Buoyancy Driven Flow in an Underground Metro Station for Different Climate Conditions – Experimental and Numerical Investigation

Matthes Dietrich, Christian Knaust
Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany

Markus Brüne
Ruhr-Universität Bochum, Bochum, Germany

Lucas Arnold
Forschungszentrum Jülich, Jülich, Germany

Sebastian Festag
Hekatron Vertriebs GmbH, Sulzburg, Germany

Abstract

In urban areas the demand for public transportation is constantly growing. Underground railway systems overcome the problem of limited space on the ground and are therefore one of the most powerful systems in urban public transportation. These facilities can be very complex and are used by a large amount of passengers. Therefore, it is important to maintain the safety for people and buildings. Especially in the case of fire or arson attack.

This paper focusses on a fire scenario in a complex subway station for different weather conditions. The purpose is to identify the influences of different weather conditions on the smoke spread and the ability of self-rescue in case of a burning luggage.

The evaluation of the fire simulations will focus on toxicity and visibility taking into account the FED concept.

Keywords: metro station, fire simulations, weather conditions, fire scenario, FED

Introduction

A lot of research has been done in the past for the case of fire in underground structures. The focus of research had been fires in rail or road tunnels. But with the view on underground stations, research is not as profound since experiments can only be done during the operating breaks without leading to any structural damage. Hence, there have been only some numerical investigation on fictive and existing stations [1] [2]. A lot of research in the ventilation of subways and tunnels has been done in the past [3]. Also a combination of different weather conditions has to been taken into account [4].

In this research an existing underground station for different weather conditions is considered. To validate the results of the simulation, the research consists of an experimental and numerical part. The aim is to identify the impact of different weather conditions on a specific fire scenario and the corresponding escape routes.

Method

To record data for different weather conditions, two experiments have been done in the subway station Osloer Straße. One experiment took place in January 2016 and the other one in June 2016. The station is a three-level cross section station in Berlin (Germany). The two lower levels connect two subway lines and the upper level serves as a distribution level were several shops are located. Fig. 1. shows an on top view of the three levels of the 3D CAD model of the station.

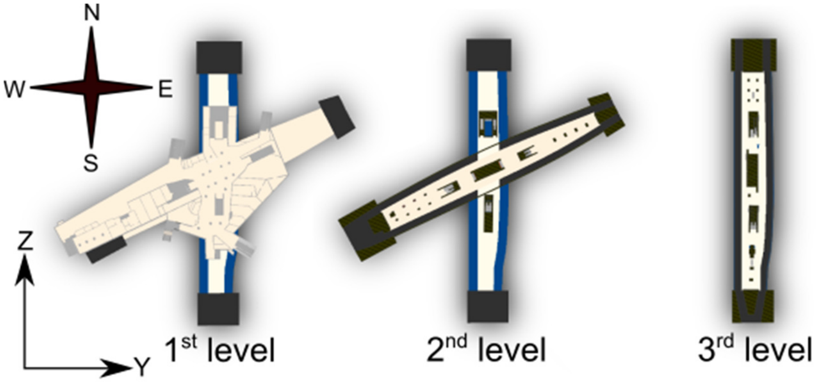

Fig. 1. 3D CAD model of the subway station, separation of the three levels.

The experimental data has been recorded at night during the operating breaks. For this time, there is no impact of the moving trains on the temperature and velocity distribution. During the experiment, the pressure, temperature and velocity were recorded. The pressure has been measured at the surface by a fixed installed weather station. The velocities were measured with ultrasonic anemometers at the entrances to the station and the tunnel sections of the 2nd and 3rd level. The temperature measurements have been done with temperature sensors in the station and the tunnel sections. Inside the station a total of 44 vertically temperature chains have been installed. Every temperature chain consists of up to eight thermocouples with a uniform distance of 0.3 m over the height.

In Fig. 2. the directions of the main background flow for winter in blue and summer in red are shown. During the experiments two main background flows have been identified. In winter, colder air from the surface is pushing into the 1st level and over the stairways into the 2nd and 3rd level. In summer, warmer air from the 2nd and 3rd level is propagating over the stairways into the 1st level and is leaving the station through the entrances. Additionally, colder air from outside the station is pushing into the 1st level at three entrances. This leads to a flow in both directions at these entrances.

