1. MARTS 2024

HEAT LOSS OF AN OUTDOOR POOL

A STUDY OF THEORETICAL HEAT LOSS DURING ALL OF 2023, BASED ON WEATHER DATA FOR TÓRSHAVN

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Contents

Introduction

In some ongoing work on heat loss of an outdoor pool in the Faroes during the year, there was a need to reference previous work on heat loss from an outdoor water surface.

The following is a summary of a study into heat loss for an outdoor pool, which may help others in their initial study of the subject.

Heat energy needs

There are some studies of energy loss from water surfaces of pools (e. g. Nouanegue et al. 2011, Bernhard et al. 2019, Shah 2014, Smith, LÖF and Jones 1994). The study by Smith et al. (1994), although it, as the other studies, is for low wind speeds up to 3 m/s, is taken as basis..

Therefore, precautions must be taken for results at high wind speeds, although higher wind speed must be expected to give higher cooling of the pool, as expressed by the equations below.

The main contribution to heat loss of a hot pool is from the surface as:

- Evaporation
- Convection
- Radiation

Below equations are described in Appendix A.

In addition, the heat loss to the bedrock by conduction is estimated.

Evaporation

$$\dot{q}_{evap} = \frac{(30.6 + 32.1 \cdot u)(P_w - P_a)}{3600 \cdot 133.322}$$

Equation 1

$\dot{q}_{evap}\ \left[\frac{kW}{m^2}\right]$: Rate of heat transfer from evaporation.

$u\ \left[\frac{m}{s}\right]$: Air velocity over water surface.

$P_w\ [Pa]$: Saturation vapor pressure at the water temperature. Saturation vapor pressure is from table in Appendix D from water temperature and air temperature.

$P_a\ [Pa]$: Saturation vapor pressure at the air dew point. Saturation vapor pressure at air temperature multiplied with relative humidity.

See Appendix D for vapor pressure as function of temperature.

Radiation

$$\dot{q}_{rad} = \frac{25.1 + 34\ (T_w - T_a)}{3600}$$

Equation 2

$\dot{q}_{rad}\ \left[\frac{kW}{m^2}\right]$: Rate of heat transfer from radiation

$T_w\ [K]$: Water temperature

$T_a\ [K]$: Air temperature

Convection

$$\dot{q}_{conv} = h \cdot (T_w - T_a)$$

Equation 3

$h\ [\frac{kW}{m^2\ K}]$: the convective heat transfer coefficient, between 0.005 and 0.025 for water air transmission.

Heat loss by conduction to bedrock

Heat loss at the other boundaries of the pool is from conduction of heat in the bedrock. It is the heat transmitting properties and temperature of bedrock that determines the heat loss at the boundaries. Therefore, 3D modelling (Petersen et al. 2022) of heat transmission in bedrock is used to get an estimate of the heat loss to bedrock.

The modelling is for 1.5 m deep, 600 m^2 wide pool, kept at constant temperature of 40 °C. At each time step the energy needed to maintain the pool temperature at 40 °C is calculated. The heat loss at the surface is subtracted and the remaining energy is the energy lost to the bedrock.

Initially, with 40 °C hot water surrounded by ~7 °C bedrock, there is significant heat flux, but as the bedrock heats up the heat flux goes towards a thermal equilibrium and the total heat loss of the pool to the bedrock is about 6 kW (Figure 1).

See Appendix C for the modelling parameters.

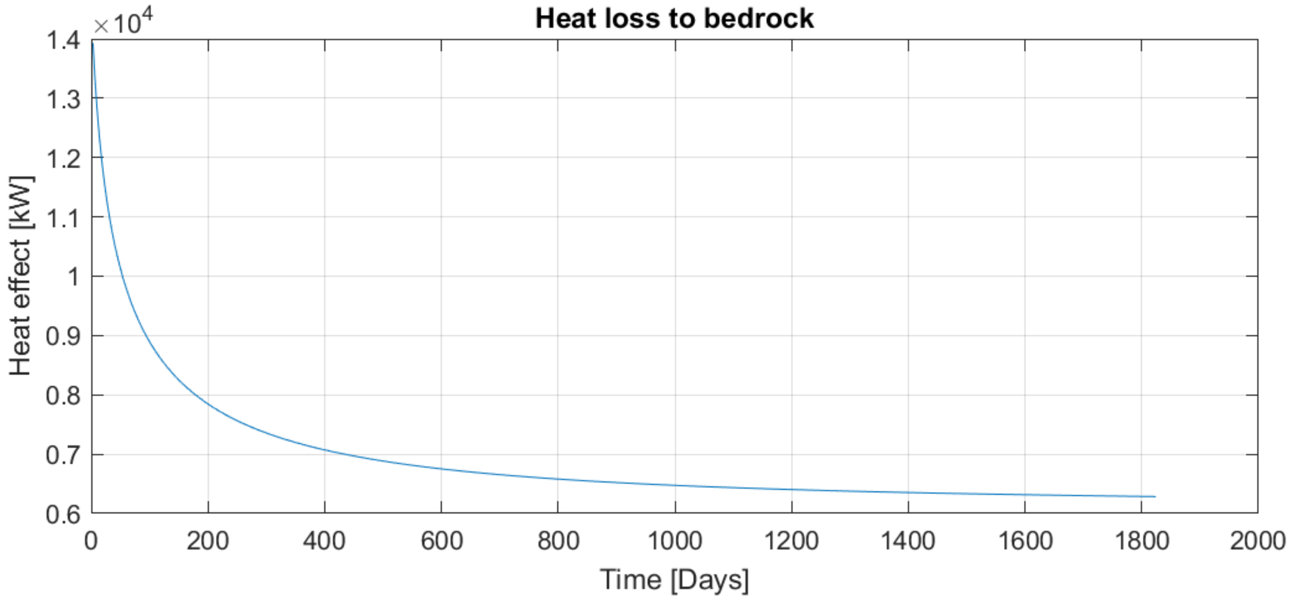

Figure 1. The total heat effect needed to maintain pool temperature at 40 °C after heat loss at surface is subtracted. That is 6/600=0.01 kW/m^2 and is therefore disregarded in the remaining heat calculations.

