SMOKE EXTRACTION IN TUNNELS WITH CONSIDERABLE SLOPE

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ABSTRACT

In many tunnels with transverse ventilation, the smoke-extraction capacity is determined on the base of the estimated smoke production rate of the design fire. This design method implicitly assumes a stable stratification of the smoke layer.

As the assumption of a stratified smoke layer is not justified when higher flow velocities are expected, the entire air volume that flows in the tunnel must be removed. In tunnels with gradients exceeding three percent, the chimney effect due to the rising temperature in the tunnel may cause flow velocities of 4 m/s and more. Therefore, the smoke-extraction capacity has to be designed for an anticipated longitudinal flow at the fire location.

In this paper, three models for the calculation of the effective pressure difference due to the chimney effect are compared. With these models, the expected flow velocity in the tunnel can be calculated based on buoyancy and external forces.

Examples for smoke extraction systems are given for existing and planned tunnels. In the tunnel Gotschna, the smoke extraction capacity is designed for an expected maximum flow velocity during the design fire. In the tunnel Vue-des-Alpes, the extraction capacity is not sufficient and the longitudinal flow during the fire is limited by means of several jet fans.

NOMENCLATURE

A	[m^2]	area
c_p	[W/kgK]	thermal capacity
g	[m/s^2]	gravity constant
i	[-]	inclination
L	[m]	length
Dp	[Pa]	pressure difference
Q	[W]	heat flux
T	[K]	temperature
t	[s]	time
U	[m]	perimeter
u	[m/s]	velocity
x	[m]	axial distance
DH	[m]	elevation difference
DT	[K]	temperature difference
Dx	[m]	element length
a	[W/m^{2}K]	heat conduction coefficient
e	[-]	emissivity
h	[-]	reduction coefficient
r	[kg/m^3]	density of air
s	[W/m^{2}K^4]	Stefan-Boltzmann constant

fire	related to the fire
stack	related to chimney effect
T	tunnel
wall	tunnel wall
0	initial condition

1. INTRODUCTION

1.1 Smoke Extraction

In many tunnels with transverse ventilation, the smoke-extraction capacity is determined on the base of the estimated smoke production rate of the design fire. This design method implicitly assumes a stable stratification of the smoke layer and therefore a small flow velocity in the tunnel.

In tunnels with considerable slope, one major influence on the flow velocity during a fire is the chimney effect due to the rising temperature in the tunnel. In such a tunnel, the smoke-extraction capacity has to be designed for an expected longitudinal flow at the fire location. As the assumption of a stratified smoke layer is not justified when higher flow velocities are expected, the entire air volume that flows in the tunnel must be removed. The only alternative is to apply a closed-loop control in order to minimise the flow velocity at the fire. However, such an approach is very difficult due to the many unknowns responsible for the development of the time-dependent flow velocity.

1.2 Chimney Effect

The longitudinal flow in a tunnel with considerable slope is a function not only of traffic and ventilation. Especially when the traffic is stopped, the chimney effect becomes the driving force on the tunnel air. The effective pressure difference produced by buoyancy forces can be derived from

$$\Delta p_{stack} = \Delta H \cdot r \cdot g \cdot \frac{T_1 - T_0}{T_1} \qquad (1)$$

The effective pressure difference is a function of the elevation difference of the two portals and of the temperatures of the tunnel air and the ambience.