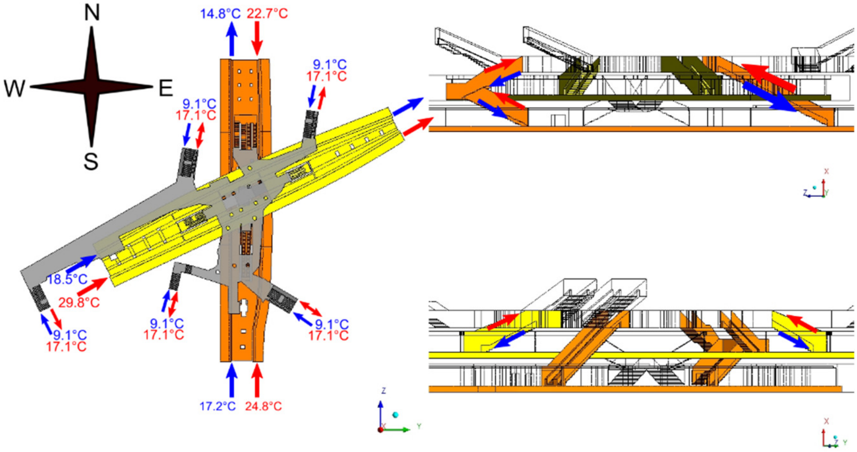

Fig. 2. Directions and temperatures of the main background flow for winter (blue) and summer (red), 3rd level (orange) and 2nd level (yellow).

In January 2017, a third experiment took place for which Hekatron provided 196 fire detectors of the type EN 54-31. The additional data of smoke density, CO concentration, and heat enables a better understanding of the background flow and smoke spread in the station. These results will be published in an additional publication.

The numerical investigations of the background flows and the fire scenarios are carried out with ANSYS CFX.

The discretization of the model is based on unstructured tetrahedrons and a prism layer near the walls. The maximal extension of the tetrahedrons is 0.3 m. The prism layer consists of 5 layers with an expansion rate of 1.3 and the size of the first layer is 0.04 m. This grid setup leads to a total of 6.2 million elements. The actual discretization of the model is a compromise between accuracy and computing resources and will be further investigated.

The non-wall boundary conditions are treated as openings and the experimental data were used to define the pressure at these surfaces. Hence, air can enter and exit the domain depending on the flow conditions. The pressure values were gained with an additional simulation. For the first simulation, the value and direction of the velocity measurements were set at these boundary's.

From this solution, the pressure values were adopted to the final simulation. All other surfaces are treated as solid walls with a no-slip boundary condition. The model is divided into three domains to satisfy the demand of different temperatures at each level.

The final calculations are also done in two steps. In a first step the background flow is calculated as a steady state case. This solution is then taken as an initial condition to run the transient calculations of the fire scenarios. The used solver settings are listed in Table 1. The numerical models have been validated based on laboratory experiments in Aachen and the experiments in the subway station Osloer Straße [5].

Table 1. Solver settings.

Analysis Type	**Steady State**	**Transient**
Time Duration		3600 s
Time Step		
adaptive		0.01 – 1 s
Convergence Criteria		
Max. Iteration	1000	
Residual Target	< 0.0001	< 0.0001
Conservation Target	< 1%	< 1%
Fluid Models		
Heat Transfer	Thermal Energy	Thermal Energy
Turbulence	Shear Stress Transport	Shear Stress Transport
	-	Buoyancy Turbulence
Combustion		Eddy Dissipation
Thermal Radiation	Discrete Transfer	Discrete Transfer

The fire scenario is a burning suitcase, located in the middle of the 3rd level. The heat release rate is adopted from J. Bulk [6], with a maximum heat release rate of 250 kW. The combustible material is polyvinyl chloride and with the yields for carbon monoxide and soot [7] the following reaction equation is used.

$$C_2H_3Cl+1,53O_2+5,76N_2 \rightarrow HCl+H_2O+0,14CO+0,96CO_2+0,9C+5,76N_2$$

The evaluation of the fire simulations will focus on toxicity and visibility considering the FED concept [8]. For this scenario, the most relevant parameter is the visibility, hence the fractional smoke concentration concept FEC_{smoke} is applied. For large enclosures, this concept is defined as

$$FEC_{smoke} = (OD/m)/0.08 \qquad \text{(Eq. 1)}$$

OD is the optical density and is defined as

$$OD = \log e^{\alpha} \quad \text{(Eq. 2)}$$

α is the light extinction coefficient, which is defined as

$$\alpha = \alpha_m \cdot m_s \quad \text{(Eq. 3)}$$

were α_m is the specific light extinction coefficient and can be suggested with $\alpha_m = 8700\ m^2/kg$ for flaming combustion of plastic fuels and m_s is the soot mass concentration. If the FEC_{smoke} equals one, then a visibility of 10 m is not satisfied which seriously affect escape attempts.