Results, heat energy needs

Weather data for wind speed, air temperature, and humidity are inserted into equations 1, 2, and 3. Figure 2 shows the effect of the heat loss for a 600 m^2 wide pool.

The yearly heat demand calculation is from weather data for Tórshavn during all of 2023 (see Appendix B). Data are downloaded from https://vedur.fo/weather/archive at 1-day sample intervals.

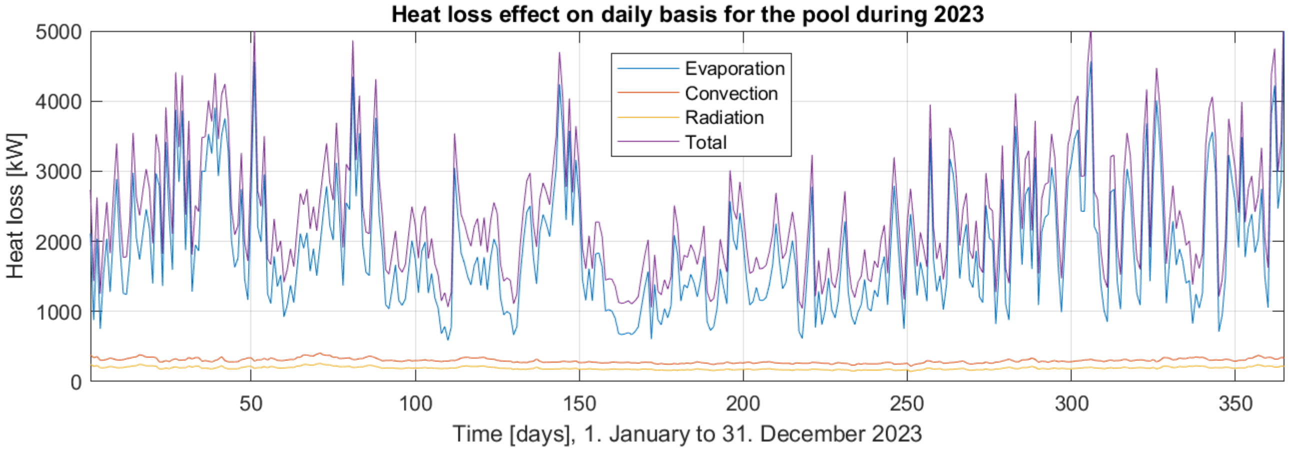

Figure 2. Heat loss effect for the 600 m^2 pool.

Figure 3 that shows the dynamic total heat demand each day of the year expressed as MJ/h.

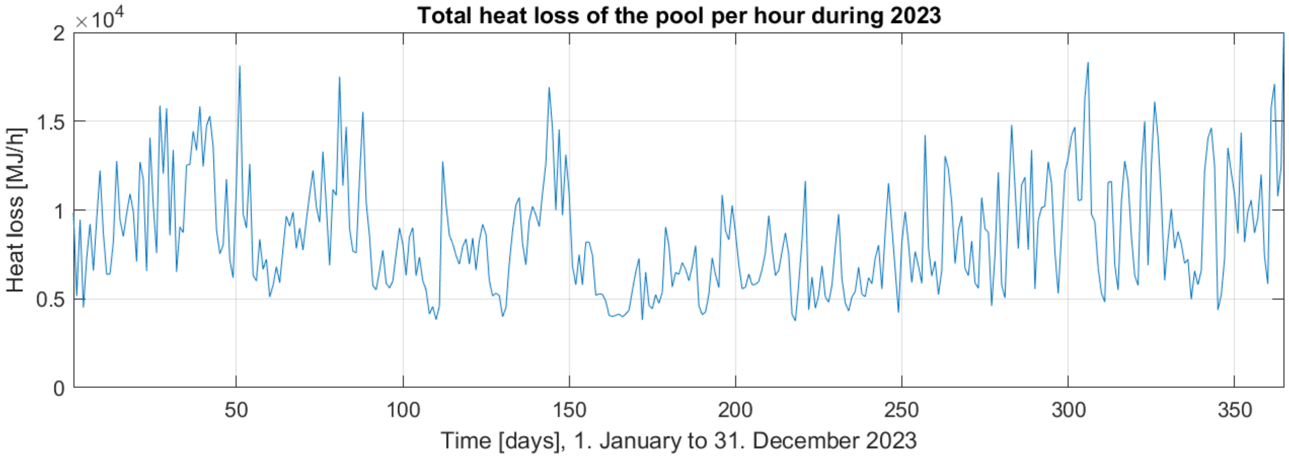

Figure 3. Total loss effect for a 600 m^2 wide pool in Figure 2 converted from kW per day to MJ/h.

Energy loss by evaporation, convection, and radiation at the surface accounts for most of the energy loss while heat transmission and conduction the other boundaries of the pool accounts for a very small part of the total heat loss. Based on daily average, the heating effect needed during the year is in the range ~1,400 to ~4,000 kW with a yearly average heat effect of 2,400 kW and a yearly heat consumption of 21,000 MWh.

Appendix A

Evaporation rate equation

Based on the form in *ASHRAE Handbooks HVAC Applications*:

$$\frac{\dot{m}}{A} = \frac{(a + b \cdot u)(P_w - P_a)}{\Delta H_w}$$

$\frac{\dot{m}}{A}\ \left[\frac{kg}{m^2\ hour}\right]$: Evaporation rate per m^2 surface

$u\ \left[\frac{m}{s}\right]$: Air velocity over water surface

$P_w\ [mmHg]$: Saturation vapor pressure at the water temperature

$P_a\ [mmHg]$: Saturation vapor pressure at the air dew point. Saturation vapor pressure at air temperature multiplied with relative humidity. Saturation vapor pressure is from table in Appendix D from water temperature and air temperature

$\Delta H_w\ [\frac{kJ}{kg}]$: Latent heat of water at the pool temperature

a and *b* are parameters to be determined by experiments.

