Calculation of minimum water flow through a hydropower tunnel required to prevent freezing in permafrost rock near Ilulissat, Greenland, using a transient, three-dimensional heat transfer model

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Introduction

Permafrost in rock which is found in cold regions near the Arctic Circle can cause problems during the construction and operation of hydropower plants. Where the headrace and/or tailrace tunnels lie at shallow depths near the surface, there is always a risk of water freezing, especially if water flow is stopped due to operational problems. A three dimensional finite element modelling methodology has been developed to calculate the heat transfer from water, through the rock to the cold surroundings. By estimating the heat loss from the flowing water, the minimum water flow can be determined, that prevents the water from freezing.

1 Project background

The Ilulissat power project - currently under construction - is located on the West coast of Greenland, in the Disco Bay (69°28'N). It is to provide the town of Ilulissat and its 4,500 habitants with green energy and replace diesel generators currently producing electricity for the town. The first turbine of three is to be commissioned in November 2012 and the other two about a year later or in September 2013.

The project owner is the Greenland's national energy company Nukissiorfiit. The contract is for complete design and construction and is the Icelandic contractor company Ístak the main contractor with Verkís consulting engineers as their main designers.

The project harnesses the discharge from two natural glacial lakes in the area "Paakitsup Akuliarusersua" with storage obtained by drawdown of the water levels by respectively 30 and 50 m from the present. Water is diverted from the upper lake, at 233 meters above sea level, through a transfer tunnel controlled by gates. The lower lake, at 187 meters above sea level, serves as the intake reservoir and from there water is diverted through an intake structure equipped with bulkhead gates. From these the water is conveyed through an inclined unlined 1.4 km long headrace tunnel, partly in permafrost, down to three 7.5 MW Francis turbines on a vertical axis in an underground powerhouse. The powerhouse is at sea level some 400 m inside the mountain. The three turbines in the station generate a total of 22.5 MW, with a maximum water flow of 14.4 m^3/s. For each turbine, a throttling by-pass has been designed, that allows for 0.4 m^3/s flow or a total of 1.2 m^3/s. The results from this study are used to determine the capacity of these by-passes. Adjacent to the powerhouse is a transformer and a switchgear cavern. The tailrace tunnel is 1.8 km long diverting the water directly into the sea.

TECHNICAL INFORMATION

Commissioning:	2013
Installed capacity:	22.5 MW
Turbines:	Francis, 3×7.5 MW
Rated speed:	1.000 rpm
Generators (10 kV):	3×9.4 MVA
Excitation:	Brushless
Unit transformers:	3×10 MVA 63/10 kV
Substation, 3 bay:	63/10 kV
transformers:	2×16/21 MVA
Energy production:	65 GWh/a
Gross head:	186 m
Rated discharge:	3×4.8 m^3/s
Sø 187 live storage:	54×10^6 m^3
Sø 233 live storage:	65×10^6 m^3
Headrace tunnel:	1.4 km 4.0×4.5 m = 16.3 m²
Tailrace tunnel:	1.8 km 4.0×4.5 m = 16.3 m²
Access tunnel:	374 m 5.0×6.0 m = 27.3 m²
Diversion tunnel:	1.0 km 3.0×4.0 m = 11.0 m²
Powerhouse:	35×10.5×22 m
Transformer hall:	28.5×9×8 m
Service building:	35.6×10.4 m
Transmission line (60kV):	50 km
Location:	69°12' N, 51°05' W

A concrete service building is located at the access tunnel portal, housing service facilities and storages for the power station and its personnel. In addition, the building includes fully equipped accommodation for ten people. The project also includes a harbour and a harbour building housing the emergency diesel engine and transport vehicles. A substation equipped with two transformers, switchgear and the pertinent controls is located in the town of Ilulissat.

2 Finite element model and boundary conditions

The finite element model and boundary conditions are described below. The model is used for numerical approximation of the linear heat equation, used to solve transient three-dimensional heat transfer in solid rock from known material properties (conductivity, specific heat capacity and density) and boundary conditions (temperature, heat flux and convection).