The evaluation of the fire scenario is done for the winter and summer case from the experiments and a default case. For the default case, a reference pressure of 1 atm and a temperature value of 25 °C is set for the station and the surrounding regions. The visibility is evaluated at the bottom of the staircases and the entrances and exits of the station in 1.8 m height. The connection between the 2nd and 3rd level is the only exception. There the evaluation is done in the middle of the staircases in 1.8 m height.

Results

In Fig. 3. the temperature distribution for the winter and summer background flow with a cut plane through the middle of the 2nd level is shown.

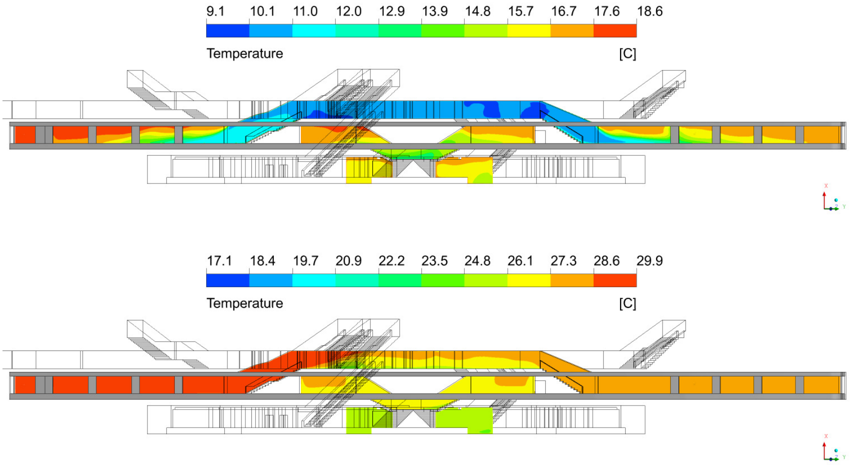

Fig. 3. Temperature cut plane through the middle of the 2nd level; winter at top and summer at bottom.

In the winter case the total temperature range is 9.5 K with a maximum temperature of 18.6 °C in the 2nd level and a minimum temperature of 9.1 °C on the surface. For the summer case the total temperature range is 12.8 K with a maximum temperature of 29.9 °C in the 2nd level and a minimum temperature of 17.1 °C on the surface.

The temperature chains are used to compare the results with the experiments. For the winter case the average deviation from the experiment and the simulation is 0.4 K with a Root Mean Square (RMS) of 0.6 K for all temperature couples, which corresponds to a deviation of about 6.3 % to the total temperature range. For the summer case the average deviation for all temperature couples is 0.7 K with a RMS of 1.0 K (7.8% deviation). For this case the biggest deviations are in the north-western part of the 1st level. Even if the flow direction and speed of the numerical simulations are close to the experimental data, the temperature profiles do not fit. The average deviation of the four chains is 2.2 K in the north-western region. A possible reason could be the colder air moving on ground of the 1st level during the experiment than in the simulation. If these four chains are excluded, the average deviation is 0.6 with a RMS of 0.8 K. This would lead to a similar deviation of about 6.3 % to the winter background flow. Both background flows are matching the experimental data, even if not all phenomena can be resolved by the simulations.

In Fig. 4. is the FEC_{smoke} profile over time for selected positions shown. There are significant differences in the smoke spread for the different weather conditions.

