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ZFOAM Thermal Study

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1 Introduction

ZFOAM aims to computationally assess the performance of their product through simulations of the conditions found in Norwegian tunnels. These simulations are conducted using the Finite Element Method software COMSOL Multiphysics. To validate our models, we initially simulated conditions experimentally tested by SINTEF[1], achieving a high degree of accuracy and confirming the reliability of our approach.

In the subsequent phase, we simulated different scenarios in which ZFoam panels are installed in the tunnel. This setup demonstrated efficiency even under the most extreme conditions documented by SINTEF. Specifically, the simulation maintained an above-zero temperature for the rock's outer surface in a variety of situations, effectively preventing issues related to ice formation on the rock surface. This ice accumulation causes problems by reducing the tunnel clearance and can potentially obstruct traffic. Likewise, once the ZFOAM panel is installed, it is important to prevent sub-zero temperatures on the rock surface to avoid damage caused by water infiltration and expansion during freezing in the gap between the rock and the panel.

This comprehensive validation underscores the robustness of ZFOAM panels in harsh environments, ensuring reliable performance and enhanced safety in tunnel applications.

2 Modelling approach and validation

Our validation process is anchored in the experimental results obtained by SINTEF during their Frost Laboratory project[1]. This project involved constructing a specialized test rig that was divided into two separate rooms, each serving a distinct purpose. These rooms were separated by a mass of granitic rock, meticulously built using rock blocks to closely replicate real-world conditions. One room was designed to simulate the extreme temperature conditions found in tunnels, which can plummet to -20°C. This was achieved by employing a highly effective climate control system. The other room maintained the stable temperature of the mountain rock core, set at a constant 8°C throughout the duration of the experiments, to mimic the natural thermal environment.

The test rig's design was crucial for simulating the environmental conditions accurately. The room mimicking the tunnel conditions was equipped with advanced sensors and a powerful climate control system capable of maintaining extreme low temperatures. The other room, representing the core temperature of the mountain rock, was kept at a consistent 8°C to provide a realistic thermal gradient across the rock mass.

While various experiments were conducted, we specifically focus on the first two tests, as they provide the most relevant data for our validation purposes:

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- Test 1: In this test, the temperature of the tunnel room was maintained at -10°C for a continuous period of 300 hours. This setup resulted in a cumulative thermal exposure of 1500 hC (hours Celsius), providing a substantial dataset for analyzing the thermal response of the granitic rock and the simulated tunnel conditions.

- Test 2: This test involved setting the tunnel room temperature to -20°C for 200 hours. The extreme conditions of this test resulted in a cumulative thermal exposure of 4000 hC. The data from this test was particularly valuable for assessing the model's performance under the most severe conditions expected in Norwegian tunnels.

The remaining tests involved cycles of varying temperatures, which, although informative, did not contribute significantly to the context of validating our model due to their complex and less consistent nature.

To simulate the thermal processes accurately while ensuring computational efficiency, we assumed that the insulation of the test rig was perfect. This means that the lateral surfaces, roof, and floor were considered adiabatic, with no heat transfer occurring through these boundaries. Given this assumption, the problem can be effectively reduced to a two-dimensional model. This simplification is supported by the symmetry and negligible heat flux in the insulated directions, allowing us to focus computational resources on the primary areas of interest without losing accuracy.

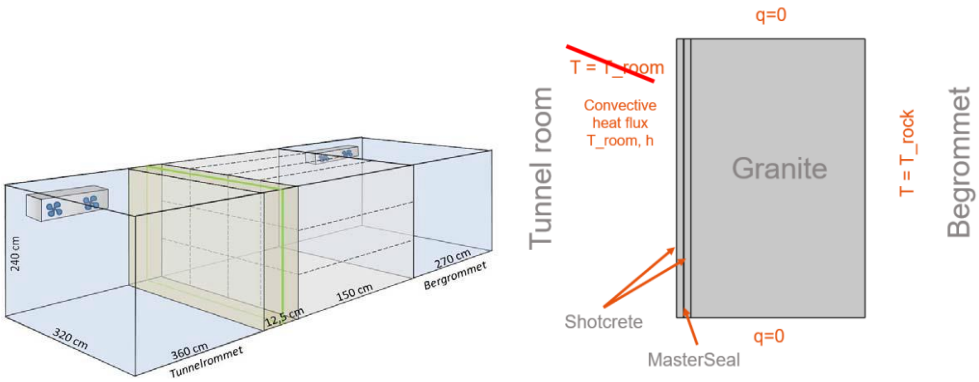


Figure 1. Experimental rig schematic (left) and 2D simulation approach to the problem (right)