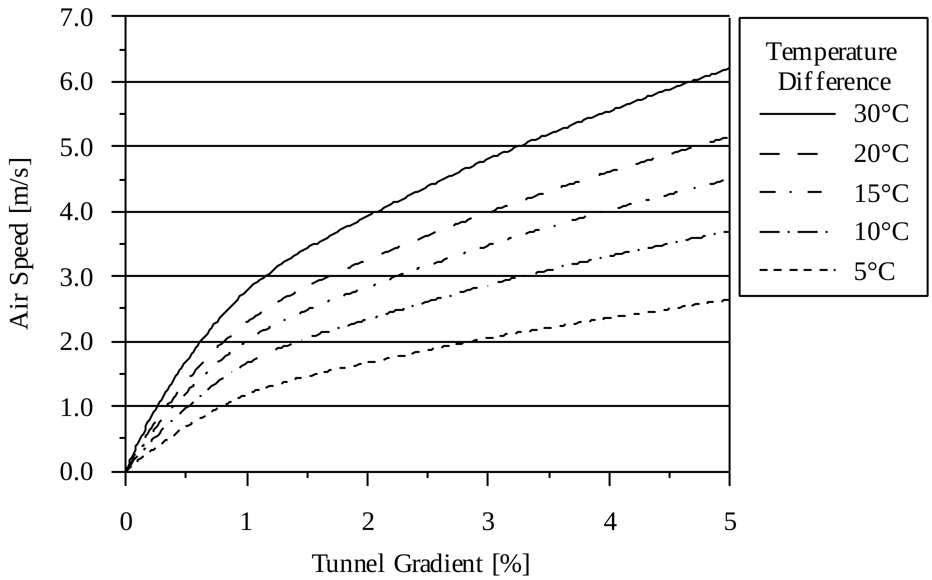

Figure 1: Air speed vs. tunnel gradient and temperature difference in a 3000 m long tunnel

For comparison, figure 1 shows the velocity due to a given temperature difference, say, between 5 and 30°C. The velocity depends on tunnel length as well, the given values refer to a 3000 m long tunnel without traffic.

In a tunnel with a gradient of two percent, a small temperature difference can cause a flow velocity in the range of the critical velocity. A temperature difference of five to ten Kelvin between tunnel and ambient air may be present before a fire even starts. With a flow velocity exceeding 2.5 m/s, the smoke layer will quickly mix over the whole tunnel cross-section. Removing the de-stratified smoke from the tunnel requires a higher extraction rate than the one derived from the fire's smoke production.

1.3 Control of Longitudinal Flow With Jet Fans

The longitudinal flow during a fire incident in a road tunnel depends on a number of parameters. Most of these parameters remain constant during an incident. Examples are the fire location, the tunnel geometry, barometric pressure differences between the portals, wind pressure on the portals (might though change during the fire), the installed ventilation capacity and the position of fans. However, the size of the fire may vary rapidly. The heat release rate is essential for the buoyancy forces. The number of cars in the tunnel, their travel velocity and the number of halted cars inside the tunnel have a major impact on the airflow velocity. A more detailed description of different parameters is given in [1]. These parameters change dramatically during the first minutes following the ignition but may become stable a few minutes after the fire has been detected at which time the tunnel is closed for further traffic.

The time varying forces on the longitudinal flow in a tunnel are not measurable during a fire situation. Therefore, a control of longitudinal flow using jet fans is a very difficult task.

2. MODELS TO ASSESS THE CHIMNEY EFFECT

The difficult part for the calculation of the effective pressure difference due to the chimney effect is the estimate of the temperature distribution in the tunnel. The temperature distribution is governed by the flow velocity in the tunnel, by heat conduction an radiation and by the (time varying) heat-release rate of the fire. In this section, a comparison is made of three different models that allow to calculate the buoyancy forces in a tunnel with considerable slope. The models are very different in their complexity. Therefore, the applicability of each model must be looked at for each tunnel situation.

2.1 Swiss Guideline [2]

	Design Fire	
	5 MW	30 MW
ΔT_{fire} witout smoke extraction	25 K	65 K
ΔT_{fire} with smoke extraction	20 K	40 K
Length of fire section L_{fire}	400 m	800 m
Temperature rise time Δt_{fire}	7 min	10 min
Blockage parameter η_{fire}	0.85	0.75

Table 1: Design fire parameters given in the Swiss guideline [2]

In a draft of the new Swiss guideline on tunnel ventilation [2], a simple, easy to use model is given. The temperature in the tunnel is not calculated, but an empirical temperature rise is given. For a given length, the tunnel is influenced by the temperature rise. The temperature rise is assumed to be constant within this tunnel section. Taking the blockage of the tunnel due to the fire into account, an empirical reduction factor is applied to the effective pressure difference.

The pressure difference is given by

$$\Delta p_{stack} = i_{fire} \cdot L_{fire} \cdot r_0 \cdot g \cdot h_{fire} \cdot \frac{\Delta T_{fire}}{T_0 + \Delta T_{fire}} \tag{2}$$

The temperature is assumed to be constant over the given length of the fire section (Figure 1). However, in a real fire, the temperature decreases rapidly with the distance from the fire. The model is applicable only for tunnels with constant gradient in the fire section. If applied for a tunnel shorter than the length of the design fire section, the chimney effect may be underestimated.