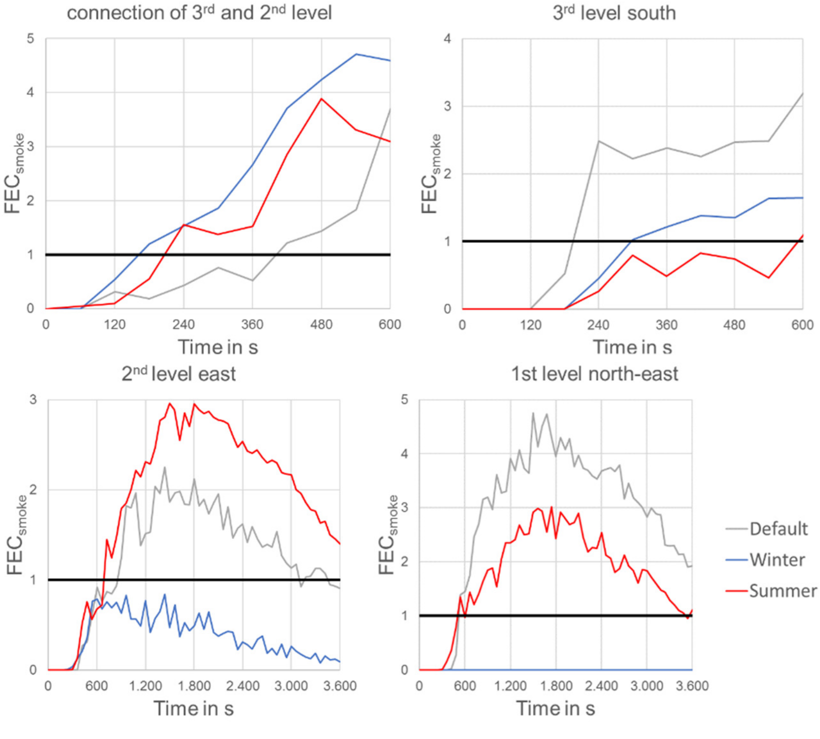

Fig. 4. FEC_{smoke} profile over time for selected positions, black line (FEC_{smoke}=1) indicates impairment of escape.

In the winter case, no smoke spreads into the 1st level at all and all entrances and exits are possible exit routes. In the summer case, only the north-eastern exit of the 1st level is obstructed by the smoke after 9 minutes. In the default case, all exits are obstructed by the smoke after 29 minutes. The first exit that is not suitable for escape is the north-eastern after 9 minutes and the last exit is in the north-western of the 1st level. In the 2nd level the influence of the weather condition is also to observe. In the winter case the smoke is spreading into the 2nd level but both staircases to the 1st level are always available for escape. For the summer and default case both staircases to the 1st level are obstructed by the smoke, but the time when they are obstructed differ. Table 2 shows, that in the default case both exits are obstructed almost at the same time point, but in the summer case the escape through the western exit is twice as long possible as the eastern exit.

Table 2. Time in minutes until the FEC_{smoke} reaches 1 at the staircases in the 2nd and 3rd level for winter (blue), summer (red) and default (black).

2nd level		**western**				**eastern**			
		24		16		12		15	
3rd level	**northern**			**connection**			**southern**		
	6	6	6	3	4	7	5	10	4

In the 3rd level the FEC_{smoke} reaches one at all chosen locations and for all cases but at different points in time. Table *2* shows the points in time for the different locations and cases. At the southern staircase, the escape is twice as long possible in the summer as in the winter and default case. The connection between 2nd and 3rd level is first obstructed for the winter and summer case, but is the last suitable escape route for the default case.

In addition, the weather conditions influence the smoke temperatures and thus the stratification of the smoke. This phenomenon occurs in the 2nd level where cooled smoke from the 3rd level is also spreading on the ground in the winter and summer case. The results show that the weather conditions have significant impact on the smoke spread and the responding possible escape routes for this fire scenario.

Conclusion

The results proved that there is a relevant background flow in subway stations which needs to be considered in the analysis of fire scenarios. The different weather conditions lead to different smoke spreads in the subway station and the obstruction of escape routes at different time points for this scenario. The knowledge of the smoke spread and available escape routes in a subway station for different weather conditions is essential to develop safety systems for existing and planned stations.

There are uncertainty's which could lead to possible inaccuracies in the solutions of the background flow and smoke spread. These are for example the discretization of the model, the geometry of the CAD model, the positions of the measuring devices and the measuring inaccuracies itself.

In further investigations, additional fire scenarios need to be considered, for example a burning subway and a burning shop in the 1st level.

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