2.1 Finite element model

An isometric view of the finite element model and a cross-section perpendicular to the water tunnel is shown in Fig 1. The surface elevations are based on a map of the land surrounding the head- and tailrace tunnel from reservoir to fjord, the length of which is around 3.3 km. The bottom elevation of the model is set 200 m below sea level. The width of the model is 400 m or 200 m from each side of the tunnel. The ends of the model reach around 100 m beyond both ends of the tunnel.

The finite element distribution along the length and height of the model can be seen in the upper part of Fig 1. The mesh perpendicular to the tunnel can be seen in the lower part of the figure. A finer mesh nearest to the tunnel is needed, due to high thermal gradients in that region compared to the rest of the model.

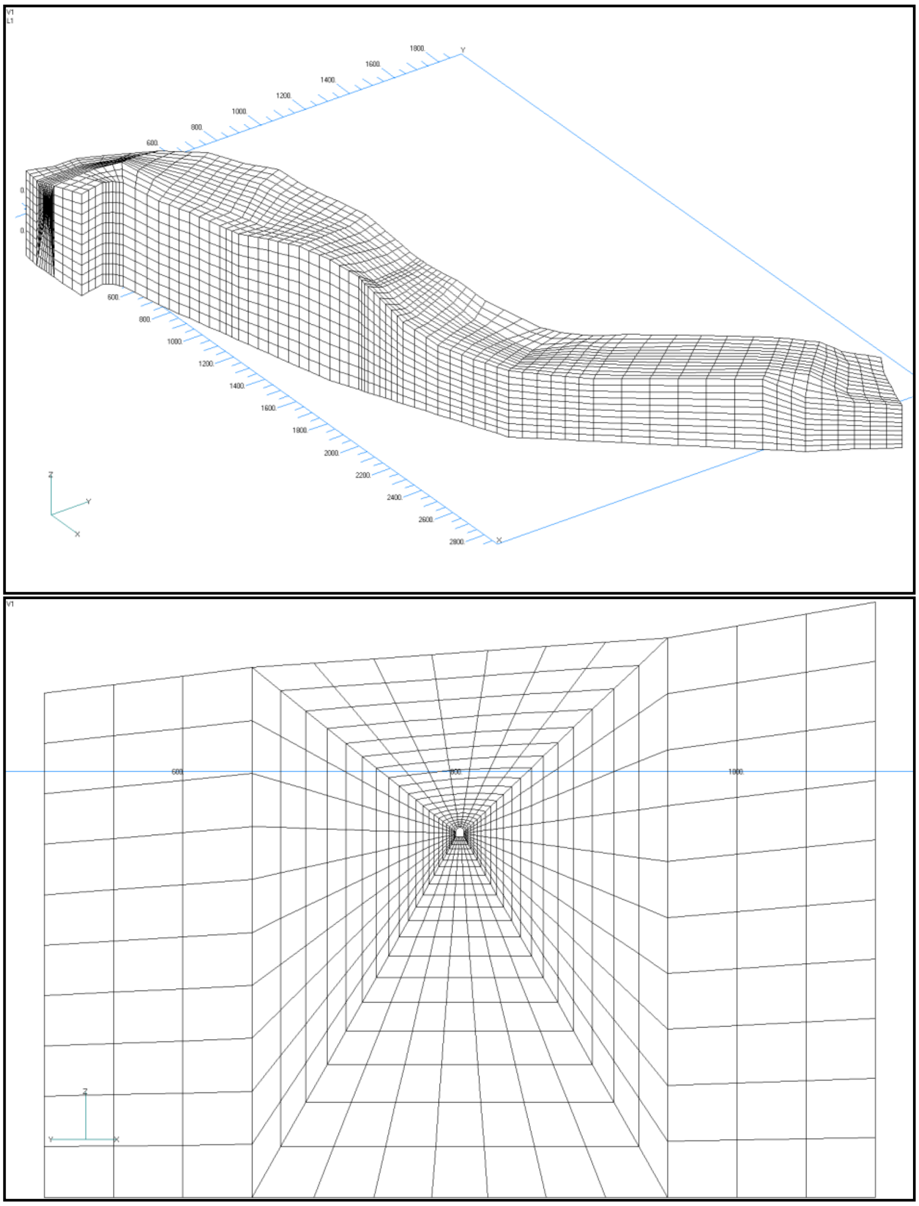

Fig 1 Finite element model, isometric view (above) and cross-section (below)

The division of the model into 6 zones, the location of three temperature measurement wells (K 84901, -902 and -903) and the location of the reservoir (Sø187), the fjord and the power station are shown in Fig 2. Temperature measurement wells are located within zones 4 through 6. Average results from model calibration in these three zones are used as boundary conditions in zones 1 through 3.

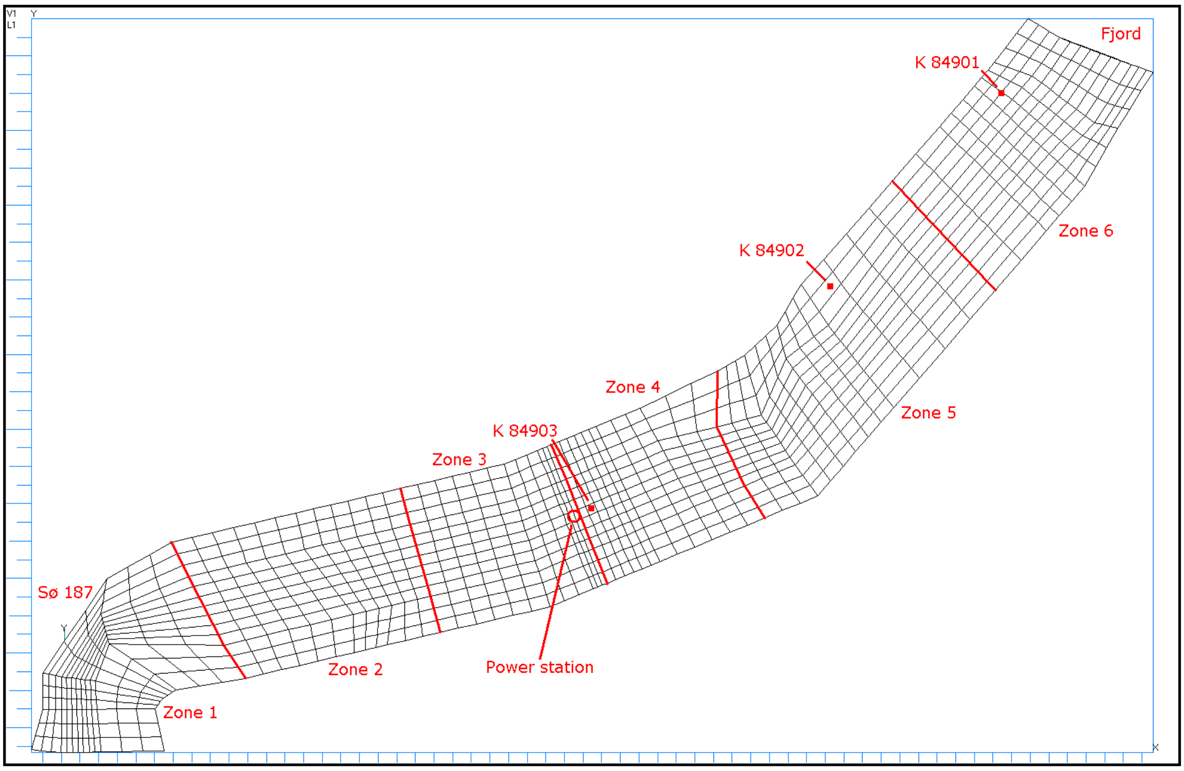

Fig 2 Overview of model zones 1 through 6 and rock temperature measurement boreholes.