Based on experiments, Smith et al. (1994) provided improved parameters for an outdoor swimming pool. Notice it was under inactive condition meaning no people were in the pool. Activity in the pool is known to affect the heat loss due to induced waves and water spray. And if water is significantly colder than 37 degrees, people in the pool will also contribute to the heating of the pool (e. g. Nouanegue et al. 2011, Bernhard et al. 2019, Shah 2014).

Smith et al. (1994) determine:

$$a = 30.6 \left[\frac{m}{s}\right]$$

$$b = 32.1 [no\ unit]$$

The actual evaporation will be strongly affected by on site configuration. Therefor results must be taken as order of magnitude.

For comparison directly with energy loss from radiation and convection, the evaporation effect per m^2 is calculated. At the same time units for pressure are changed from mmHg to Pascal.

$1\ [mmHg] = 133.322\ [Pa]$

$\Delta H_w = 2410\ \left[\frac{kJ}{kg}\right]$

$$\frac{\dot{m}}{A} = \frac{(a + b \cdot u)(P_w - P_a)}{\Delta H_w}$$

Change to energy loss by evaporation per second.

$$\frac{\dot{m}}{A} \cdot \Delta H_w \left[\frac{kg \cdot kJ}{m^2 \cdot hour \cdot kg} = \frac{kJ}{m^2 \cdot s \cdot 3600}\right] = \frac{\dot{m} \cdot \Delta H_w}{A \cdot 3600} = \dot{q} \left[\frac{kW}{m^2}\right]$$

$\dot{q} \left[\frac{kW}{m^2}\right]$: Effect of energy loss per m^2 surface

$$\frac{\dot{m}}{A \cdot 3600} \cdot \Delta H_w = \frac{(a + b \cdot u)(P_w - P_a) \cdot \Delta H_w}{\Delta H_w \cdot 3600} = \frac{(a + b \cdot u)(P_w - P_a)}{3600} = \dot{q} \left[\frac{kW}{m^2}\right]$$

Change pressure unit in formula from mmHg to Pa

1 mmHg = 133.322 Pa

1 Pa = 1/133.322 mmhg

$$\dot{q} \left[\frac{kW}{m^2}\right] = \frac{(a + b \cdot u)(P_w - P_a)}{3600 \cdot 133.322}$$

Equation 4

Equation 4 is a function of water temperature, air temperature, relative humidity of air, and air velocity. In the Faroes typical relative humidity is about 80% (Figure 12). Water temperature is 40 °C. The two remaining variables are plotted in Figure 4 as function of air temperature for different wind speeds and in Figure 5 as function of wind speeds for different air temperatures.

Maximum air temperature in the used weather data is 15 °C. However, in figures air temperatures all way up to 40 °C are included to show the dependency of difference in temperature between water and air.

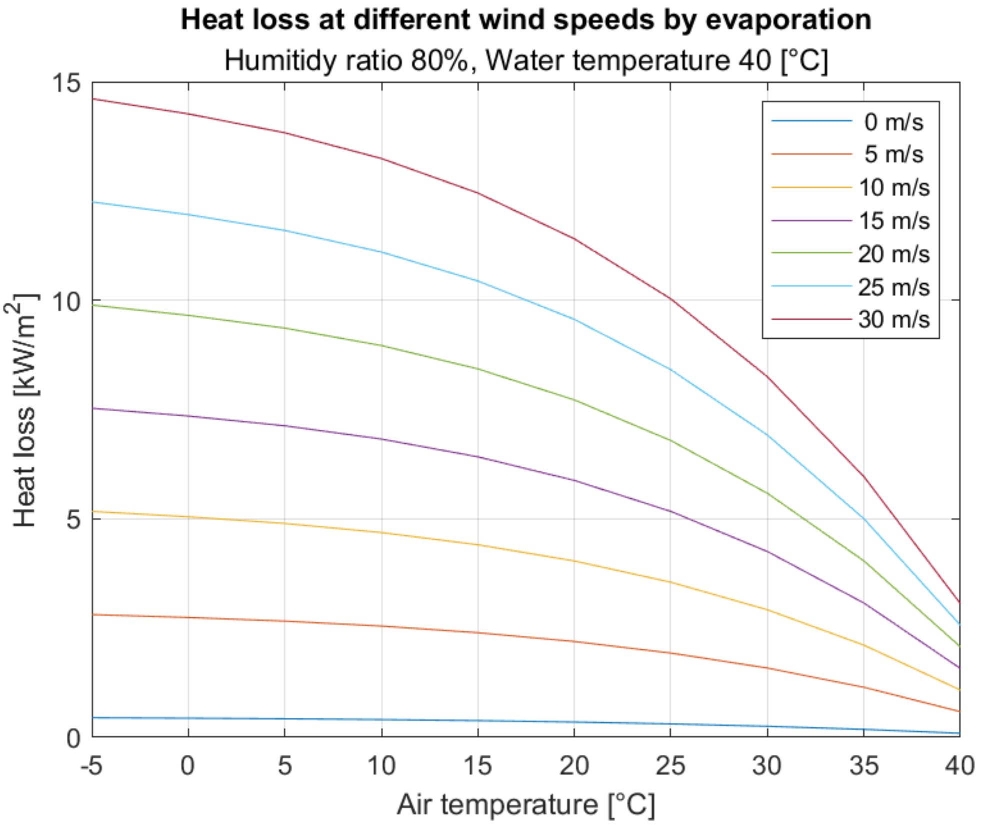

Figure 4. Heat loss as function of air temperature for different wind speeds.

