4	5	-50cm	+50cm	40cm		37.13
32	(3+5)+4	7	-50cm	+50cm	40cm		36.59
33	(3+5)+4	9	-50cm	+50cm	40cm		31.34
34	(3+5)+4	1	-50cm	+50cm	90cm		30.08
35	(3+5)+4	3	-50cm	+50cm	90cm		35.53

36	(3+5)+4	5	-50cm	+50cm	90cm		33.93
37	(3+5)+4	7	-50cm	+50cm	90cm		37.79
38	(3+5)+4	9	-50cm	+50cm	90cm		34.72
39	(3+5)+4	1	-25cm	+100cm	40cm		26.79
40	(3+5)+4	1	-25cm	+150cm	40cm		21.28
41	(3+5)+4	3	-25cm	+100cm	40cm		34.10
42	(3+5)+4	5	-25cm	+150 cm/turn	40cm		36.87
43	(3+5)+4	7	-25cm	+150 cm/turn	40cm		35.62
44	(3+5)+4	9	-25cm	+150 cm/turn	40cm		31.06
45	3+5	9	-25cm	+150 cm/turn			26.21
46	3+5	7	-25cm	+150 cm/turn			30.74
47	3+5	5	-25cm	+150 cm/turn			33.16
48	3+5	5	+15 cm	+150 cm/turn			31.26
49	3+5	7	+15 cm	+150 cm/turn			30.85
50	3+5	9	+15 cm	+150 cm/turn			27.30
51	(3+5)+1	9	+15 cm	+150 cm/turn	40cm		32.70
52	(3+5)+1	7	+15 cm	+150 cm/turn	40cm		38.40
53	(3+5)+1	5	+15 cm	+150 cm/turn	40cm		35.50
54	3	7	+50cm/turn				17.71
55	3	7	+50cm				19.21
56	(3+5)+4	3	-25cm	+150cm	40cm		33.92
57	(3+5)+4	3	-25cm	+150cm	90cm		31.17
58	(3+5)+4	3	-25cm	+150cm	turn close		31.96
59	(3+5)+4	3	-25cm	+150cm	turn far		32.81
60	(3+5)+4	5	-25cm	+150cm	turn far		34.75
61	(3+5)+4	7	-25cm	+150cm	turn far		34.69
62	(3+5)+4	9	-25cm	+150cm	turn far		34.95
63	(3+5)+4	3	-25cm/18°	+150cm/18°	turn far		34.54
64	(3+5)+4	5	-25cm/18°	+150cm/18°	turn far		35.24
65	(3+5)+4	7	-25cm/18°	+150cm/18°	turn far		32.98
66	(3+5)+4	9	-25cm/18°	+150cm/18°	turn far		34.62
67	(3+5)+4	5	-25cm/18°	+150cm/18°	turn far		36.80
68	(3+5)+4+1	3	-25cm	+150cm	turn far	L: 0 cm	34.15
69	(3+5)+4+1	5	-25cm	+150cm	turn far	L: 0 cm	35.38
70	(3+5)+4+1	7	-25cm	+150cm	turn far	L: 0 cm	38.86
71	(3+5)+4+1	9	-25cm	+150cm	turn far	L: 0 cm	35.44
72	(3+5+4)+1	3	-25cm	+150cm	turn far	+67 cm	37.11
73	(3+5+4)+1	5	-25cm	+150cm	turn far	+67 cm	42.54
74	(3+5+4)+1	7	-25cm	+150cm	turn far	+67 cm	47.85
75	(3+5+4)+1	9	-25cm	+150cm	turn far	+67 cm	41.71
76	(3+5+4)+1	5	-25cm/18°	+150cm/18°	turn far	+67 cm/18°	39.44

77	(3+5)+1	5	-25cm/18°	+150cm/18°	turn far		36.10
78	(3+5)+1	5	-25cm/18°	+150cm/18°	turn far		37.42
79	(3+5)+1	3	-25cm/18°	+150cm/18°	turn far		36.70
80	(3+5)+1	3	-25cm/18°	+150cm/18°	turn far		35.62
81	(3+5)+1	7	-25cm/18°	+150cm/18°	turn far		34.22
82	(3+5)+1	7	-25cm/18°	+150cm/18°	turn far		35.89
83	(3+5)+1	9	-25cm/18°	+150cm/18°	turn far		33.52
84	(3+5)+1	9	-25cm/18°	+150cm/18°	turn far		32.61
85	(3+5)+4+1	3	-25cm	+150cm	turn far	L: 0 cm	33.27
86	(3+5)+4+1	5	-25cm	+150cm	turn far	L: 0 cm	36.50
87	(3+5)+4+1	7	-25cm	+150cm	turn far	L: 0 cm	37.42
88	(3+5)+4+1	9	-25cm	+150cm	turn far	L: 0 cm	34.75
89	(3+5)+4+1	3	-25cm/18°	+150cm/18°	turn far	L: 0 cm/18°	38.08
90	(3+5)+4+1	5	-25cm/18°	+150cm/18°	turn far	L: 0 cm/18°	39.41
91	(3+5)+4+1	7	-25cm/18°	+150cm/18°	turn far	L: 0 cm/18°	36.77
92	(3+5)+4+1	9	-25cm/18°	+150cm/18°	turn far	L: 0 cm/18°	36.60
93	(3+5+4)+1	3	-25cm	+150cm	turn far	+67 cm	37.22
94	(3+5+4)+1	5	-25cm	+150cm	turn far	+67 cm	40.71
95	(3+5+4)+1	7	-25cm	+150cm	turn far	+67 cm	41.72
96	(3+5+4)+1	9	-25cm	+150cm	turn far	+67 cm	42.80
97	(3+5+4)+1	3	-25cm/18°	+150cm/18°	turn far	+67 cm/18°	41.06
98	(3+5+4)+1	5	-25cm/18°	+150cm/18°	turn far	+67 cm/18°	42.83
99	(3+5+4)+1	7	-25cm/18°	+150cm/18°	turn far	+67 cm/18°	40.92
100	(3+5+4)+1	9	-25cm/18°	+150cm/18°	turn far	+67 cm/18°	37.56
101	((3+5)+4)+1	7	-25cm	+150cm	turn far	+67 cm, 9 m	42.52
102	((3+5)+4)+1	7	-25cm	+150cm	turn far	+67 cm , 11m	39.89
103	((3+5)+4)+1	7	-25cm	+150cm	turn far	+67 cm , 13m	35.87
104	((3+5)+4)+1	7	-25cm	+150cm	turn far	+67 cm , 15 m	33.91