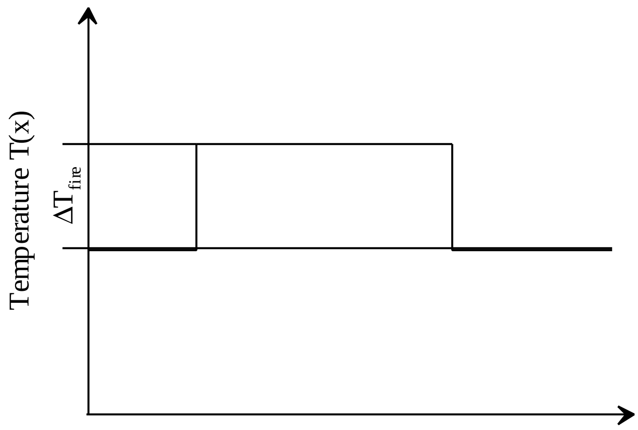

Figure 2: Idealised temperature distribution in the vicinity of the fire, Swiss guideline [2]

2.2 Opstad et al. [3]

The second model has been presented by Opstad, Aune and Henning in 1997 [3]. Here, the heat conduction from the hot smoke gasses into the tunnel wall is being calculated analytically. This gives a varying temperature downstream of the fire location. For the heat fluxes, a constant heat conduction coefficient α is assumed. The model has been validated by comparison with fire-test data obtained from measurements in a Norwegian sub-sea road tunnel.

The main goal of the model is to determine the number of jet fans needed in order to push the smoke through the tunnel opposing the chimney effect. The model is easily adapted in order to obtain the flow velocity in the tunnel due to buoyancy and external forces.

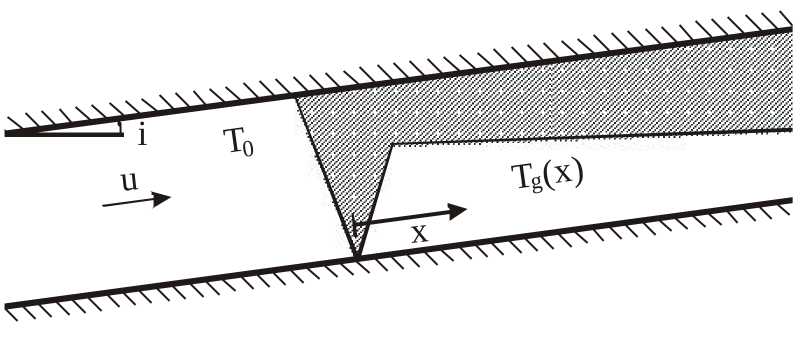

Figure 3: Flow model, Opstad et al. [3]

Figure 3 shows the relevant parameters of the calculation. In the graph the smoke is shown stratified in the upper part of the tunnel. Nonetheless, it is a strictly one-dimensional model with constant temperature in the tunnel cross-section.

The temperature at the fire location $T_{fire}(0)$ is given by

$$T_{fire}(0) = \frac{Q}{r_0 \cdot A_T \cdot c_p \cdot u} + T_0 \quad . \tag{3}$$

The tunnel slope is assumed to be constant. The highest average temperature in the tunnel is given for the fire location at the lower portal. This is the worst case for the calculation of the expected chimney effect, because there is always heated air leaving the upper tunnel portal.

For the calculation of the buoyancy forces, the heat rise in the tunnel is integrated over the tunnel section from the fire location to the upper tunnel portal. This leads to

$$\Delta p_{stack} = \frac{u \cdot g \cdot i \cdot r_0}{c} \cdot \ln\left[\frac{T_0 + \left(T_{fire}(0) - T_0\right) \cdot \exp\left(\frac{c \cdot L_T}{u}\right)}{T_{fire}(0)}\right] \quad . \tag{4}$$

The parameter c is defined in order to simplify the calculations.

$$c = -\frac{a \cdot U_T}{r_0 \cdot A_T \cdot c_p} \tag{5}$$

Radiation from the fire to the tunnel walls has not been included. Therefore, the design fire rate has to be reduced by the fraction of the heat release rate that is related to radiation (30 to 40 percent).

If the buoyancy forces is to be calculated for a situation with natural ventilation, an iterative calculation is necessary, because the flow velocity is a parameter in the calculation of the buoyancy forces. A stable solution is quickly obtained.

The temperature distribution along the tunnel follows an exponential function. The distribution is shown qualitatively in figure 4.