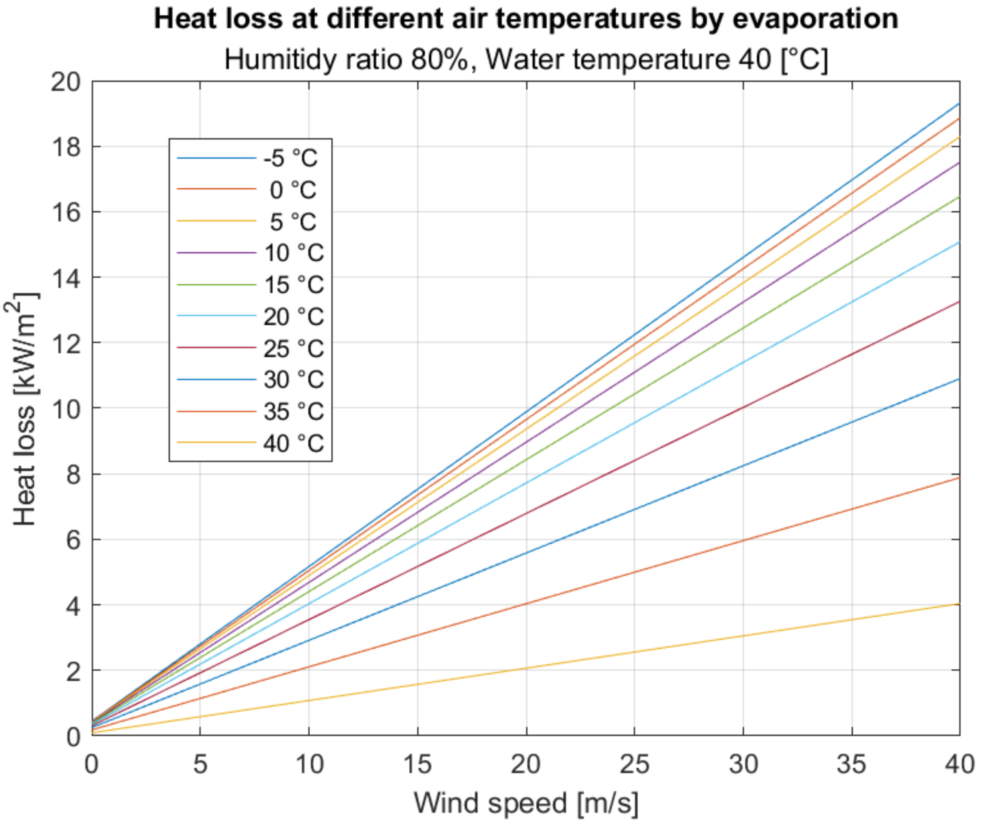

Figure 5. Heat loss as function of different wind speeds for different air temperatures.

Radiation

The Smith et al. (1994) experiment also includes radiation loss

Generally, the Stefan-Boltzmann law describes the low-frequency radiation loss:

$$Q_{rad} = \epsilon \cdot \sigma \cdot A \cdot \left(T_{water}^4 - T_{sky}^4\right)$$

$\sigma = 5.670374419 \cdot 10^{-8} \left[\frac{W}{m^2 \cdot K^4}\right]$: Stefan-Boltzmann constant

$\epsilon =$: Emissivity

T_{sky} is 10 to 30 °C lower the air temperature and has to be determined.

Smith et al. (1994) present the linear relationship:

$$Q_{rad} = 25.1 + 34\ (T_{water} - T_{air})$$

$Q_{rad}\ \left[\frac{kJ}{hour \cdot m^2}\right]$: heat transfer

Calculating the effect, the formula is:

$$\dot{q}_{rad} = \frac{25.1 + 34\ (T_{water} - T_{air})}{3600}$$

Equation 5

$\dot{q}_{rad}\ \left[\frac{kW}{m^2}\right]$: Effect of heat loss from radiation

The parameters are derived from data with air temperature in the 5 – 17 °C range and with conditions of relative low humidity and clear skies. So general radiation loss in the Faroes may be expected to be lower.

Radiation accounts for 20 – 40 % of total (Bernhard et al. 2019).

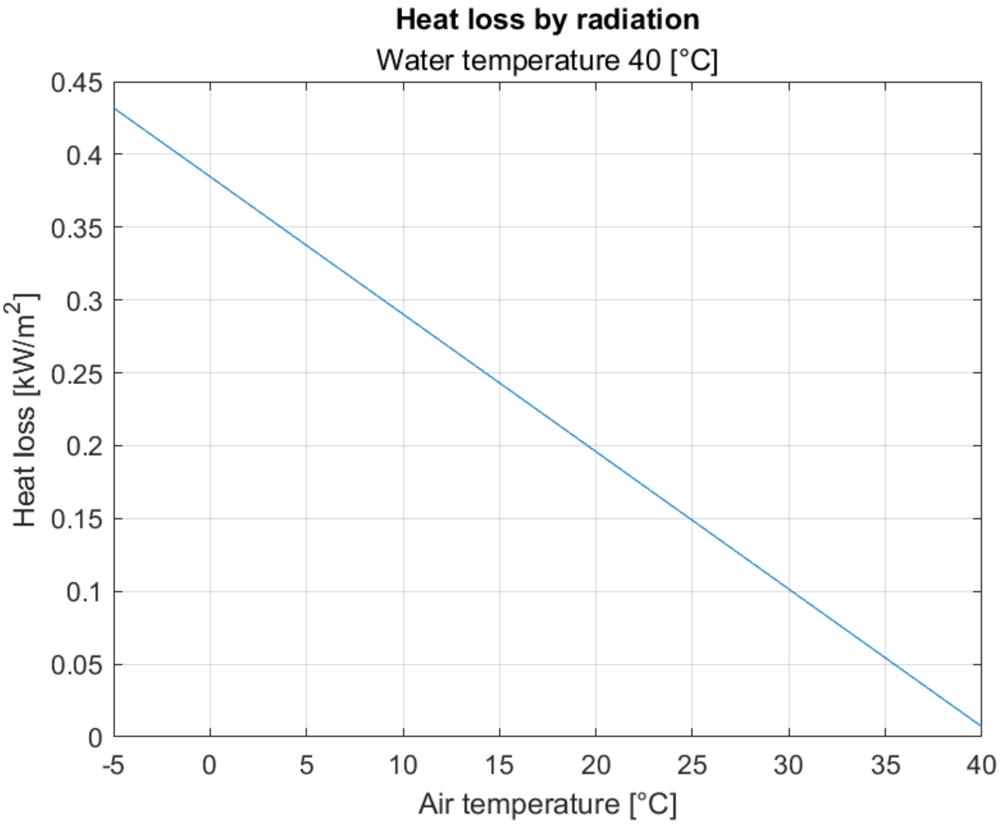

Figure 6. Heat loss by radiation (Equation 5). (plottempradiation.m)

Convection

$$\frac{\dot{Q}}{A} = h \cdot (T_w - T_a) = \dot{q}$$

Equation 6

$\frac{\dot{Q}}{A} = \dot{q}\left[\frac{kW}{m^2}\right]$: Rate of heat transfer

$h_{conv}\ [\frac{kW}{m^2\ K}]$: the convective heat transfer coefficient

$T_w\ [K]$: Water temperature

$T_a\ [K]$: Air temperature

h_{conv} is ideally a function of wind speed and is typically in the range 0.005 – 0.025 $[\frac{kW}{m^2\ K}]$. For calculations in this report, we use h=0.015 $[\frac{kW}{m^2\ K}]$.