2.2 Thermal properties and temperatures

The assumed rock thermal conductivity, specific heat capacity and density are 3.5 W/m°C, 730 J/kg°C and 2,700 kg/m^3, respectively ([1], page 787).

Average annual air temperature is assumed to be -5°C at sea level and to drop by 0.7°C by 100 m increase in elevation ([1], page 787). The coldest temperature is around -7.1°C at 300 m altitude, which is the highest point in the model.

Water temperatures in reservoir "Sø 187" and the fjord (from [3]) are averaged over one year from several measurements taken during a 1 year period. Each measuring point is near the reservoir and fjord shores that correspond to the top surfaces at each end of the finite element model (see Fig 2). The calculated average temperatures are 0.838°C in the reservoir and -0.050°C in the fjord. These values are applied as constant temperature boundary conditions, as annual fluctuations have no effect on temperatures deep in the bedrock.

Rock temperature measurements (from [2]) are obtained in three boreholes at various depths between 15 and 64 meters below the surface and range from -0.8°C to -5.1°C. The location of the sites and a cross-section showing the measured temperatures at various depths are shown in Fig 2 and Fig 4 respectively. These measured temperatures are used for model calibration.

2.3 Constant and initial boundary conditions

Variation of vertical heat flux is assumed to be negligible at 100-200 meters horizontally from the hydraulic tunnel. Zero heat flux is therefore assumed through the four vertical edges (sides and ends) of the model, see upper half of Fig 1. The air temperature, convection and heat flux values that are used as top and bottom boundary conditions in the 6 model zones (see Fig 2) are shown in Table 1.

Table 1 Boundary conditions, overview

Zone	Average elevation	Average air temperature, T_{air}	Surface convection, h	Heat flux from ground, Φ
	m.a.sl.	°C	W/m^2°C	W/m^2
1	214.2	-6.50	0.0375	0.0856
2	254.5	-6.78	0.0375	0.0856
3	240.9	-6.69	0.0375	0.0856
4	115.0	-5.80	0.2031	0.1865
5	46.8	-5.33	0.0532	0.1302
6	50.3	-5.35	0.0218	0.0700

For each of the six zones, the heat flux (heat flow, *q* per unit area, *A*) into the bottom of the model is calculated as $q/A = \Phi$ [W/m^2]. The heat flux out of the top of the model is calculated as $q/A = h \times (T_{surf} - T_{air})$ [W/m^2°C], where h and T_{air} are from Table 1 and T_{surf} is the surface temperature, calculated from the model.

The values used were found through trial and error until values calculated by the model corresponded closely enough to measured temperatures in zones 4, 5 and 6. The average of obtained values in these zones was used as boundary conditions in zones 1, 2 and 3. Zone 4 was not used, as these values are relatively high compared to zones 5 and 6.

3 Calculations and results

This section describes how the model results from boundary conditions are used to calculate heat loss from the water, flowing from reservoir Sø 187 to the fjord. The nominal and extreme worst case assumptions for water cooling calculations are listed and finally, the estimated minimum required flow for preventing freezing is presented.

3.1 Steady-state result (initial conditions)

The temperature profile on the outer edge of the model can be seen in Fig 3 and is a result of calculations described in the previous section. Fig 4 shows two cross sections of the tailrace tunnel that lies in the coldest region of the rock, near the surface. They include rock temperatures, elevation, tunnel length co-ordinates, calculated and measured temperatures in wells and the location of the power station. These results are used as initial conditions for water cooling calculations.

Temperatures calculated with the model are between 0.02 and 0.08°C lower than measured temperatures, which is a conservative result. The only temperature which deviates markedly is from measurement point K 84903, nearest to the surface, where calculated temperature is 0.86°C higher than measured temperature. Since this point is 120 meters above the water tunnel, it is not assumed to affect the overall calculation in the model.