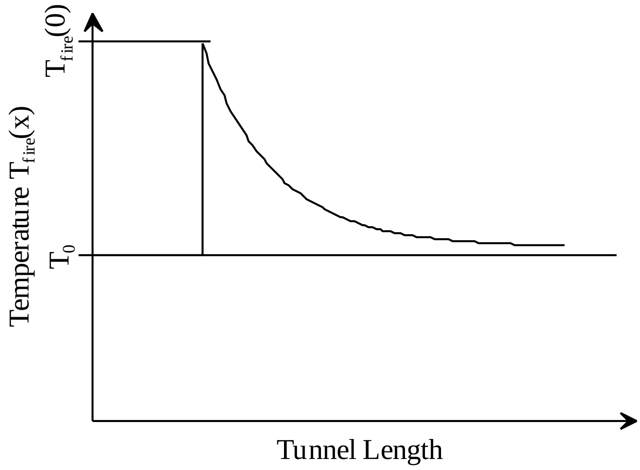

Figure 4: Temperature distribution in the vicinity of the fire according to the model [3]

The graph shows a rapid cooling of the hot gasses in the vicinity of the fire. The model is applicable for long tunnels with constant gradient. Yet, the imminent advantage over the Swiss guideline-model lies in the applicability for tunnels shorter than the length of fire section, i.e. shorter than 400 m or 800 m.

2.3 Sprint [5]

Sprint is a one-dimensional computer model that was developed for the simulation of fire scenarios. Initially, it was not intended to be a tool for the design of the smoke extraction capacity. Sprint has been used solely for the testing of the ventilation design and the control routines. Obviously, a routine that calculates the temperature distribution along the length of the tunnel is included as well as the computation of buoyancy forces. More details about the computer model including validation cases can be found in [4] and [5]. The model has been validated using the Memorial-Tunnel Fire Test data.

For the calculation of the temperature in the tunnel, the tunnel is divided into small sections. The energy equation is solved for each element. The fire is modelled as a heat source. Heat fluxes are modelled as convection with the flow as well as conduction and radiation into the tunnel wall. A sketch of the heat fluxes is shown in figure 5.

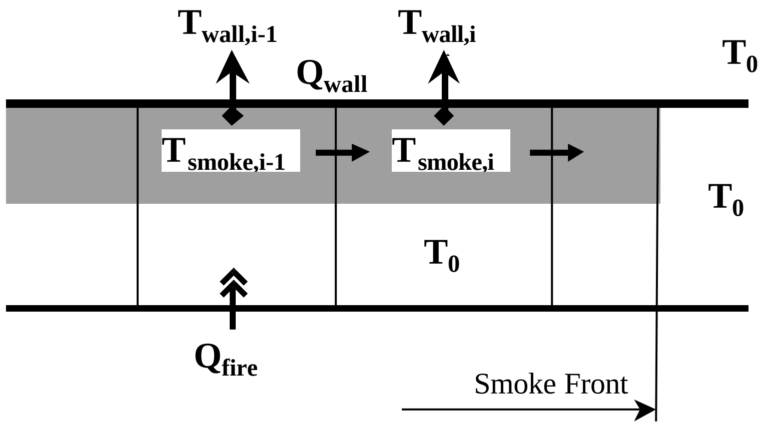

Figure 5: Model for the heat fluxes as modelled in Sprint [4]

The tunnel air underneath the smoke layer is assumed to stay at the initial temperature. Heat transport from the smoke to the lower air is neglected. The temperature used for the heat transport are the temperatures of the smoke layer and the wall. The heat conduction coefficient α depends on the local Reynolds and Nusselt numbers. The heat flux into the tunnel wall is given by

$$Q_{wall,i} = U_T \cdot \Delta x \cdot \left(a \cdot \left(T_{smoke,i} - T_{wall,i}\right) + e \cdot s \cdot \left(T^4_{smoke,i} - T^4_{wall,i}\right)\right) \quad , \qquad (6)$$

In Sprint, the wall temperature is not assumed to be constant. A limited thermal capacity of the concrete wall is defined. The drawback for the comparison with other models is that no time invariant flow velocity is obtained. As the wall temperature increases with time, the heat flux into the wall decreases consequently. The average temperature in the tunnel and the stack effect increase with time.

