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Foreword

On behalf of the organisers and the dedicated Technical Advisory Committee, I'm honoured to welcome you to the 20th International Symposium on Aerodynamics, Ventilation, and Fire in Tunnels, now in Scandinavia for the first time. Since 1973, this symposium has been the key event for idea exchange and learning in the field. This year, we received a record number of paper submissions, leading the committee to carefully review and select the best, which have been organized into the following sessions:

- CFD/1-D Modelling
- Design Methods Using Artificial Intelligence and/or Machine Learning
- Digitalisation
- Equipment
- High Speed Rail Tunnels & Hyperloop Systems
- Innovations in Ventilation Design and Control
- New Energy Carriers
- Platform Screen Doors
- Railway Case Studies
- Road Tunnel Case Studies
- Road Tunnel Refurbishments
- Smoke Control and Critical Velocity
- Smoke Management and Egress (Tenability)
- Sustainability in Underground Design and Construction
- Testing and Commissioning

Sincere thanks to the authors, the key-note speakers, the delegates, the exhibitors, the technical advisory committee, and the organisers. As a result of the contributions, work and passion for aerodynamics, ventilation, and fire in tunnels, this symposium offers an excellent opportunity to experience and to discuss, so that we collectively can raise the bar, for the very state of the art.

Dr Rune Brandt
Chairman of the Technical Advisory Committee

Simulation of air temperatures in the rail tunnel network of Stuttgart 21 to assess the risk of frost in fire-fighting water pipes

E. Doehler, P. Reinke, HBI Haerter AG, Switzerland

ABSTRACT

The Stuttgart 21 project (S21) comprises the transformation of the existing main station from an above-ground terminal station to an underground through-station with 8 tracks and the construction of 30 km of tunnels. The tunnels include water pipes for firefighting. Due to the length of the tunnels and the resulting filling times, water mains at distances of more than 1 km from the portals must remain constantly filled with water.

The risk of water freezing in these pipes is assessed by one-dimensional aero-thermal simulations. The modelling considers outside temperature variations of the past 15 years. The analysis of the tunnel network identifies short time and local freezing risks only.

1 INTRODUCTION

Portals, shafts, and accesses, lead to an air-exchange between the rail tunnels and the outside. In addition to the dominating train-induced pressure changes, the air-exchange is driven by thermal buoyancy pressures, wind pressures at the portals, and barometric pressure differences. As a result of these pressures and air flows, the tunnel air temperatures are influenced by the outside weather conditions. During winter and depending on the flow patterns, extended parts of a tunnel may cool down to freezing temperatures.

The distribution and temporal changes of air temperatures within a tunnel ("tunnel climate") results from various simultaneous flow and heat transfer phenomena. Daily and yearly temperature variations of the tunnel air as well as the surrounding lining and underground are influenced by the factors illustrated in Figure 1. The following phenomena must be considered for tunnel environmental simulations ("tunnel climate"):

- Pressure forces by moving trains and resulting motion of air
- Pressure forces by temperature/density differences between outside and inside air
- Pressure forces by meteorology (wind, pressure difference across mountain rims)
- Heat and humidity transport by bulk motion of air and air exchange (convective heat transfer)

- Heat sources and sinks in the tunnel (rolling stock, trackside equipment)
- Heat transfer between tunnel air, walls/inner lining and surrounding ground/rock
- Heat transfer by condensation and evaporation of water at tunnel and train walls
- Heat transfer from and to trains

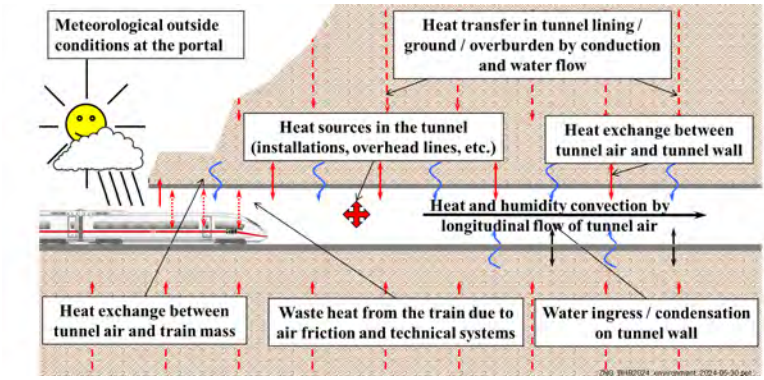

Figure 1. Factors affecting the tunnel environmental conditions (tunnel climate)

Typically, new rail tunnels in Germany are equipped with dry firefighting water pipes. In the extended tunnels of the S21 project, and because of the associated long filling times, the firefighting water pipes in the tunnel tubes located more than 1 km away from a portal are permanently filled with water. This pre-filling of water pipes implies the risks of freezing, damage, and of becoming non-functional during winter conditions. It is therefore necessary to assess the risk of frost in the charged firefighting water pipes of the tunnels.