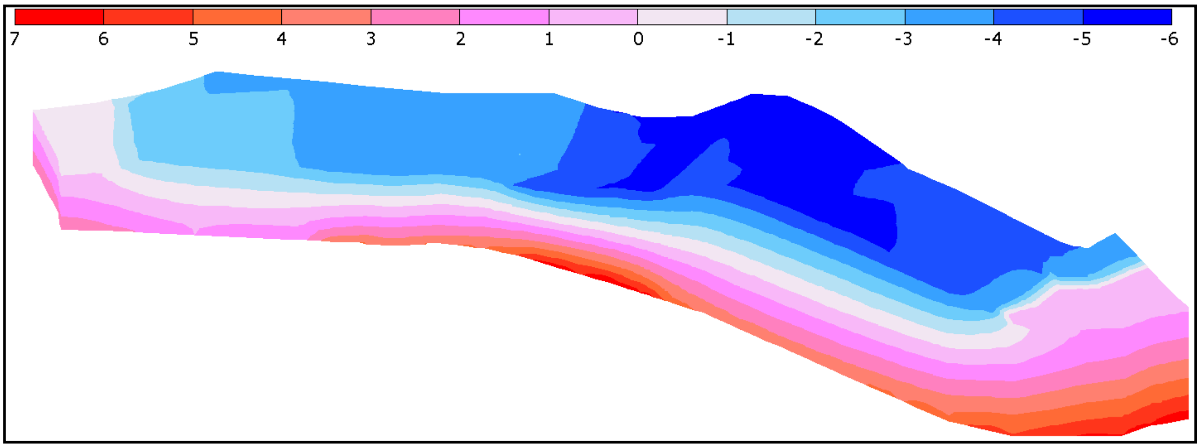

Fig 3 3D-model, isometric view showing temperature profile through rock

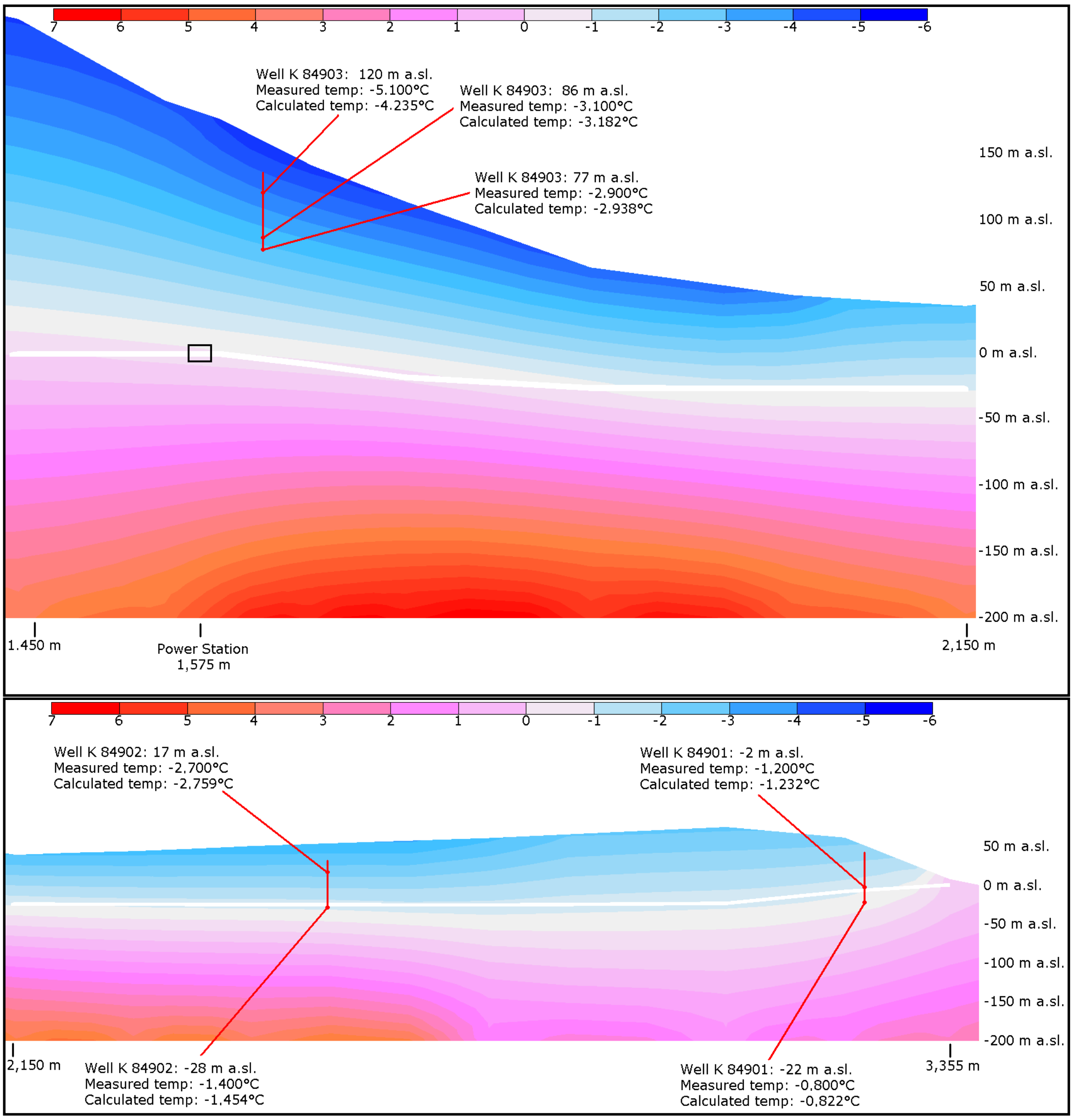

Fig 4 Temperature profile around head- and tailrace tunnel, initial conditions

3.2 Calculation of heat loss from water, nominal worst conditions

The following conditions are assumed when calculating heat loss from water, running through the tunnel at the minimum flow rate that ensures that water temperature never goes below 0°C:

- No heating of tunnel walls has taken place, neither from tunnel construction nor from heating from water flow through tunnel.
- The tunnel wall temperature is the same as the water temperature in the tunnel. This is a conservative assumption, since a film co-efficient between water and rock (which is very high for water) means that the rock would be at a slightly lower temperature than the water.
- Water from the reservoir is 0.05°C when entering tunnel.
- If water enters rock at higher temperature than the fluid, it does not absorb heat from the rock. It only loses heat to colder rock. Again, this is a conservative assumption.
- When water is throttled in the water by-pass orifice, all the throttling energy (product of mass flow, gravity acceleration and head loss) is converted to heat, that increases water temperature correspondingly.

The calculation is performed in the following steps, where the 3.3 km long tunnel is divided into 22 sections:

- Initial temperature of water (0.05°C) is set as a temperature boundary condition on the tunnel walls. Wall temperature is equal to water temperature.

- The program calculates the heat flow through the walls, based on temperature gradient through the rock, after being exposed to constant 0.05°C water temperature for 24 hours.
- The total heat flow (q, kW) into each tunnel section is equal to the heat lost from water, which is the product of the water mass flow, heat capacity and temperature drop in the fluid ($q = \dot{m} \times C_p \times \Delta T$). This quantity is always positive, i.e. temperature change is always zero or negative.
- The temperature profile of the water is calculated through each section. In the section running through the power station, the heating through throttling of water is calculated as $\dot{m} \times g \times \Delta h = \dot{m} \times C_p \times \Delta T$, or $\Delta T = g \times \Delta h / C_p$.
- The new temperature profile of the water is added as a new temperature boundary condition (step 2 through 5 repeated) and flow is varied until water temperature is always at least 0°C.