Figure 6 shows the development of the flow velocity and the smoke propagation in a 2000 m long tunnel with a constant gradient of five percent. In the simulation, no traffic has been modelled. The fire releases heat at a constant rate of 30 MW. The fire starts at t = 0 min. The left hand graph shows the changes of the flow velocity versus time.

At t = 0 min the tunnel air is at rest. The fire starts instantly with the full heat release rate of 30 MW. With the temperature rise in the tunnel, the chimney effect sets in, the tunnel air is accelerated towards the upper (right hand) portal. Approximately five minutes later, the phase of rapid acceleration is finished. Any further increase of flow velocity happens relatively slowly.

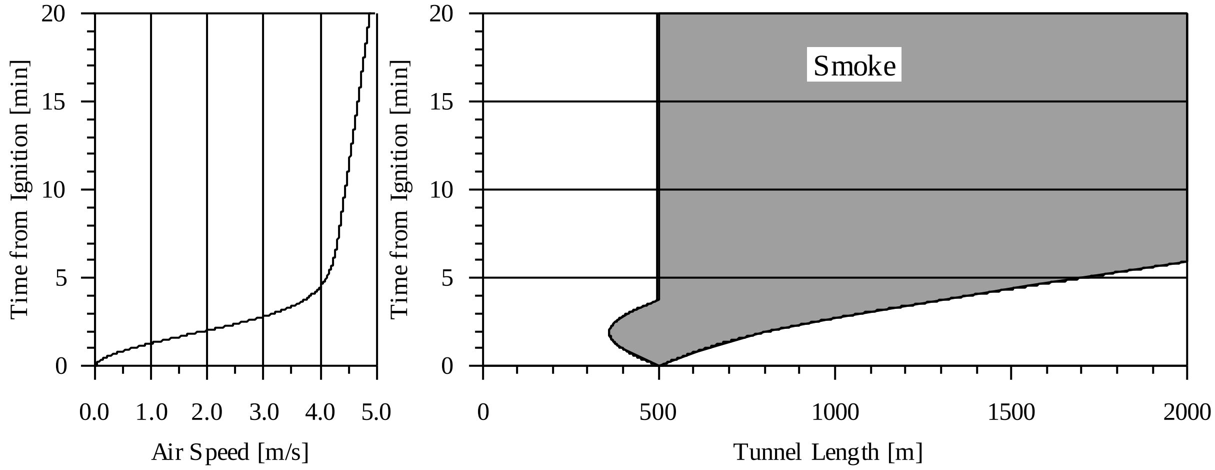

Figure 6: Flow velocity and smoke propagation in the tunnel, fire load 30 MW, tunnel length 2000 m, 5% gradient from left to right , without traffic and mechanical ventilation

The right hand graph in figure 6 shows the position of the smoke fronts versus time and tunnel length. As long as the flow velocity is rather small, the smoke propagates towards both sides of the fire. At higher velocities, the left hand (lower) smoke front is driven back to the fire location, while the right hand (upper) smoke front is accelerated towards the tunnel portal. In the simulation, the smoke front reaches the tunnel portal approximately 6 min after ignition.

Assuming a constant wall temperature, the calculation would reach a steady state solution very quickly. Then, there would be an equilibrium between the heat release at the fire, the heat flux into the tunnel wall and the heat leaving the tunnel with the air flow. However, due to the limited heat capacity of the wall, the wall temperature rises with time. The heat flux to the wall is inhibited and therefore, the average temperature in the tunnel rises. For the comparison of the three models, we chose to compare the pressure forces due to buoyancy ten minutes after ignition of a sudden 30 MW fire.