The tunnel network of S21 with its predominant twin-tube, single-track, high-speed tunnels is shown in Figure 2.

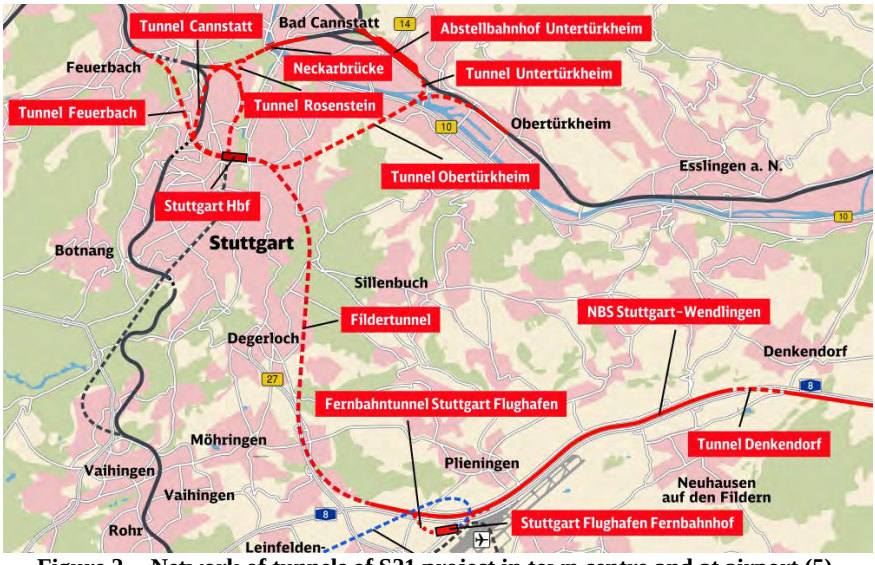

Figure 2. Network of tunnels of S21 project in town centre and at airport (5)

The vertical alignment and further tunnel data are given in Figure 3 and Table 1.

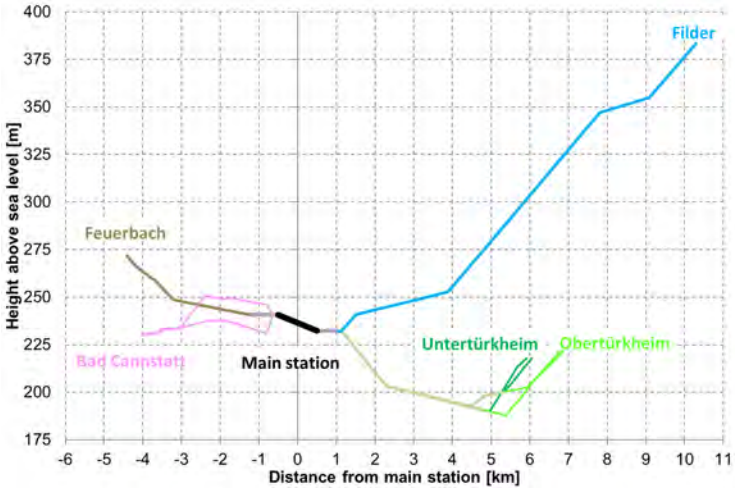

Figure 3. Vertical alignment of tunnels of the S21 project (2)

Table 1. Parameters of the S21 tunnel network

Tunnel	Length [m]	Local max. gradient [%]	Free cross-sectional area [m^2]	Number of tracks per tube	Max. ground overburden [m]
Fildertunnel	9667	2.1	60.5	1	220
Obertuerkheim	6127	2.8	42	1	125
Untertuerkheim	5233	3.1	42	1	125
Feuerbach	3440	1	42-79	1-2	100
Bad Cannstatt	3930	2.6	42-79	1-2	150

The principal locations of the frost-sensitive, water-filled firefighting mains and the hydrants inside the running tunnel are shown in Figure 4.

Figure 4. Firefighting water pipes in tunnel invert (left) and hydrant at wall (right)

2 METHODOLOGY

2.1 Sequence of simulations

For the tunnel environmental simulations of the S21 tunnel network, THERMOTUN (developed by Prof. A. Vardy, UK) and THERMO (developed by HBI Haerter, CH) were employed. THERMOTUN computes the aerodynamic effects such as pressure waves, airflows, train tractive efforts, and the dispersion of diesel emissions or other gaseous pollutants. THERMO models the tunnel environmental conditions (tunnel climate) predicting tunnel air and lining/ground/rock temperatures as well as tunnel air humidity based on the thermal behaviour and interactions between tunnel air, rolling stock, inner lining and surrounding ground and the outside atmosphere.