The water mass flow is the product of the water density (1000 kg/m^3) and water flow, in l/s. Water heat capacity is C_p=4.224 kJ/kg°C at 0°C, g=9.81 m/s^2 is the gravitational acceleration and the head loss through throttling (Δh) is equal to the elevation of the reservoir, 186.1 m a.sl. Temperature rise of water from throttling, calculated as 0.43°C is directly proportional to the reservoir elevation.

The result from the calculation is that at least 124 l/s of water flow are required for tunnel water to stay above 0°C. The temperature profile of water and initial rock temperature can be seen in Fig 5. In this case, the water enters the power station at 0.02°C and exits the tailrace tunnel at 0°C. Heat loss from water to rock (in W/m) can also be seen in the chart.

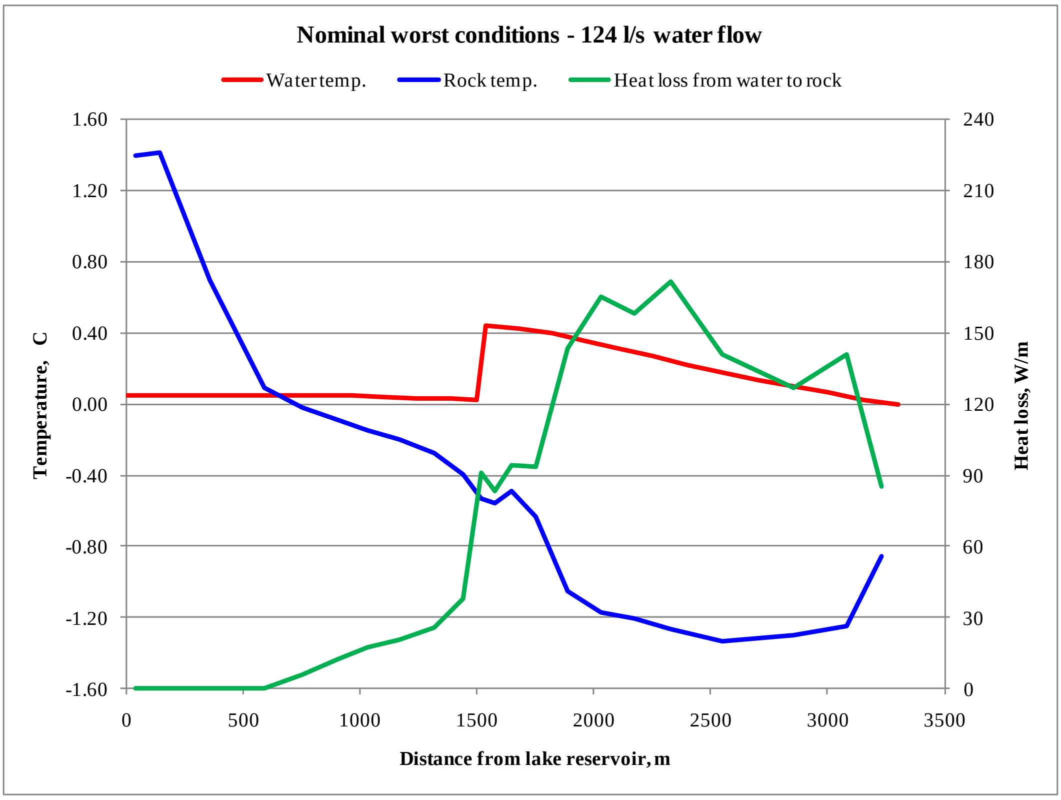

Fig 5 Temperature profile of water and rock by tunnel wall, nominal worst conditions.

3.3 Calculation of heat loss from water, extreme worst conditions

Since 124 l/s is around 10 times lower than the originally assumed 1.2 m^3/s flow needed in the by-pass, the same calculations as above are repeated, except for the following two variations:

- Water from the reservoir is 0.01°C when entering tunnel, instead of 0.05°C
- Only 75% of the throttling energy in each by-pass is converted to heat instead of 100%, resulting in 0.32°C water heating instead of 0.43°C.