As detailed in the SINTEF report[1], the rock is further isolated from the tunnel room by two shotcrete layers, separated by a thin layer of BASF MasterSeal. Each of the shotcrete layers is 6 cm thick, while the MasterSeal layer is just 4 mm thick, as depicted in Figure 10 of the SINTEF report. This multi-layered isolation approach is crucial for accurately simulating the thermal interactions between the rock and the tunnel environment.

For computational efficiency, this setup is simplified into a 2D geometry, as illustrated in Figure 1 on the right. To streamline the simulation, we avoid modeling the air in the rooms directly. Instead,

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we impose a constant temperature boundary condition of 8°C on the rock room side, based on established literature and experimental data.

Initially, we attempted to apply a similar constant temperature boundary condition on the tunnel room side. However, this approach did not replicate the experimental results obtained for Test 1 accurately. The discrepancy indicated the need for a more nuanced approach to model the thermal dynamics on the tunnel room side.

To address this, we implemented a convective heat flux boundary condition on the tunnel room side. This involved using the tunnel room temperature of -10°C, as used in the experimental tests, and applying an appropriate heat transfer coefficient. Drawing from previous literature specific to this context, we tested various values for the heat transfer coefficient to identify the most accurate correlations.

This approach better captured the heat exchange dynamics between the tunnel air and the shotcrete layers, aligning our simulation results more closely with the experimental data. The use of a convective heat flux boundary condition reflects the real-world conditions more accurately, where air movement and temperature gradients significantly impact the thermal behavior of the tunnel environment.

The refined simulation approach, incorporating convective heat flux, underscores the importance of accurately modeling boundary conditions to replicate experimental results. By aligning our model more closely with the observed data, we enhance its reliability and predictive power. This improved accuracy is critical for assessing the performance of ZFOAM panels and their effectiveness in preventing ice accumulation and maintaining structural integrity in harsh tunnel environments. Some heat flux formulas for tunnels were found in the literature[2,3] and are presented here for convenience:

General formula:	$h = 0.0265 \cdot Re^{0.8} \cdot Pr^{0.33} \cdot {}^{\lambda_{am}}/_{D_h} \dots\dots\dots\dots\dots\dots\dots\dots$	$= 7.58\ W/m^2K$
Sieder-Tate formula:	$h = 0.027 \cdot Re^{0.8} \cdot Pr^{0.3} \cdot \frac{\lambda_{am}}{D_h} \cdot \left(\frac{v_m}{v}\right)^{0.14} \dots\dots\dots\dots\dots\dots\dots\dots$	$= 8.11\ W/m^2K$
Newman formula:	$h = 0.026 \cdot Re^{-0.2} \cdot (1 + (D_h/1500)^{0.7} \cdot 1.2 \cdot 1010 \cdot u_m)$	$= 7.48\ W/m^2K$
Pethukov:	$h = \frac{f_D}{8} \cdot c_p \cdot \rho \cdot u \Big/ 1.07 + 12.7\left(Pr^{2/3} - 1\right)\sqrt{\frac{f_D}{8}} \dots\dots\dots\dots$	$= 5.03\ W/m^2K$

A parametric study was conducted to evaluate the impact of these heat transfer coefficients on the simulation results. After careful consideration, we derived heat transfer coefficients using both the General and the Sieder-Tate formulas. These coefficients demonstrated exceptional agreement with the experimental results obtained in Test 1 and 2. A comparative figure, as shown in Figure 2, illustrates this agreement clearly.

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The figure highlights the temperature profiles at various probe points. For example, the left-side figures illustrating Test 2, show that for probes B2-1 and B2-2, both experimental and simulation results indicate temperatures slightly below -8°C at 200 hours. Similarly, for probe B2-4, the temperatures are slightly below -6°C, and for probe B5, the temperatures are under -4°C. This close alignment between the experimental data and our simulations underscores the accuracy of our model.