The one-dimensional simulation package consisting of THERMOTUN and THERMO is validated by measurements and analytical comparisons. It has been employed in several railway tunnel projects worldwide. PYTHON is used to manage computation steps and data transfers between the simulation tools (see (1)(2)).

Considering both, the aerodynamic effects and the heat transfer phenomena, the simulations are cyclically staggered using THERMOTUN and THERMO. The cycle established for the S21 tunnel environmental analysis is illustrated in Figure 5.

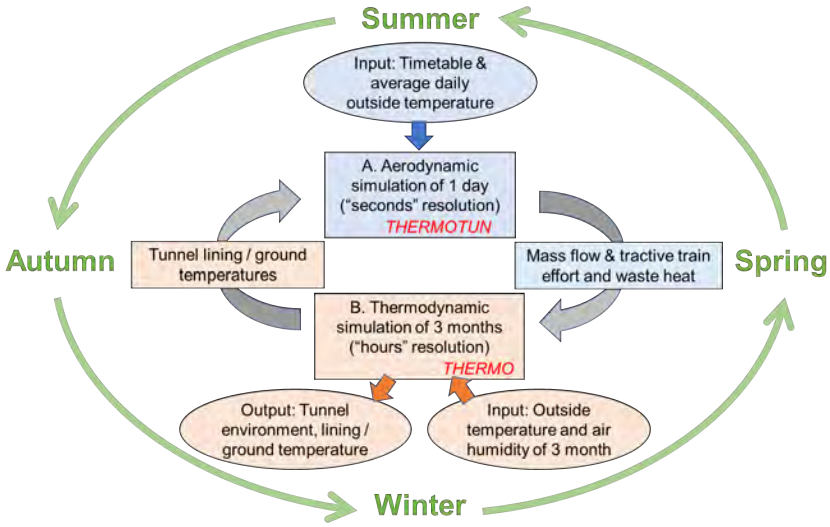

Figure 5. Cycle of tunnel environmental simulations of S21 network with THERMOTUN and THERMO

Short-term aerodynamic simulations covering 24 hours of operation are conducted with THERMOTUN for each season, followed by long-term thermodynamic simulations covering 3 months with THERMO. The temporal resolution of THERMOTUN is of the order of seconds while the temporal resolution of THERMO is of the order of minutes or hours. To account for both aerodynamic and thermodynamic effects, THERMOTUN results, including volumetric flow rates and tractive waste heat release to tunnel air, serve as input to thermodynamic simulations with THERMO. Subsequently, tunnel environmental conditions are determined by thermodynamic simulations providing, amongst others, the wall temperature settings in THERMOTUN to model the thermal

draught pressures in aerodynamic simulations. This cycle is repeated four times a year, ensuring consistency in the annual simulation.

Other time-stepping and frequencies of iteration cycles are possible. The temporal resolution of the different computations was chosen for efficiency reasons and was found to be appropriate considering the objectives of the analysis. In particular, the approach yields a sufficient representation of the annual variation of thermal draught pressures. Overall, THERMO simulates 15 railway operational years to establish quasi-stationary aero-thermal conditions, resulting in a total of 60 computation cycles between THERMOTUN and THERMO.

2.2 Simulation parameters

2.2.1 THERMOTUN

Selected data for THERMOTUN input is given in Table 2 and Table 3.

Table 2. Simulation settings for THERMOTUN

Parameter	Value
Duration of simulation	24 h
Time step	Approx 0.15 s

Table 3 shows the train schedule employed for THERMOTUN simulations. Peak hours are from 6 to 8 AM and from 4 to 6 PM, while off-peak hours are all other times. Table 3 also lists the maximum train speed in the tunnels. The speed profile of trains in THERMOTUN is adapted to the maximum available traction power of the trains. Therefore, the maximum train speed in the Filder tunnel, for example, is 250 km/h for downhill journeys and 180 km/h for uphill travel.

Table 3. Train schedule for peak and off-peak hours and train speed in tunnels

Tunnel	Trains per hour and direction (peak)	Trains per hour and direction (off-peak)	Max. train speed in tunnel [km/h]
Filder	14	11	250
Obertuerkheim	7	6	160
Untertuerkheim	4	3	160
Bad Cannstatt	7	6	160
Feuerbach	18	14	160
Total	**50**	**40**	-

2.2.2 THERMO

Selected data for THERMO input is given in Table 4.

