

MINIMUM FLOW VELOCITY THROUGH OPEN CROSS PASSAGES IN TWIN BORE RAIL TUNNELS

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ABSTRACT

An important basis for the design of a tunnel ventilation system in twin bore rail tunnels is the minimum flow velocity through open cross passages which prevents smoke from propagating into the safe opposite tube. 3D-CFD fire simulations were carried out to analyze the relationship between the minimum flow velocity in a cross passage and the longitudinal flow velocity in the tunnel. The results show that for a 28 MW fire longitudinal flow velocities of approximately 2.0 m/s require the highest flow velocities through open cross passages. Lower cross passage flow velocities are sufficient for low longitudinal flow velocities because of the smoke layering, and for high longitudinal flow velocities because of the greater dilution and cooling of the fire gases.

Keywords: ventilation design, critical velocity, incident ventilation

1. INTRODUCTION

In twin bore rail tunnel systems, which are connected with cross passages, the opposite tube serves as a safe area. In case of fire, smoke must be prevented from propagating through the cross passage(s) into the safe tube by the tunnel ventilation. Usually this is ensured by creating a pressure difference between the tubes in order to generate an air flow from the safe tube towards the incident tube during the passengers escape.

For the design of a tunnel ventilation system a minimum flow velocity through open cross passages has to be defined. The choice of an adequate value is not trivial. A low flow velocity increases the risk of smoke propagation into the safe opposite tube. If the chosen flow velocity is too conservative, a high amount of air and therefore a high power requirement results. In addition to this, for some ventilation systems (e.g. point extraction from the incident tube) high longitudinal flows, which can affect a possible smoke layering, can result.

In literature different values for minimum flow velocities for emergency exit doors can be found, but none take into account the special geometric conditions of cross passages with two separate doors.

On behalf of the Austrian Railway (ÖBB-Infrastruktur AG) 3D-CFD fire simulations were carried out to optimize the design of emergency ventilation systems. Various scenarios were considered for a typical cross section geometry with differing longitudinal flow velocities in the incident tunnel, two different heat release rates and with/without a train in front of the cross passage.

2. MINIMUM FLOW VELOCITY

The minimum flow velocity is defined as averaged minimum flow velocity through the emergency exit door necessary to prevent smoke penetration into the opposite tube (and not into the cross passage itself).

Different values for the minimum flow velocity through emergency exit doors were found in literature. The value 1.0 m/s is for example recommended for the ventilation design of road tunnels [ASTRA, 2008]. The value 2.0 m/s is recommended for pressure ventilation design for buildings [TRVB, 2004]. In both cases only one emergency exit door separates the location of the fire from the safe area.

For Austrian rail tunnels there is no guideline that states a minimum flow velocity through open cross passages. In other rail tunnel projects (e.g. AlpTransit or Brenner Base Tunnel) a flow velocity of 2.0 m/s is used as design criteria (for a 20 MW fire). This value is based on a theoretical one-dimensional approach that is derived from the calculation of the critical velocity that prevents backlayering in the incident tube [Tarada, 2000]. In this simplified approach it is assumed that the smoke is fully mixed (no stratification) and that the fire is situated exactly in front of the cross passage. This theoretical model predicts the highest cross passage flow velocity when there is no longitudinal flow in the incident tunnel. On increasing the longitudinal flow, the temperature in the tunnel decreases due to the greater dilution and cooling of the fire gases and so a lower flow velocity through the cross passage is required.

In all listed cases the three dimensional nature of the typical cross passage geometry (lower height of the cross passage than of the tunnel, two emergency exit doors in the cross passage) and also possible smoke stratification is not considered.

3. CFD SIMULATIONS

3.1. Model details

The simulations were carried out with a 3D-CFD simulation program [STAR, 2009]. The model includes one segment of the incident and one segment of the opposite tunnel (with a cross-section of approx. 44 m²) as well as the connective 40 m long cross passage. The cross passage is equipped with two emergency exit doors with a free cross-sectional area of 4.4 m² (see **Figure 1**).