Experiments show the convective heat transfer to be in the range 10 – 18 % (Bernhard et al. 2019, Smith et al. 1994).

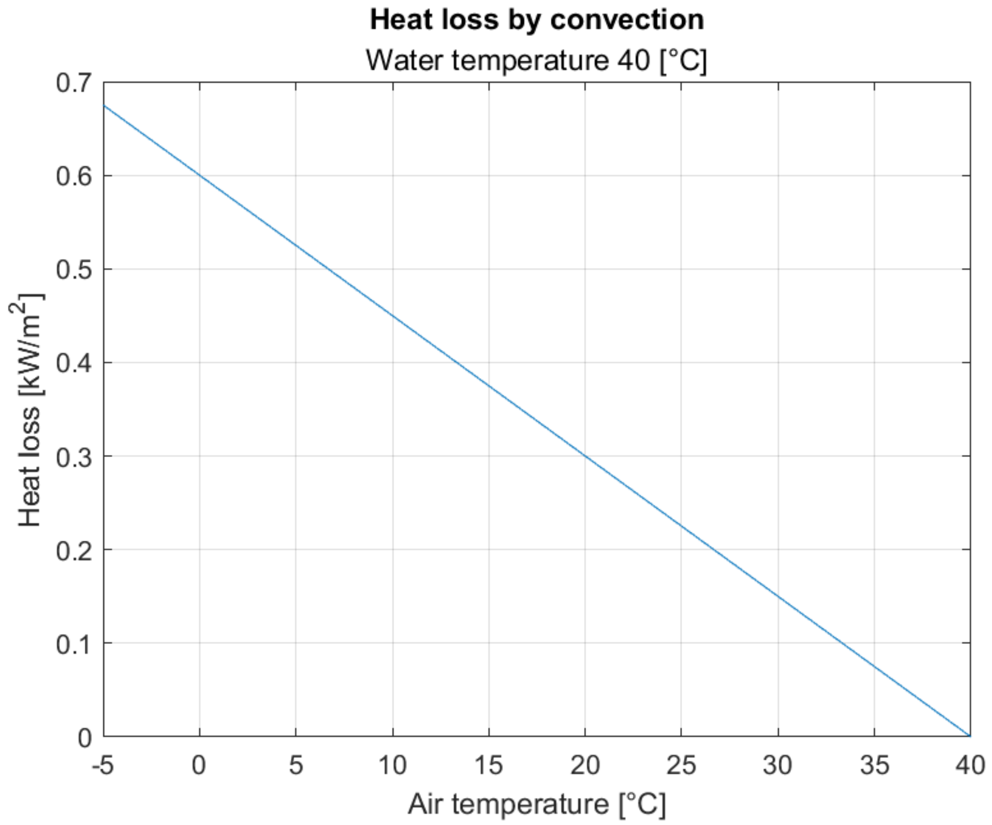

Figure 7. Heat loss by convection (Equation 6)   (plottempconv.m)

Smith et al. (1994) determine the total energy loss by the cooling of the pool. Loss by evaporation and radiation is determined as above. Thus, energy loss from evaporation is 56%, from radiation is 26%, and from convection is 18%. These experiments were conducted during night so the solar influx is not contained in the calculation.

Total heat loss is therefore expressed by evaporation, radiation, and convection.