Table 4. Simulation settings for THERMO

Parameter	Value
Duration of simulation	¼ year
Time step	1 s of subsection; 30 min overall
Thermal conductivity of the ground	3.3 W/(m·K)
Heat capacity of the ground	682 J/(kg·K)
Density of the ground	2708 kg/m^3
Constant ground temperature at a depth of 90 m (initial rock temperature)	11°C (annual average temperature)
Number of shells representing the inner lining and the ground	25

2.3 Simplifications

In the simulations, various simplifications are made compared to the real conditions in the railway tunnel, all of which are deemed acceptable considering the scope of the modelling:

- Constant, averaged external temperatures for 24 hours at the portals regarding updraft and downdraft flows (THERMOTUN calculations only).
- Volume flow rates determined for 4 characteristic days of the year (1 day in January, April, July, October each) and used for 3 months as THERMO input.
- Wall temperatures in THERMOTUN resulting from preceding THERMO simulations.
- Only one type of train is used in the aerodynamic simulations.
- Uniform distribution of train journeys over an operating hour, subdivided into peak hour and off-peak hour; no specific nighttime schedule or operational downtime.
- Neglect wind pressures at portals and openings of the tunnel network

Simplifications are made because of their minor impact on the results and their beneficial increase to computation efficiency. For example, neglecting specific night schedules or operational downtimes may influence the tunnel air temperatures. Therefore, simplifications considering the uncertainties about the future detailed train schedules and train features are made in a conservative manner. For example, train operation is modelled in such a manner that it leads to maximum entrainment of cold outside air during winter nighttime.

2.4 Weather data

The weather data for 15 years (2008 – 2022) was taken as the input for the tunnel environmental simulations. The data was recorded by the local weather station closest to the main station of the S21 tunnel network (4). Figure 6 shows the outside temperature variations over 15 years. The coldest period of several days can be found in February 2012. The temperature ranges between -4°C and -16°C for 10 days. The outside air temperature for year 2012 is shown in Figure 7.

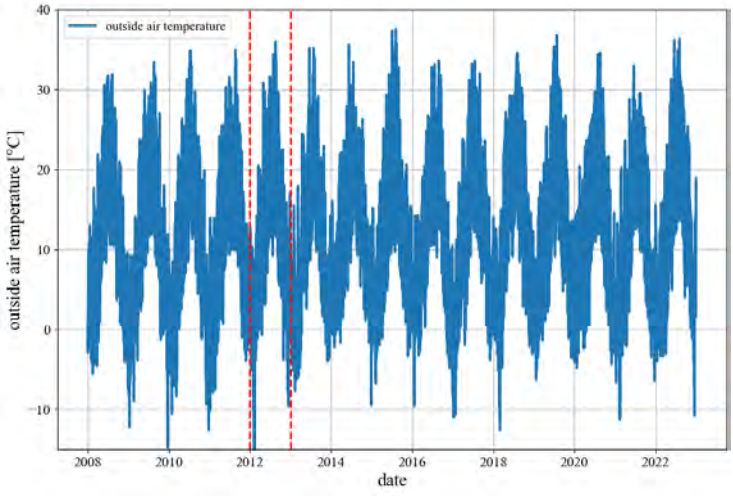

Figure 6. Outside air temperatures from 2008 to 2022 with lowest temperatures noted in 2012 (year highlighted by red lines)

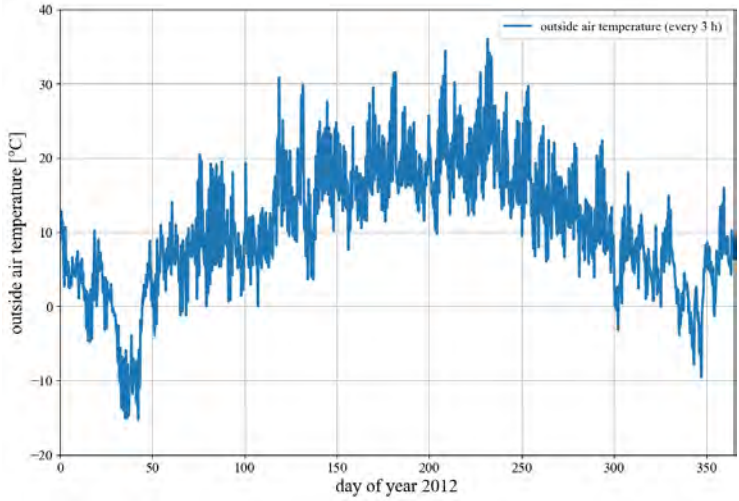

Figure 7. Outside air temperature in the year 2012 with the coldest period

3 RESULTS

For the analysis of 15 years of operation, 60 cycles between THERMOTUN and THERMO are computed and analysed. Even though all seasons are examined, only the coldest periods are significant for the assessment of risk of frost in the water-filled firefighting pipes of the tunnel network. The coldest period of past temperature recordings is noted for the outside conditions of February 2012, with temperatures between -4°C and -16°C for 10 consecutive days. It is the longest period with such low temperatures of the recordings under consideration. Therefore, only results from the year 2012 are shown here, even though 15 years of outside temperature variations have been modelled.