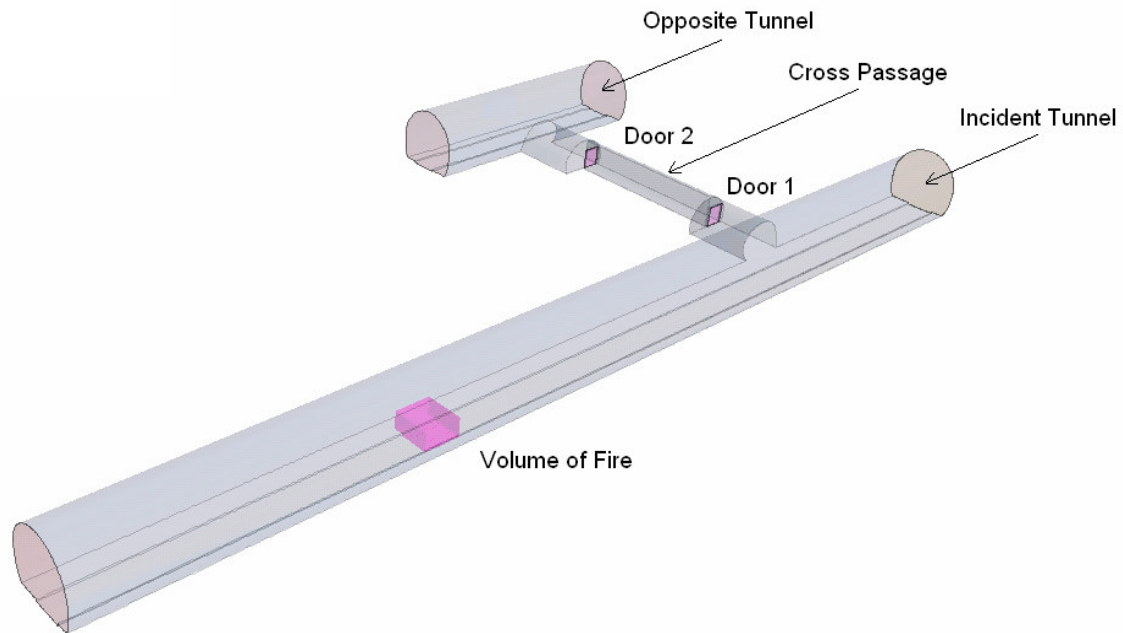


Figure 1: Simulation model

At the boundaries of the opposite tube ① and ② as well as at boundary ③ of the incident tube an inlet flow velocity is specified (**Figure 2**). The downstream boundary of the incident tube ④ is modelled as pressure outlet. The fire in the incident tube ⑤ is a volumetric energy and passive scalar source. For the heat release rate of 28 MW a volume of 32 m³ was chosen in order to limit the maximum temperature at the fire source.

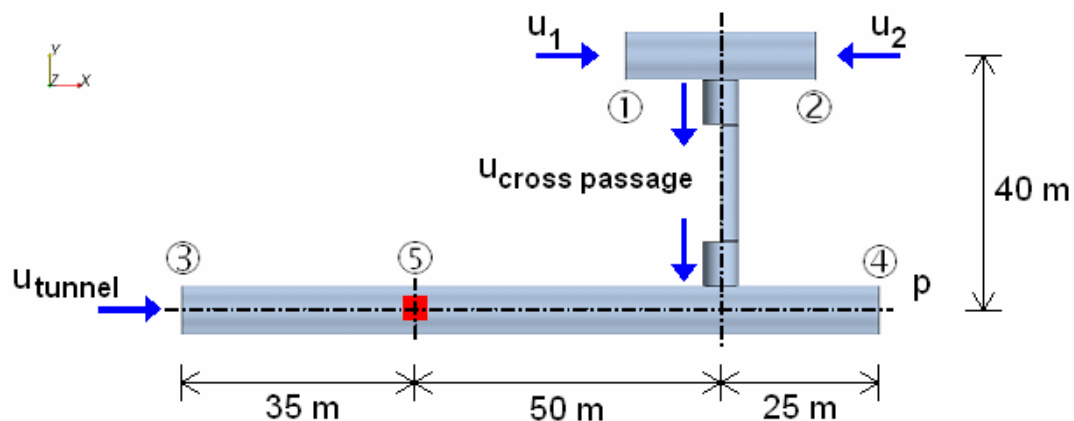


Figure 2: Boundary conditions, and position of the fire source

In the simulations different longitudinal flow velocities u_{tunnel} were combined with different flow velocities through the cross passage $u_{\text{cross passage}}$.

In a first phase the simulations were carried out with a heat release rate of 28 MW and without a train in front of the cross passage. In a second phase the scenarios included a standing train in front of the cross passage, and also a lower heat release rate (8 MW).