$$\dot{q}_{tot} = \dot{q}_{evap} + \dot{q}_{rad} + \dot{q}_{conv}$$

Total heat loss

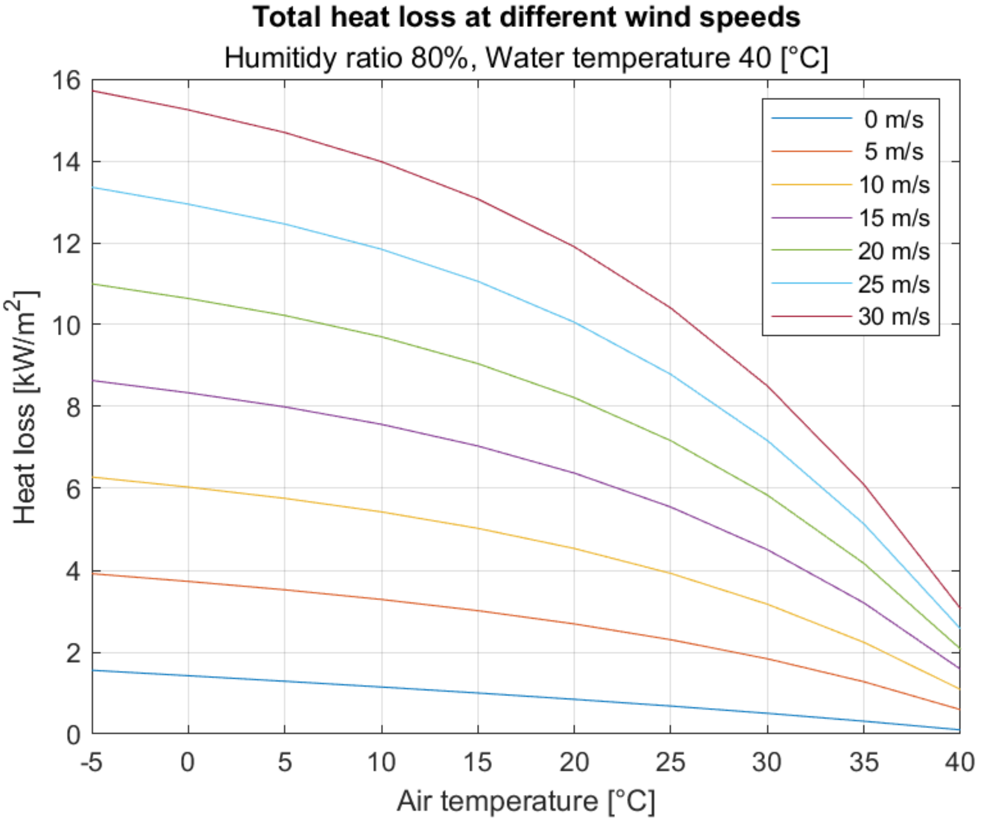

Figure 8. Total heat loss. Figure 4 + Figure 6 + Figure 7

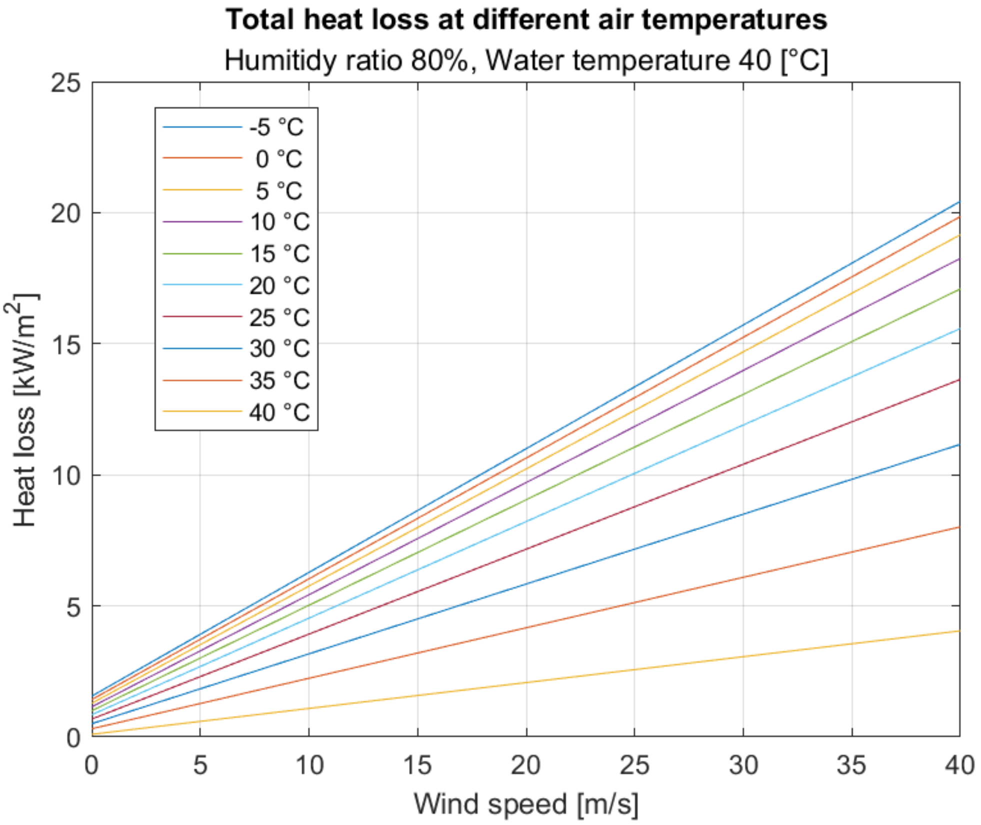

Figure 9. Figure 5 + Figure 6 + Figure 7.

Appendix B

Weather data for Tórshavn 2023.

Notice the relatively low max wind of 15 m/s for Tórshavn.

The data are from the Faroes Weather institute: https://vedur.fo/weather/archive.

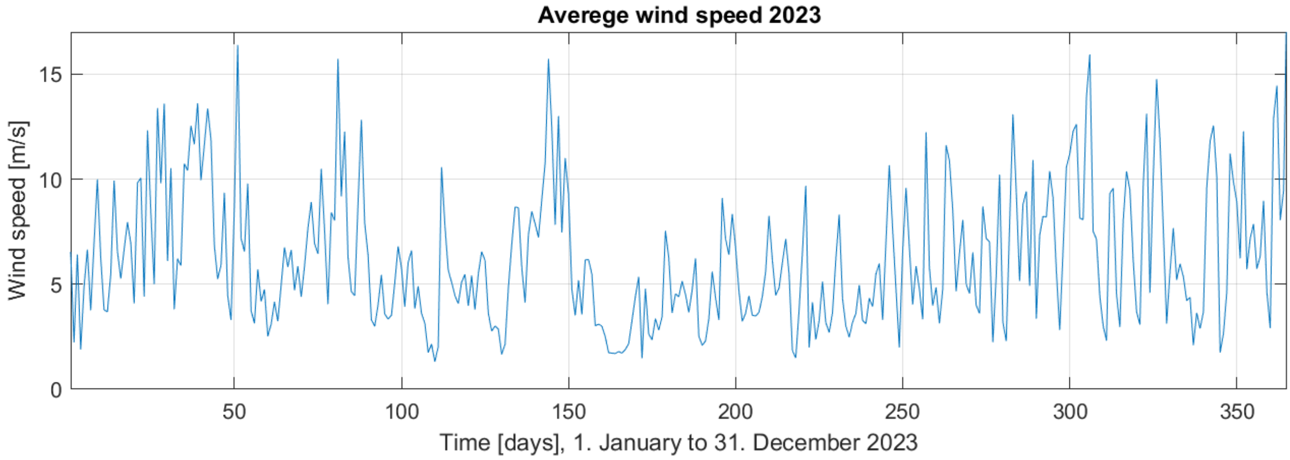

Figure 10.