In the following sections, the modelled air and the inner lining/ground temperature are presented. For the firefighting water extraction points (hydrants), the tunnel air temperatures are relevant, whilst for the water pipes, which are located at a depth of 0.5 m in the tunnel invert, the lining/ground temperatures are decisive.

3.1 Air temperature

In Figure 8, the range of calculated air temperatures inside the inbound trackway of the Filder and Feuerbach tunnels is shown. The “Filder – Main Station – Feuerbach” stretch is the most frequented route of the tunnel network. Figure 8 illustrates that the air temperatures inside the tunnels do not exceed the maximum and minimum outside temperatures. However, the range of the air temperatures inside the inbound tube of the Filder tunnel, for example, nearly matches the range of the outside air temperature at least in the vicinity of the portal. With increasing distance from the portal, the annual temperature range reduces. In the Feuerbach tunnel, the annual temperature variation decreases along a shorter tunnel section. The mean range close to the portal varies more than at 500 m further inside the tunnel. The reason for this smaller annual temperature range is that the first 400 m of the Feuerbach tunnel near the portal is built as a double-track tunnel with trains traveling in both directions. As such, tunnel air is more frequently being pushed back and forth rather than being forced to a constant in or outflow of air.

Openings and the impact of meteorological conditions are noted at the portals at the left and right end and at the main station with major draught relief shafts located at the extremities of the station box. While negative temperatures are recorded at the portals, the waste heat of stationary trains in the main station prevents the air temperature reaching the freezing point.

The tunnel air temperatures are predominantly influenced by the train-induced longitudinal air flows and, therefore, are typically well predicted by one-dimensional analysis. The thermal conditions of the main station are characterised by thermal stratification effects and air exchange via access openings and shafts as well. Three-dimensional effects are not properly modelled by the one-dimensional analysis at hand. As such, the thermal results for the station area must be confirmed by three-dimensional analysis.

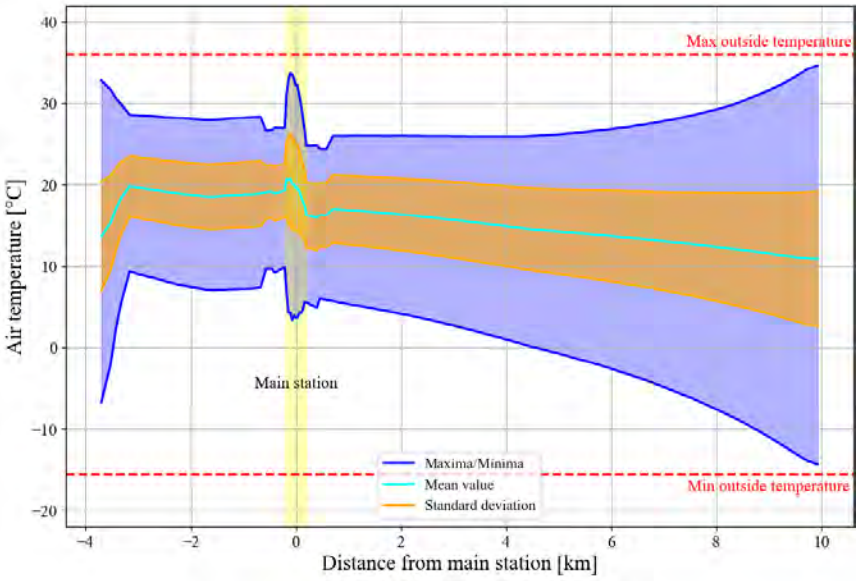

Figure 8. Air temperature inside Filder (positive kilometres) and Feuerbach (negative kilometres) tunnel for outside temperatures of year 2012

The coldest air temperatures inside the entire tunnel network are noted at the end of the cold period in February 2012. For this time, the air temperatures of the entire tunnel network are shown in Figure 9. The lines “Feuerbach W” and “Filder E” are the same as the minima in Figure 8. While along major parts of the tunnel network including the main station, air temperatures of more than 0°C prevail. Temperatures below the freezing point more than 1 km away from the portal are identified in the following tunnels:

- Filder East (inbound tube): negative temperatures until about 5 km from the portal
- Obertuerkheim East (inbound tube): negative temperatures until about 3 km from the portal
- Untertuerkheim East (inbound tube): negative temperatures until about 2 km from the portal

For the other tunnels, temperatures lower than 0 °C appear only within distances of less than 1 km from the portal, where the firefighting water pipes are empty. As with the Feuerbach tunnel, the air temperature in the Bad Cannstatt tunnel rises much faster than in the Filder and Obertuerkheim tunnels at increasing distance from the portal. This effect is attributed to the double-track tunnels. In the Obertuerkheim, Untertuerkheim, and Filder east tubes, trains are traveling in only one direction, and cold air is carried into the tunnel. Due to the higher train speeds and the higher train frequencies in the Filder tunnel (see Table 3) air temperatures below the freezing point appear much further inside the tunnel than in all the other tunnels. This is visible by the lower temperature gradient of the Filder east tube line.

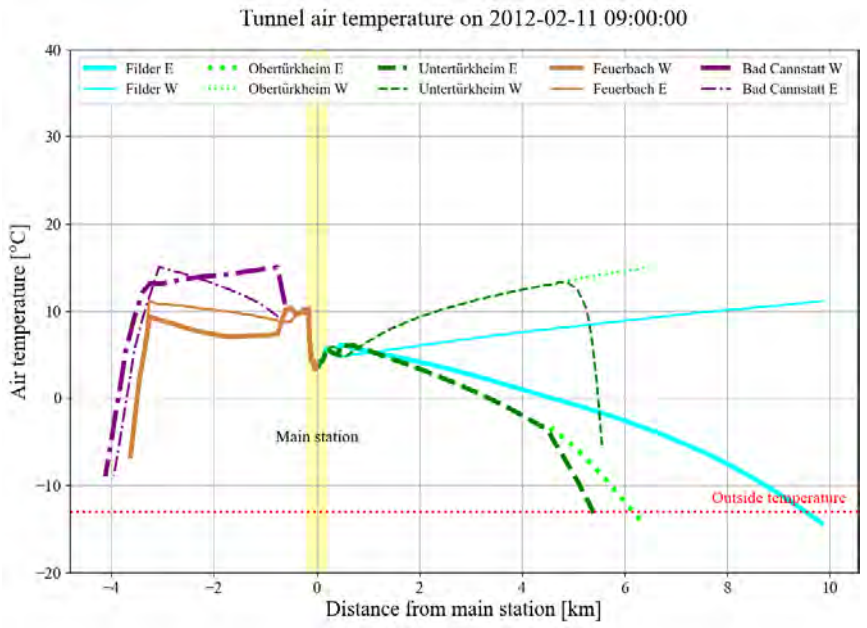

Figure 9. Tunnel air temperature of the S21 tunnel network after the coldest period in February 2012

The air temperature inside the Feuerbach and Filder tunnels is shown for the entire year 2012 in Figure 10. The distance from the main station is shown versus the days of the year 2012 starting from January. Figure 10 confirms that areas with low air temperatures in February 2012 extend further into the Filder tunnel than into the Feuerbach tunnel. It also shows that the air temperatures inside the Feuerbach tunnel are generally higher than those in the Filder tunnel. The double-track tubes at the beginning and end of the Feuerbach tunnel reduce the convective flow of cold and warm air in and out of the single-track tubes but support mixing of cold outside and warmer tunnel air.

Comparing the eastern and the western tubes of the Filder tunnel in Figure 9, for instance, the different patterns of air temperature variation are noted. These are dominated by the driving direction of the trains. As such, the tunnel environmental conditions depend mainly on the train-induced air movement rather than natural air flows, i.e., thermal down- and up-draught pressures in the summer and the winter, respectively. This conclusion is visible in Figure 11 as well.