The result is shown in Fig 6. Required flow is 315 l/s in this case and is required because of low water temperature from the reservoir. The critical point is the end of the head-race tunnel, where temperature is expected to reach 0°C.

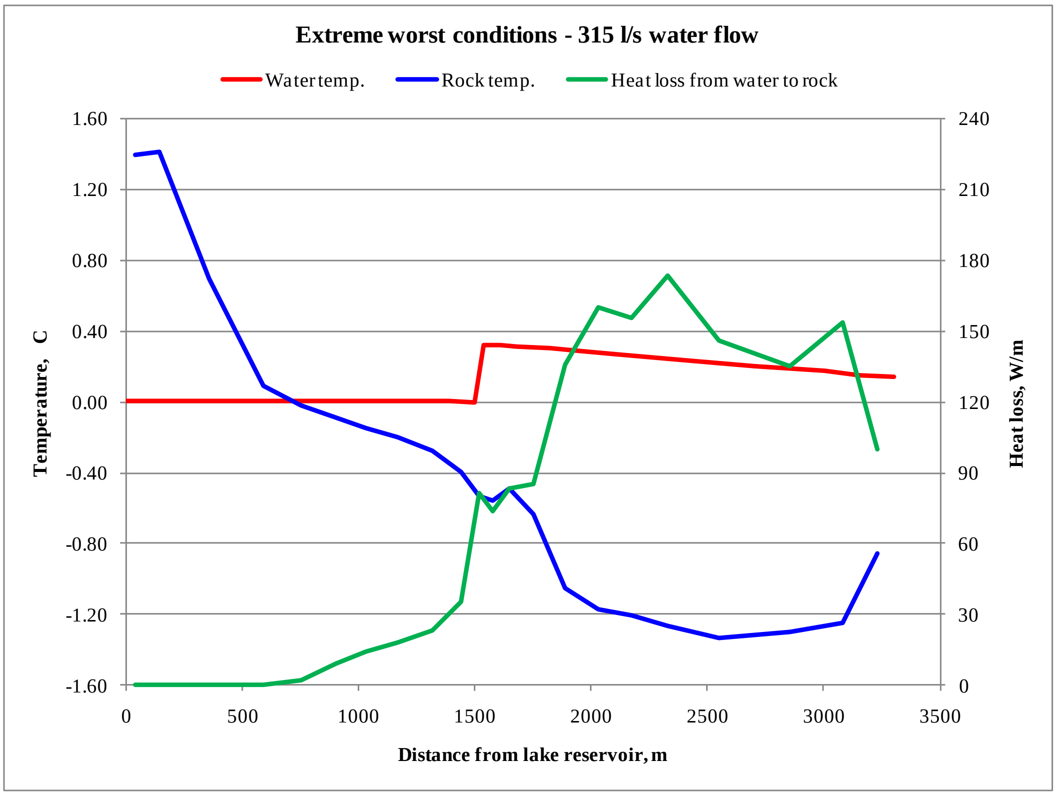

Fig 6 Temperature profile of water and rock by tunnel wall, extreme worst conditions.

4 Conclusion

A 3D heat transfer model has been calibrated to fit known temperature measurements and used to estimate the minimum required water flow that prevents water from freezing in the head- and tailrace tunnels of the Ilulissat power station. Using a combination of calibrated boundary conditions vs. known data, conservative assumptions and a number of worst case scenarios, it is concluded that the minimum water flow required through the tunnel is no more than 315 l/s.

This value is presented without a safety factor, as a combination of several unlikely worst case scenarios has been assumed. The required by-pass flow has been reduced from 1.2 m^3/s to a more manageable 0.315 m^3/s. This flow is easily obtained with three by-pass connections, one by each turbine.

References

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