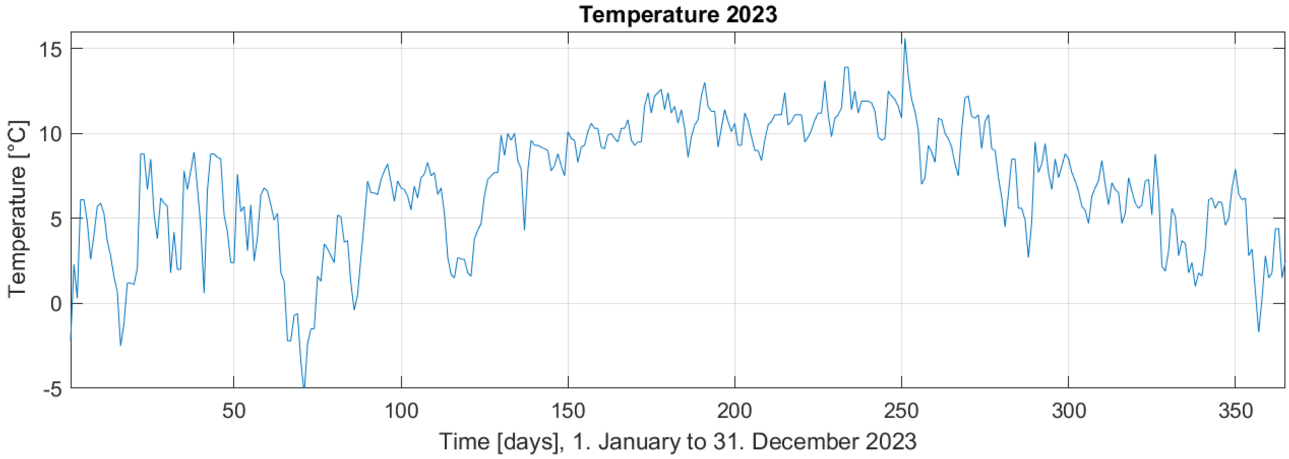

Figure 11.

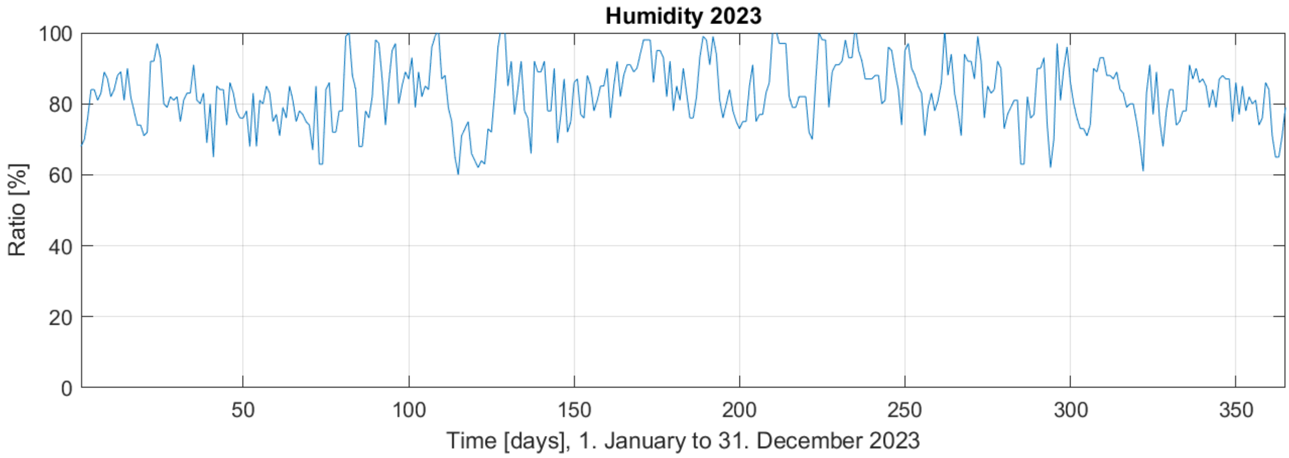
Humidity 2023
100
80
60
40
20
0
Ratio [%]
50
100
150
200
250
300
350
Time [days], 1. January to 31. December 2023

Figure 12

Appendix C

Modelling is based on the 3D geothermal algorithm described in Petersen et al. (2022). It is subsequently used in connection with prediction of heat flow for geothermal wells (e.g. Petersen and Ólavdóttir 2022, Ólavdóttir et al. 2022).

Modelling of pool heat loss to bedrock

Modelling grid:

100x100x40 (x,y,z) grid 2x2x1.5 m grid spacing.

```
k=1.875; % [W/(m*K)]
C=2520000;% olivine [J/(m3*K)]
Cvatn=4.186*1000000;% [J/(m3*K)]
kvatn=0.6; %W/(m*K) at 20deg C
dTgrad=0.032 % deg/m
dt=3600*24*3;% 3 days
```

With 7.7 °C in top layer.

Hot pool is modelled as 10*15 grid cells in top layer representing 600 m^2, 1.5 m depth.

For each time step, temperature of grid points in pool are set to 40 °C. The energy added the pool is calculated. Energy lost at the surface is calculated and the remaing energy is the energy lost at the other boundaries than the surface.

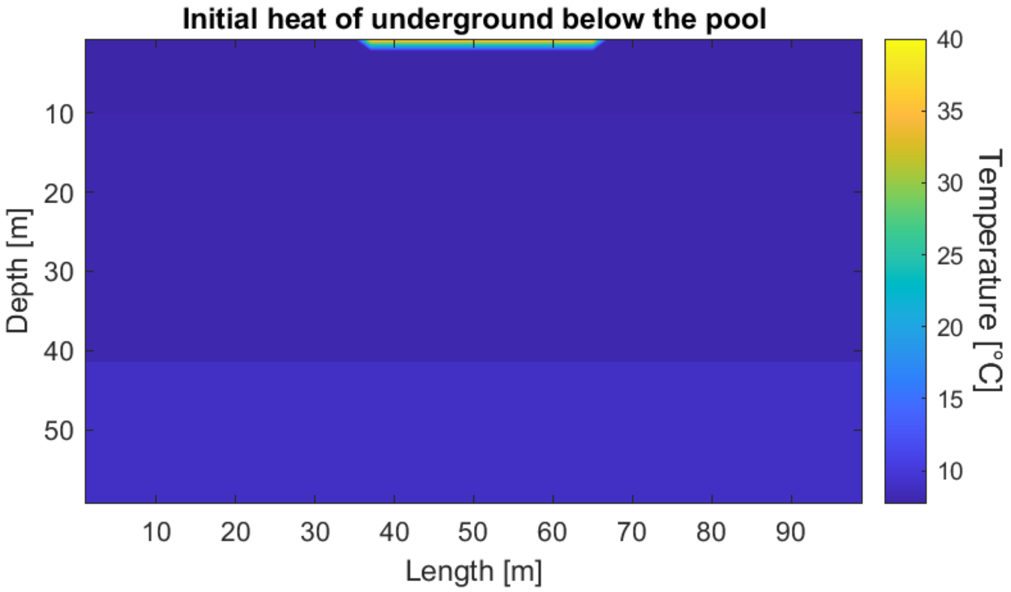

Figure 13. Cross section of initial temperature in underground.