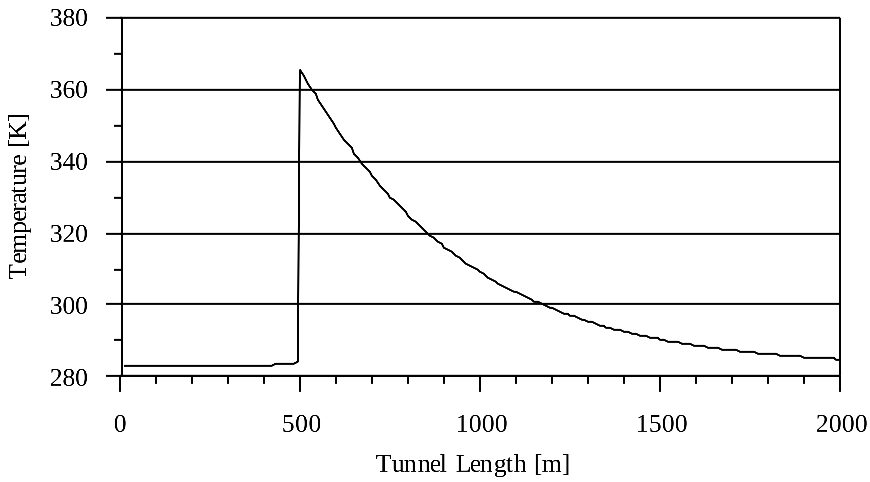

Figure 7: Temperature distribution in the vicinity of the fire, t = 10 min, fire load 30 MW, tunnel length 2000 m, 5% gradient, without traffic and mechanical ventilation

Figure 7 shows the temperature distribution in the tunnel ten minutes after ignition. A fully developed temperature distribution is visible. During the following minutes, changes of the temperature distribution are very small. Qualitatively, the distribution obtained from the numerical calculation is very similar to the distribution given by the analytic solution given by Opstad et al. (see figure 4).

3. COMPARISON OF MODELS

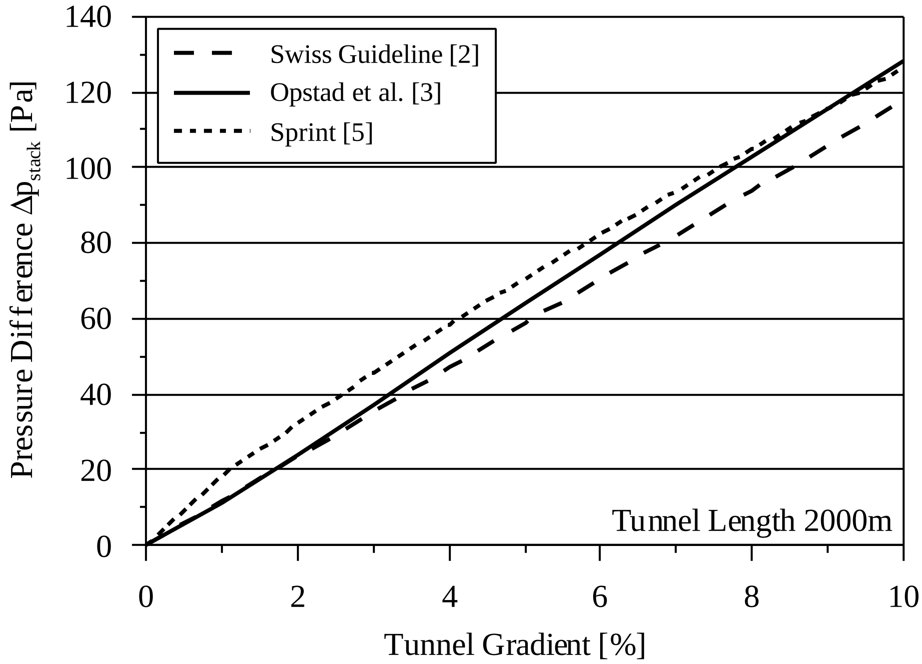

Figure 8: chimney effect versus tunnel gradient, tunnel length 2000 m, fire load 30 MW

Figure 8 gives the effective pressure difference due to buoyancy forces from a calculation with the three models. For the graph, the chimney effect was calculated for a 2000 m long tunnel with a cross-section of 50 m^2. For the calculation of flow velocity, it was assumed that there are no vehicles in the tunnel.

The model given in the Swiss guideline gives a strictly linear dependency between the pressure difference and the tunnel gradient.

The model given by Opstad et al. [3] gives slightly higher driving forces for steeper gradients. The higher flow velocity leads to a lower smoke temperature downstream of the fire. As the smoke temperature is decreased, the heat flux into the wall is decreased as well, which in this case leads to a higher average temperature in the tunnel.

The Sprint calculation shows a similar chimney effect for high tunnel gradients as from the model by Opstad et al. On the other hand for small gradients, the predicted chimney effect is up to 10 Pa higher than the one predicted by the other models. This may be caused by a higher air temperature close to the fire due to the small flow velocity, which results in a higher wall temperature. The heat flux into the wall is inhibited, which leads to a relatively high smoke temperature in this part of he tunnel.