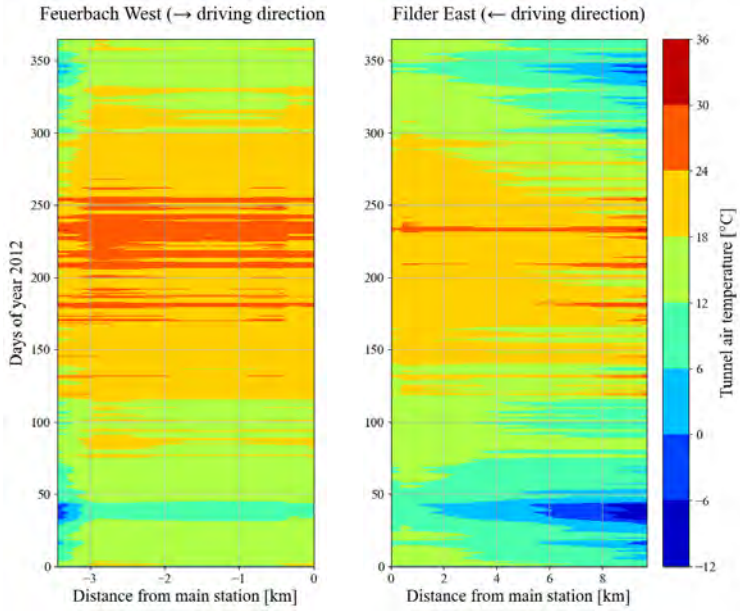

Figure 10. Air temperature inside the inbound tubes of the Feuerbach tunnel (left) and the Filder tunnel (right) for outside conditions of 2012

Figure 11 indicates the air temperatures for several positions inside the Filder tunnel in February 2012. The air temperature inside the tunnel follows the fluctuations of the outside temperature. However, the amplitude of daily fluctuations decreases with distance from the portal.

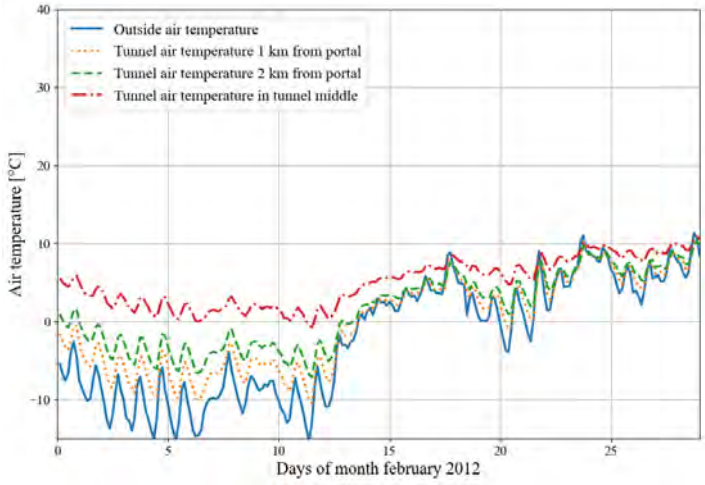

Figure 11. Air temperature at specific locations in Filder tunnel February 2012

3.2 Lining/ground temperature

Since the coldest air temperatures are noted in the Filder tunnel, the following presentation of results focuses on the lining or ground temperatures of the Filder tunnel.

For a distance of 1 km from the portal, the lining or ground temperatures of the Filder tunnel are shown in Figure 12. While the shells close to the tunnel inner lining are highly affected by the air temperatures, the lining or ground temperatures at depths greater than 6 m are not influenced by the high fluctuations of the air temperature at a distance of 1 km from the portal. The numerical model discretizes the rock up to a depth of 88 meters into 25 shells with exponentially increasing radii, but the outer layers are not affected by the annual outside temperature fluctuations.

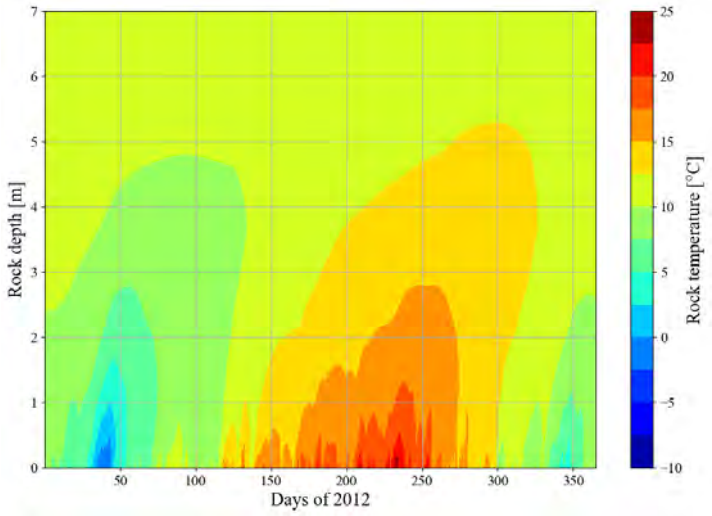

Figure 12. Lining/ground temperature at 1 km distance from the portal in Filder tunnel at outside conditions of Year 2012

The coldest period in February 2012 is noted between Days 33 and 46. Temperatures below 0 °C appear at a depth of up to 0.5 m for two days. Figure 13 illustrates the lining / ground temperatures along the Filder tunnel after the coldest period on February 12, 2012, at 6 am, i.e. 21 hours after the coldest air temperatures were recorded inside the tunnel network (see Figure 9).