3.2. Evaluation

In all simulations the temperature and the smoke extinction coefficient distribution, as well as the flow velocities in the incident tube and in the cross passage were analyzed. The evaluation of the minimum flow velocity is based on the results of the airflows only (see Chapter 3.3.2). The temperature distributions shown in Chapter 3.3.1 allow a better understanding and give additional information. Evaluation of the simulations is shown in **Table 1**.

Table 1: Evaluation criteria for the simulations

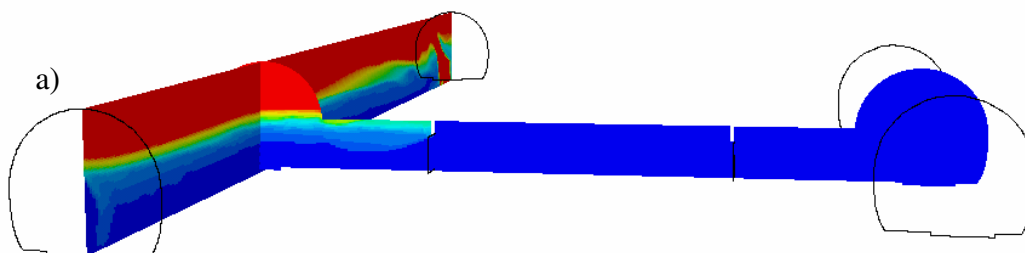
Evaluation criteria for the simulations	symbol	flow velocity through door 1	flow velocity through door 2
No smoke entry into cross passage	◆	positive	positive
Limit case of smoke entry into the cross passage	✦	threshold	positive
Smoke entry into the cross passage but no smoky entry into the opposite tube	■	negative	positive
Limit case of smoke entry into the opposite tube	✖	negative	threshold
Smoke entry into the opposite tube	●	negative	negative

Beside cases with a clearly positive flow velocity, or a clearly visible negative flow velocity (always in the upper part of the door), situations were observed whereby only marginal flow velocities at the upper frame of the door are visible. These small volumes of back-flow can be explained by pockets of local turbulence which don't transport smoke into the cross passage or opposite tunnel.

3.3. Results

3.3.1. Temperatures

All results in this chapter are based on simulations with a heat release rate of 28 MW and without a train in front of the cross passage. In **Figure 3** the temperatures in the incident tube and in the cross passage are shown for a flow velocity of 1.0 m/s in the cross passage and for three different longitudinal flow velocities in the incident tube.



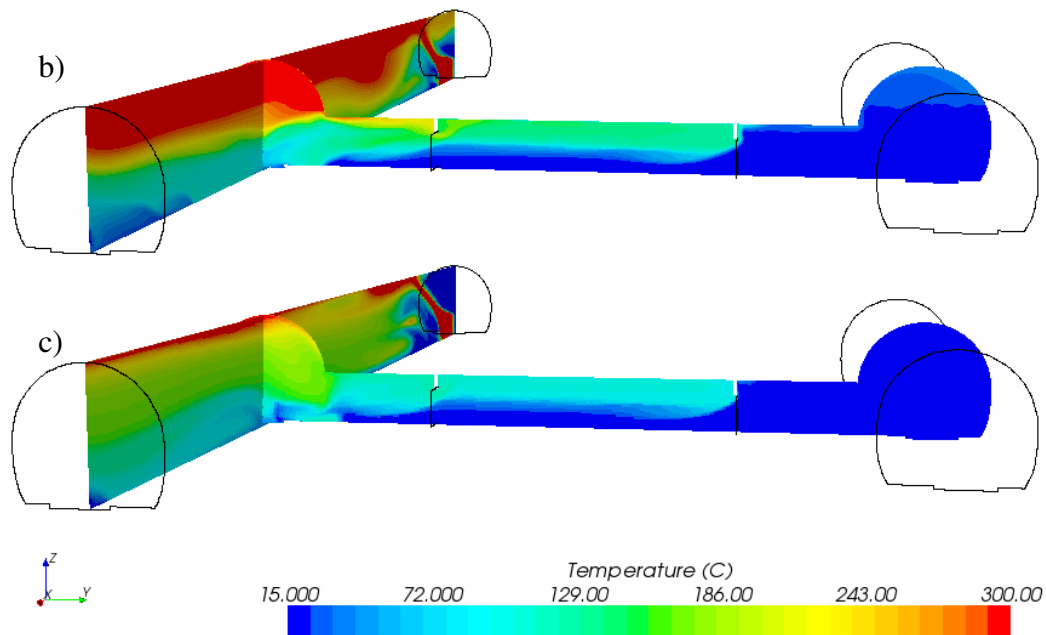


Figure 3: Temperatures in the incident tube and in the cross passage for $u_{\text{cross passage}} = 1.0 \text{ m/s}$ and $u_{\text{tunnel}} =$ a) 1.0 m/s , b) 2.0 m/s and c) 3.0 m/s