However, slightly less accurate results were observed for probes closer to the opposite boundary of the granitic rock. These discrepancies can be attributed to non-ideal temperature control within the room. Specifically, the slight increase in temperature observed at probe B2-7 in the experimental results cannot be perfectly matched by the simulation. This variation is likely due to the temperature control system in the room exceeding 8°C at the beginning of the experiment.

Despite these minor deviations, the overall agreement between our model and the experimental data is robust. The parametric study confirms that our model accurately replicates the thermal behavior observed in the experiments, particularly when using the heat transfer coefficients derived from the General and Sieder-Tate formulas.

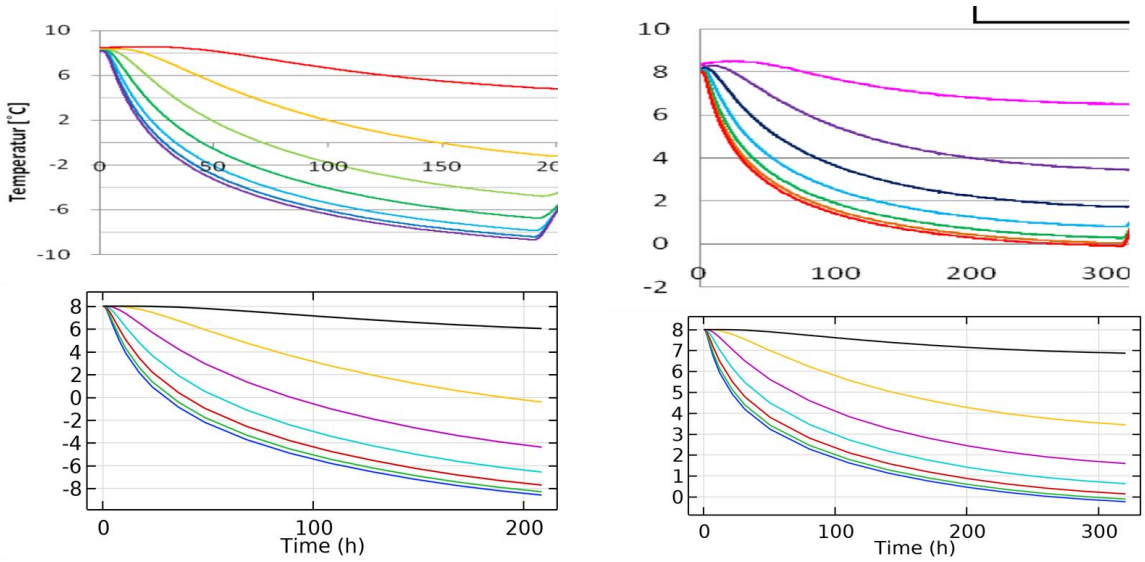


Figure 2. Experimental (top) and simulation (bottom) results for the tests 2 (left) and 1 (right)

Further validation of our model was achieved by simulating the conditions of Test 1, where the temperature of the tunnel room was set to -10°C for 300 hours. Graphical comparisons of the resulting temperature curves show that our model accurately fits the experimental data, with the same minor discrepancies observed and explained in the previous test.

In this test, the temperatures for probes B2-1, B2-2, B2-3, and B2-4 closely match the experimental results. The graphical comparison reveals that our model reliably replicates the thermal behavior

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observed in the experiments, particularly in the critical region close to the tunnel. The consistency between the simulated and experimental temperature profiles further confirms the robustness of our model.

The minor discrepancies noted, especially near the boundaries of the granitic rock, are again attributed to non-ideal temperature control in the experimental setup. Despite these slight variations, the overall agreement remains strong. The model's ability to closely match the temperatures at multiple probe points under different conditions underscores its reliability.

Taking into account all these validations, we can confidently assert that our model can accurately replicate the real conditions in the tunnel when ZFOAM panels are installed. The high degree of accuracy observed in the simulations indicates that our model is well-suited for predicting the thermal performance of ZFOAM panels in actual tunnel environments.

While having access to the raw experimental data would allow for a more precise quantification of the model's error, the graphical comparisons are sufficient to demonstrate that the discrepancies are minimal, particularly in the region of interest near the tunnel. Moreover, the fact that our model did not rely on parameter estimation but only on material properties and established heat transfer coefficients from literature further enhances our confidence in its accuracy.