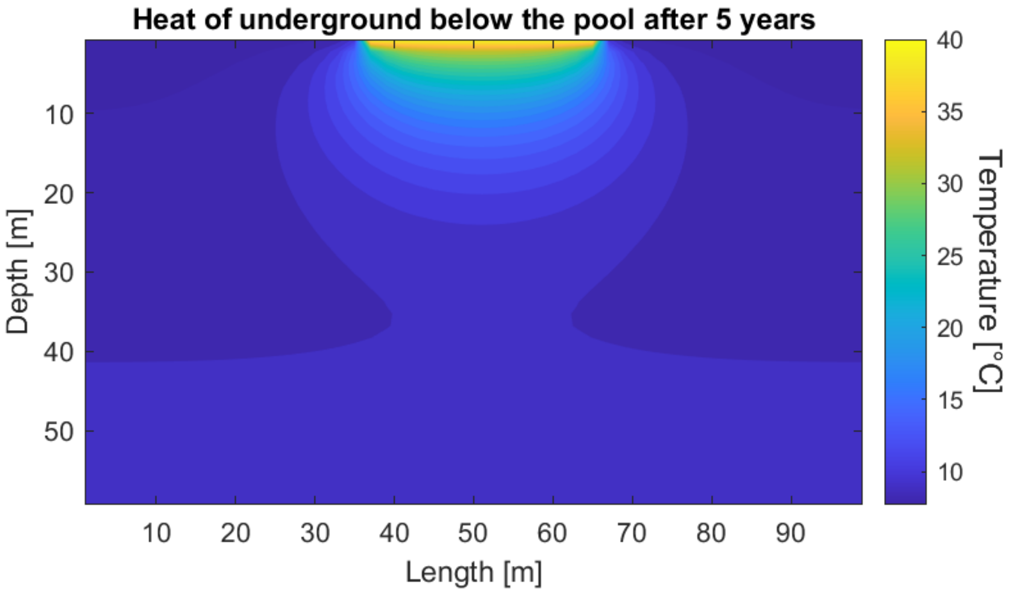

Figure 14. Cross section of temperature in underground after 5 years.

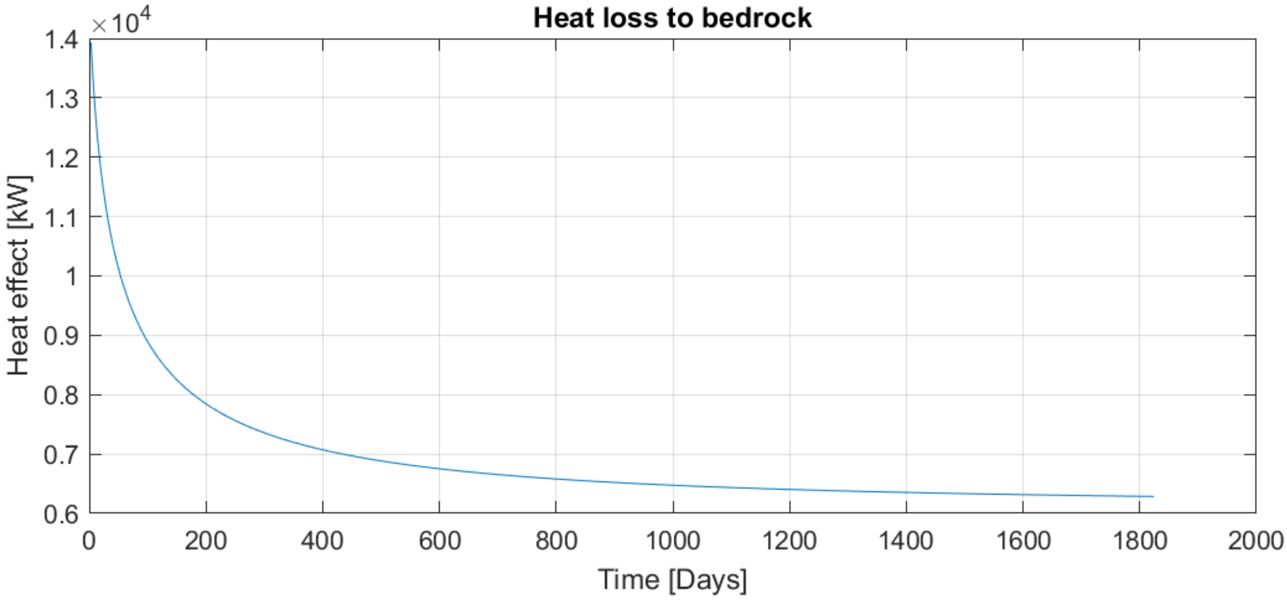

Figure 15. The total heat effect needed to maintain pool temperature at 40 °C after heat loss at surface is subtracted. That is 6/600=0.01 kW/m².

Appendix D

Saturation pressure of air

Temp.	SatPress
°C	[PA]
-40	12,84
-30	38
-25	63,25
-20	103,2
-15	165,2
-10	259,2
-5	401,5
0	610,8
5	871,9
10	1227
15	1704
20	2337
25	3167
30	4243
35	5623
40	7378
45	9585
50	12339
55	14745
60	19925
65	25014
70	31167
75	38554
80	47365
85	57809

Table 1. From `https://www.engineeringtoolbox.com/moist-air-properties-d_1256.html`

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