It can be seen that with the low longitudinal flow velocity of 1.0 m/s a thermal stratification, and thus a smoke stratification, develops in the tunnel (**Figure 3a**). Due to the low dilution of the fire gases with fresh air, high temperatures occur in the incident tunnel. These high temperatures are located in the smoke layer just under the ceiling. Because of the stratification the temperatures at the emergency exit doors are low enough that a flow velocity of 1.0 m/s is sufficient to prevent the smoke moving into the cross passage.

With a higher longitudinal flow velocity of 2.0 m/s the smoke stratification is less pronounced, i.e. hot gases are also present in lower parts of the tunnel (**Figure 3b**). The average temperature in the tunnel decreases with increasing longitudinal flow velocity (more dilution). Due to greater mixing the temperatures at the emergency exit doors are higher when the airflow is increased from 1.0 m/s to 2.0 m/s . The flow velocity of 1.0 m/s through the cross passage is in this case not sufficient to prevent smoke penetrating into the opposite tube (see **Figure 3b**, close to the ceiling).

In the case of a longitudinal flow velocity of 3.0 m/s a considerably less pronounced stratification is observed (**Figure 3c**). However because of the greater dilution and cooling of the fire gases the temperatures at the emergency exit doors are lower than in the case with the longitudinal flow velocity of 2.0 m/s . The flow velocity of 1.0 m/s in the cross passage can prevent the smoke moving into the opposite tube but not into the cross passage.

In **Figure 3** it can be clearly seen that the constriction due to the two doors (diminution from the cross section of the cross passage to the cross section of the door) have the effect of a smoke curtain. That means that the constrictions help to avoid a smoke propagation.

3.3.2. Airflows

Figure 4 and **Figure 5** show the flow velocity through the open emergency exit doors in the cross passage for the case of a longitudinal flow of 2.0 m/s in the incident tube

and a flow velocity of 1.5 m/s through the cross passage. In that case the smoke propagates through the first door (door 1) into the cross passage but not through the second door (door 2) into the opposite tube. The maximum positive velocity in door 1 reaches 2.8 m/s (i.e. in the direction of the incident tube) in the lower part of the door and a maximum negative velocity of 1.5 m/s (i.e. in the direction of the opposite tunnel tube) in the upper part of the door. In door 2 the velocity is solely positive (i.e. in the direction of the incident tube) and relatively uniform.

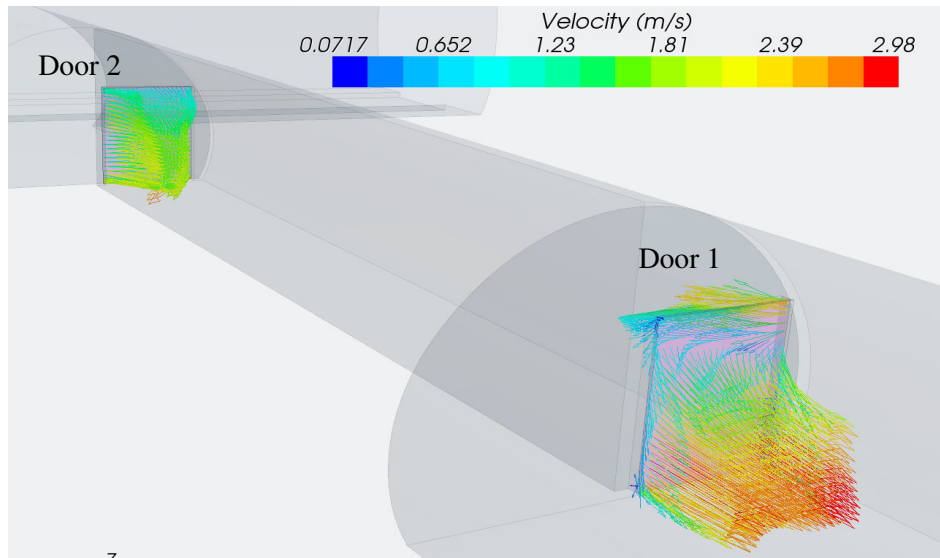


Figure 4: Velocity vectors through the emergency exit doors for the case $u_{\text{tunnel}} = 2.0 \text{ m/s}$, $u_{\text{cross passage}} = 1.5 \text{ m/s}$