Despite minor discrepancies attributable to non-ideal temperature control in the experimental setup, our model consistently replicated the observed thermal behavior. The exceptional agreement between the simulated results and the experimental data, achieved without parameter estimation but based solely on material properties and established heat transfer coefficients from literature, underscores the model's reliability. These findings confirm that our model can accurately predict the thermal performance of ZFOAM panels in tunnel environments by using the Sieder-Tate derived heat transfer coefficient, ensuring their effectiveness in preventing ice accumulation and maintaining structural integrity. This robust validation process demonstrates the model's capability to simulate real-world conditions with high precision, making it an invaluable tool for optimizing the design and application of ZFOAM panels.

3 Thermal simulation of ZFoam’s set-up for tunnel insulation

Once we confirm the validity of our model, the next step involves assessing the behavior under hypothetical scenarios when the product is installed, instead of the shotcrete and MasterSeal layers. There are two main scenarios:

1. The rock is in direct contact with the ZFOAM panel.
2. An air gap is present between the rock and the ZFOAM panel, which is installed after the gap. This setup presents a different thermal configuration compared to previous models.

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There are also, two kinds of product: 6mm and 12mm deep insulation panels. To accurately assess the thermal performance of the ZFOAM panels in these scenarios, the thermophysical properties of the panel, which comprises various material layers, must be homogenized. This homogenization process aggregates the properties of the different constituents—specifically, polyethylene foam, high-density polyethylene (HDPE), and low-density polyethylene (LDPE)—to represent the panel's thermal behavior effectively.

For specific heat capacity, we compute a mass-weighted average accounting for the mass per unit surface area of each constituent material. This calculation yields a specific heat capacity of 2107.80 J/kg·K for the 12mm panel and 2055.67 J/kg·K for the 6mm panel. These values reflect the panel's ability to absorb and store thermal energy, crucial for accurately simulating heat transfer and predicting performance under various conditions. The thermal conductivity, determined experimentally, is of 0.0372 W/m·K. The density is derived considering the composition of the panels in mass per unit area and their depth. The values used for the panels are detailed in Table 1. While this approach does not track the internal temperature distribution within the panel, it provides an accurate overall thermal performance for such a small depth within the complete model framework.

Table 1. ZFoam panels composition and homogenized properties calculated for the simulation.

PANEL	HDPE [g/m^2]	PE [g/m^2]	LDPE [g/m^2]	Density [kg/m3]	Specific heat [J/kg·K]
6mm	240	165	45	75	2055.67
12mm	240	330	45	51.25	2107.80

By homogenizing these thermophysical properties, our simulations are accurate and representative of the ZFOAM panel's actual behavior when installed in the tunnel environment. This approach enables a thorough analysis of the panel's interaction with surrounding materials and conditions, providing valuable insights into its effectiveness in maintaining structural integrity and preventing ice formation issues.

Incorporating the air gap requires approximating the heat transfer within this region, as air acts as an insulator significantly impacting the thermal performance. Experimental values for this task, particularly for calculating heat transfer in high aspect ratio air-filled cavities, are well-established in the literature[2].

For this scenario, we assumed an air layer thickness of 6 cm. Given the setup height of 240 cm, the aspect ratio of the air gap (height to thickness) is 40, representing the upper limit where the relationship holds[2]. This relationship is crucial for accurately modeling convective heat transfer within the air gap, ensuring realistic thermal behavior in our simulations.

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$$Nu = 0.42 \cdot Ra_L^{1/4} \cdot Pr^{0.012} \cdot \left(H/L\right)^{-0.3}$$

However, during simulations, the Prandtl and Rayleigh numbers were out of range, rendering this approach unfeasible. Consequently, air movement and heat transfer by convection were modeled using the Boussinesq approximation and the Reynolds-Averaged Navier-Stokes (RANS) equations with a κ-ε turbulence model.