According to Figure 9 the rock temperature increases with distance from the portal and with depth of tunnel lining/ground. While at the portal, temperatures of below 0°C are noted at nearly 0.9 m depth, the freezing area reaches a depth of 0.5 m at 1 km from the portal. This corresponds to the depth of the firefighting water pipes in the tunnel invert. As shown in Figure 12, negative temperatures reach this depth for short periods only.

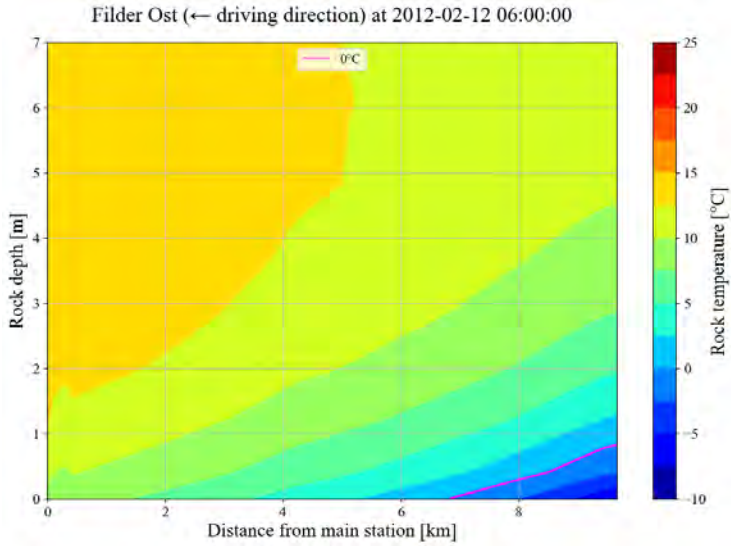

Figure 13. Lining/ground temperature along the Filder tunnel after the coldest period in February 2012

4 CONCLUSION

The calculations carried out for the tunnel network show that, based on the measurements of the DWD weather station in Schnarrenberg, there is a local and short-time risk of frost in some tunnel sections even at distances of 1 km and more from the portal over the course of a year. Major influencing factors on the rock/inner lining and air temperatures in the tunnel are:

- the assumed ground temperature at a theoretically infinite depth where the temperature remains constant throughout the year,
- thermal updrafts and downdrafts in the tunnel,
- the direction of train travel,
- the train frequency or train headway patterns,
- the speed at which trains travel through the tunnel,
- the fact that trains partially travel through the tunnel in only one direction,
- the length of the tunnel,
- the daily and annual fluctuations of outside temperatures.

All the aforementioned factors together affect the risk of frost and depend on the specific features and settings of each tunnel project. For the conditions investigated at S21, thermal updrafts and downdrafts have less impact on the tunnel climate than train-induced airflows, which are more dominant. In single-track tunnels with high-speed trains, cold air can be transported far into the tunnel leading to extended tunnel sections with temperatures below the freezing point. A short double-track section with bidirectional traffic at the portal, on the other hand, results in reduced train-induced airflow from the portal into the tunnel. The duration of a cold period is a crucial factor influencing the risk of frost in the inner lining or ground.

For the train operation scenario analysed, the water extraction points (hydrants) are exposed to tunnel air. The actual fire water pipes are located in the tunnel invert or tunnel floor, approximately 0.5 m below the walkway/trackway surface (see Figure 4). While water extraction points are exposed to subfreezing temperatures for several days in single-track inbound tunnels, the filled water pipes at a depth of 0.5 m experience temperatures below freezing only at the edge of the water-filled part in the Filder tunnel for one day in 15 years. In conclusion, the water extraction points in the identified tunnel sections must be frost-resistant. This can be achieved by increasing their robustness, adding insulation, internal heating, applying constant water circulation, or adding chemical treatment to the water.

These project-specific findings show that even though the water pipes are not charged near the portal, frost temperatures can appear further inside the tunnel, necessitating additional frost protection measures. While these findings depend mainly on project-specific properties, the risk of frost applies to all tunnel projects exposed to outside conditions with substantial frost temperatures and unprotected water-filled pipes and tapping points. Because the extent of the risk depends on many factors with varying influence, a general rule for frost protection cannot be defined, and an aero- and thermodynamic study must be conducted if the risk of freezing of water-filled pipes shall be assessed.

5 ACKNOWLEDGEMENT

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