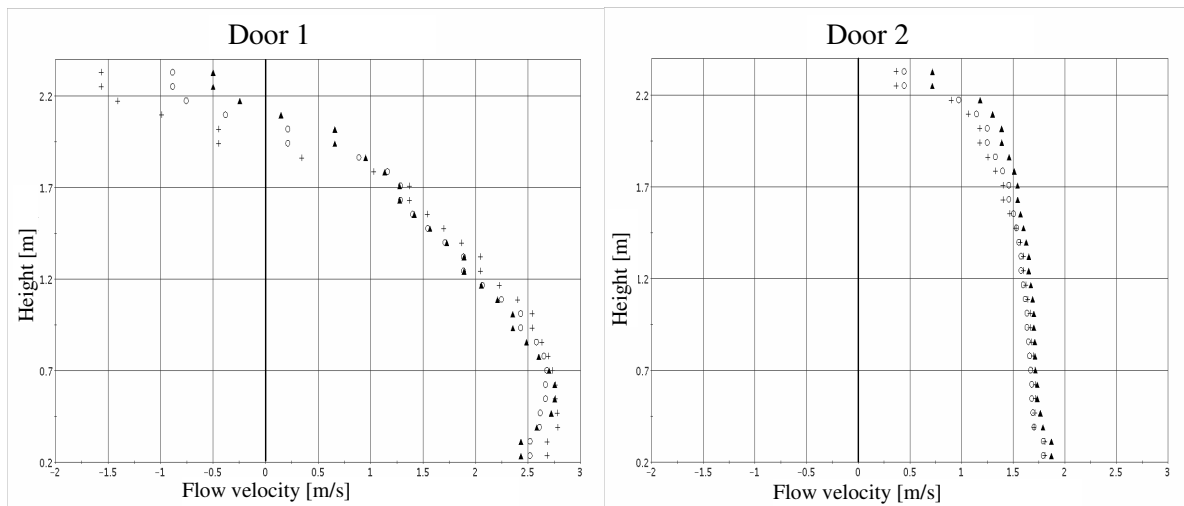


Figure 5: Flow velocity in three vertical sections in the emergency exit doors for the case $u_{\text{tunnel}} = 2.0 \text{ m/s}$, $u_{\text{cross passage}} = 1.5 \text{ m/s}$

3.4. Summary

The simulation results from the cases with the heat release rate of 28 MW and no train in front of the cross passage show that for longitudinal flow velocities of approximately 2.0 m/s the highest flow velocities through open cross passages are required. Lower cross passage flow velocities are sufficient for lower longitudinal flow

velocities because the smoke layer is situated above the door and for higher longitudinal flow velocities because of the greater dilution and cooling of the fire gases.

For longitudinal flow velocities higher than 2.0 m/s the simulation results are in good agreement with the analytical 1D approach [Tarada, 2000]. In contrast to the analytical model the required flow velocity through the cross passage is smaller for longitudinal flow velocities lower than 2.0 m/s.

Figure 6 shows the summary of the simulation results for cases with a heat release rate of 28 MW. Each point represents a single simulation with a given longitudinal airflow and a given velocity through the emergency door. The symbols used in **Figure 6** correspond to those in Table 1. The diagram is divided into three parts. The upper vertically dashed area shows conditions whereby smoke movement into the opposite tube can be avoided. The lower horizontally dashed area signifies an expected movement of smoke into the safe area. An area of uncertainty lies between the two. For combinations of longitudinal flow velocities and flow velocities through the cross passage in this transition area a smoke propagation into the opposite tube cannot be excluded.

Further simulations show that a smaller heat release rate (e.g. 8 MW) requires, as expected, a smaller cross passage flow velocity. For high longitudinal flow velocities this is clear because of the lower temperatures. For longitudinal flow velocities of 1.0 m/s the smoke stratification is less pronounced for a smaller heat release rate. But in this case the temperature at the door is also smaller which requires lower flow velocities through open cross passages. To quantify the effect of smaller heat release rates on the minimum flow velocities further simulations would be required.

Several simulations were carried out with a train standing in front of a cross passage. The results show that a slightly smaller flow velocity through the cross passage is required compared to the cases without train. The results shown in **Figure 6** are thus on the "safe side".