All three models show very similar results. The small differences visible in figure 8 are not very important for the design of a smoke extraction system. Even the simple, pragmatic model given in the Swiss guideline is fully adequate for road tunnels with a constant gradient over a length of at least 800 m. On the other hand, limitations of every model have to be considered when choosing a model for a certain application.

4. APPLICATIONS

4.1 Tunnel Vue-des-Alpes

The tunnel Vue-des-Alpes consists of a single tube with bi-directional traffic. The detailed ventilation design dates from 1985. The tunnel has been equipped with a semi-transverse ventilation system including a continuous smoke extraction via reversible axial fans. In 1999, the road authority decided to improve the ventilation in order to increase the safety of the tunnel. The tunnel Vue-des-Alpes (length 3239 m, cross-section 49 m^2) has a constant gradient of 2.45%. Today, the tunnel is equipped with a semi-transverse ventilation with dampers at intervals of approximately 54 m for local smoke extraction over a length of about 300 m.

The tunnel was closed in summer 1999. During this period, measurements of the flow velocity in the empty tunnel were conducted. Due to these measurements, it was decided to assume a pressure difference between the tunnel portals of ±30 Pa due to thermal and meteorological influences for the design of the smoke extraction system.

The three models give the same result. With a 30 MW fire and an external pressure difference of 30 Pa, a flow velocity of 3.5 m/s in the tunnel has to be expected. Without additional measures, this leads to a minimum smoke extraction rate of 175 m^3/s. Using the existing axial fans for the new extraction system, the system could be designed to meet the new Swiss recommendation. An extraction rate exceeding the required rate of 150 m^3/s could be achieved by connecting two ventilation sections and extracting smoke from both sides of the ventilation duct. As this capacity is not sufficient to control the smoke of a 30 MW fire, additional jet fans have been installed in order to limit the longitudinal flow velocity during a fire incident.

In this case, the goal of the jet fan control is not to slow down the airflow very quickly. The control routine aims to counterbalance the external meteorological pressures and the stack effect using the jet fans. For this purpose, a very slow control routine has been developed to minimise the risk of overshooting the ventilation capacity during the initial stages of the fire.

As a direct measurement of the external forces is not feasible with a reasonable accuracy, the measurement of the flow velocity in the tunnel is used as a control parameter. First, the measurements of several devices have to be compared carefully to decide if the signals are trustworthy. Then, the aerodynamic drag of the tunnel tube is estimated and the external forces are derived from a time average of the velocity measurements. Finally, the number of jet fans needed to limit the flow velocity can be calculated. This process is repeated every six minutes. The time constant of the control routine depends on the tunnel geometry and on the expected external forces. It is an individual parameter for each tunnel.

4.2 Tunnel Gotschna

The design methodology has been applied for another tunnel that is currently under construction, the Gotschna tunnel. The tunnel also consists of a single tube with bi-directional traffic. It will be equipped with a semi-transverse ventilation for normal conditions with an intermediate ceiling and a separate exhaust duct with dampers for smoke extraction. The Gotschna tunnel has a total length of 4202 m and a maximum gradient of 4.78 percent over a length of 3800 m. The cross-section area is 44.2 m^2.

Here, the three models give a very similar result. The flow velocity in the tunnel due to a 30 MW fire is calculated. Instead of using an external pressure difference, an initial temperature difference between the tunnel air and the ambience of 5K is assumed. The model in the Swiss guideline and the model by Opstad et al. give a flow velocity of 3.8 m/s. The simulation with Sprint gives a slightly higher flow velocity, 4.0 m/s. From the calculation, a minimum extraction rate of 168 to 177 m^3/s seems sufficient for the design fire case. By connecting the exhaust ducts at both ends to the two ventilation buildings, a smoke extraction rate of 210 m^3/s or higher becomes possible. The higher volume flow rate gives a safety margin for additional external forces.

5. CONCLUSION

- In a tunnel with a considerable slope, a small temperature difference can cause a flow velocity in the range of the critical velocity. As the assumption of a stratified smoke layer is not justified, the smoke-extraction capacity has to be designed for an expected longitudinal flow.
- Three models to assess the chimney effect have been compared. With these models, the expected flow velocity can be calculated based on buoyancy and external forces.
- The models give very similar results. Each of them is applicable for the design of smoke extraction systems.
- However, the three models make assumptions that have to be looked upon. Limitations of a model always have to be considered when it is chosen for a certain application.

6. REFERENCES

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