The air in the cavity was modeled using a non-isothermal flow, accounting for changes in air properties due to temperature variations. The Reynolds-averaged Navier-Stokes (RANS) equations with a κ-ε turbulence model facilitated computation. Under these parameters, simulation convergence was ensured, yielding excellent results. For each scenario considered, four key metrics are recorded: the temperature in the surface of the rock after 300 hours (T_300), the steady-state temperature (T_est), the maximum duration the rock surface remains above zero degrees Celsius (t_max), and the maximum freezing index that can be experienced with no sub-zero temperatures in the rock surface (Fmax). The results are presented in Table 2:

Table 2. Thermal simulation results

e_air [mm]	e_zfoam [mm]	T_tunnel [C]	T_300 [C]	T_est [C]	t_max [h]	Fmax [hC]
0	6	-10	-2.88	-3.60	76.79	767.9
0	12	-10	-0.91	-1.65	183.39	1833.9
200	6	-10	3.41	3.01	∞	∞
100	6	-10	3.24	2.85	∞	∞
200	6	-20	0.96	0.28	∞	∞

The results in Table 2 highlight the significant impact of including an air gap on the thermal performance of the ZFOAM panels. In the scenarios without an air gap, the rock surface temperature remains below zero for substantial periods, failing to meet the target of maintaining the rock surface temperature above zero for at least 8000 hC (Fmax). Specifically, for the 6mm panel with no air gap, the rock surface temperature remains above zero for just 76.79 hours and drops to -2.88°C after 300 hours. The 12mm panel performs slightly better but still does not achieve the desired isolation, with the rock surface temperature remaining above zero for 183.39 hours and reaching -0.91°C after 300 hours.

In contrast, when an air gap is included, the performance significantly improves. For a 200mm air gap and a 6mm panel, the rock surface temperature remains well above zero after 300 hours. In addition, no sub-zero temperature is reached until the stationary state is reached, effectively maintaining the rock surface temperature above zero continuously. This demonstrates that the air gap acts as a highly effective insulator, significantly enhancing the thermal isolation properties of the ZFOAM panels. The same is true when reducing the air gap depth to 100mm, and even when

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the tunnel temperature is further reduced to -20C, highlighting the thermal isolation capabilities of this setup.

The improved performance with the air gap scenario is crucial for maintaining structural integrity and preventing issues related to ice formation. The air gap reduces heat transfer between the rock and the tunnel environment, ensuring that the rock surface temperature remains above zero, even under extreme conditions (-20C). This is a key finding, indicating that incorporating an air gap with ZFOAM panels can achieve the desired isolation, maintaining the rock surface temperature above zero for extended periods (Fmax ≥ 8000 h·°C).

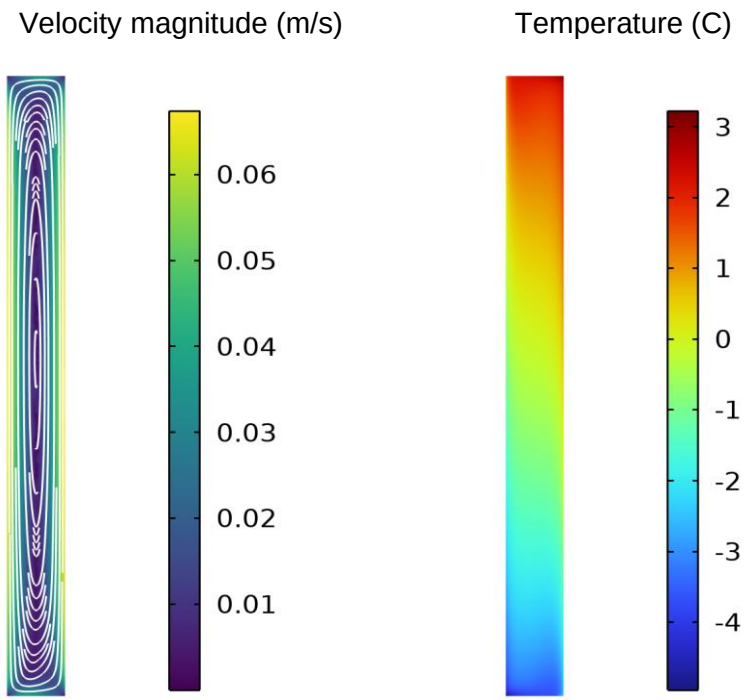


Figure 3. Results for the velocity field (left) and the temperature (right) for the simulation using an air gap of 200 mm and a tunnel temperature of -20C

In conclusion, the simulations confirm that the inclusion of an air gap between the rock and the ZFOAM panel significantly enhances thermal performance. This setup maintains the rock surface temperature above zero, thereby meeting -and exceeding- the desired isolation criteria. The results provide compelling evidence for the effectiveness of using an air gap to improve the thermal insulation properties of ZFOAM panels in tunnel environments.

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