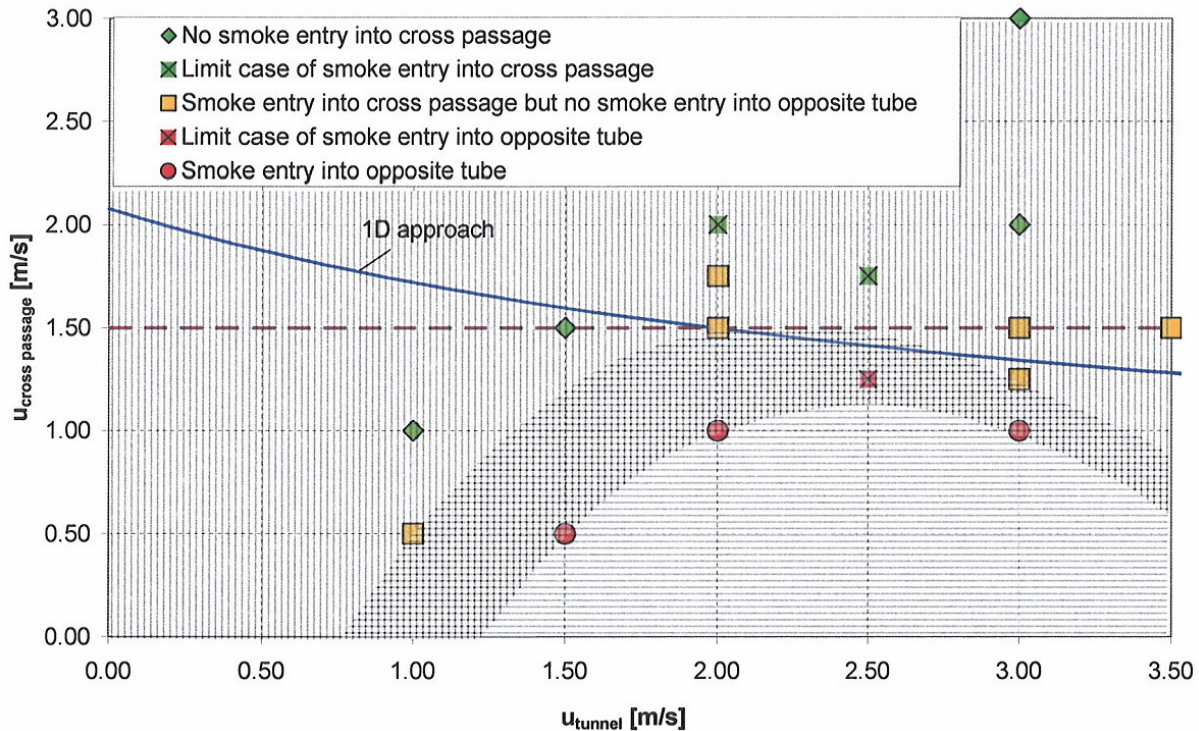


Figure 6: Summary of the simulation results (28 MW)

4. CONCLUSION

The following findings can be derived from the 3D-CFD Simulations:

- The minimum flow velocity required to prevent smoke propagation into the opposite safe tube is not only dependent on the heat release rate but also on the longitudinal flow velocity in the incident tube. Both factors have an impact on the temperature at the cross passage doors.
- The geometry of the cross passages (abrupt diminution from tunnel height to the cross passage height) as well as the geometry of the two emergency exit doors (abrupt diminution from the cross section height to the door height) helps to prevent smoke entry. If there is a smoke stratification the abrupt diminutions act like smoke curtain.
- The system configuration of the cross passage, with two doors that act like smoke barriers, plays an important role in preventing smoke penetration into the opposite tube.
- For a heat release rate of 28 MW the highest flow velocities through open cross passages are required for longitudinal flow velocities of approximately 2.0 m/s. Lower cross passage flow velocities are sufficient for lower longitudinal flow velocities because of the smoke layering, and for higher longitudinal flow velocities because of the greater dilution and cooling of the fire gases.
- For a heat release rate of 28 MW a flow velocity of 1.5 m/s (averaged over the cross section of the cross passage doors) is sufficient to prevent a smoke propagation into the opposite safe tube. A flow velocity of 2.0 m/s is required to prevent a smoke propagation into the cross passage. For heat release rates that are smaller than 28 MW smaller flow velocities are required.

- The 1D approach for a longitudinal flow of 2.0 m/s [Tarada, 2000] can be chosen as upper limit for the flow velocity through the cross passage doors.

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