GeoStudio Example File
Thermosyphon Laboratory Test

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Introduction

Thermosyphons are routinely used in colder climates for the preservation of permafrost. The preservation of permanently frozen ground in-turn protects infrastructure such as pipelines, frozen core dams, buildings, and trafficable surfaces. The objective of this example is to demonstrate how to define a thermosyphon boundary condition in TEMP/W by simulating a laboratory experiment that can be developed to measure the overall heat conductance of a thermosyphon.

Background

The overall heat conductance C of a thermosyphon [W/°C] is defined as the heat rate extracted from the device divided by the temperate difference between the evaporator and air flowing past the condenser. Haynes and Zarling (1988) conducted a number of laboratory tests on commercially available thermosyphons by placing the condenser in a wind tunnel. The air temperature was maintained at a constant temperature. The evaporator was also maintained at a constant temperature by immersion in a heated water bath. The overall heat conductance was measured at various wind speeds and the data described by an empirical relationship of the form:

$$C = A + B(V^n)$$ **Equation 1**

where A and B are coefficients, n an exponent, and V the wind speed. For example, the authors characterized a CO_2 filled thermosyphon with an evaporator sloped at 12 degrees from a horizontal reference using coefficients A, B, and n of 16.5, 26.0, and 0.62, respectively, when the wind speed was in units of m/s. The corresponding convection coefficient can be calculated by the dividing C by the surface area of the evaporator as:

$$h = \frac{C}{A_{conv.\ surface}} = \frac{16.5 + 26.0(V^{0.62})}{\pi(0.05)(6.1)} = \frac{16.5 + 26.0(V^{0.62})}{0.96\ m^2}$$ **Equation 2**

Numerical Simulation

An axisymmetric analysis was completed to mimic one of the laboratory tests conducted by Haynes and Zarling (1988). The model domain comprises a column of elements that represents the fluid into which the evaporator was immersed. The height of the column is 6.1 m, which is equal to the length of the evaporator section. The left edge of the domain represents the outside surface of the evaporator and is located at a distance from the axis of symmetry that is equal to the outside radius of the evaporator pipe (i.e. 0.025 m). The thermosyphon boundary condition is applied to the left edge.

The right edge of the domain represents the inside surface of the outer pipe that contains the fluid and evaporator. The simulated thermal response of the fluid bath is actually of no interest because the fluid was circulated and maintained at a near constant temperature during the laboratory test. A discretized domain is, however, required to complete as finite element analysis. As such, the right boundary was arbitrary located from the left boundary and a simplified material model with arbitrary properties was used to represent the fluid. The fluid material was activated at a temperature of 20°C and a temperature boundary condition with the same magnitude was applied to the right edge.

The convection coefficient was calculated in a spreadsheet at various wind speeds as per Equation 2 and the data was pasted into the Convection Coefficient Versus Wind Speed function (Define | Boundary Conditions | Thermosyphon; Figure 1). The thermosyphon boundary condition also requires a time-based function for air temperature and wind speed. The air temperature was assumed constant at -18°C. The wind speed time history was defined using a step function that increased from 0 m/s to 2 m/s at 3600 s and then to 4 m/s at 7200 s (Figure 2).

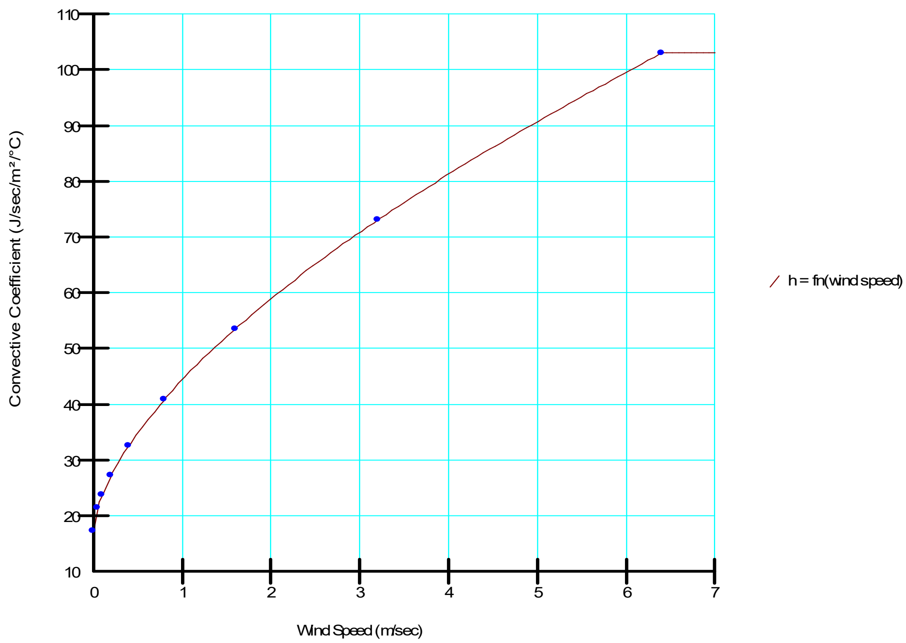

Figure 1. Convection coefficient as a function of wind speed.

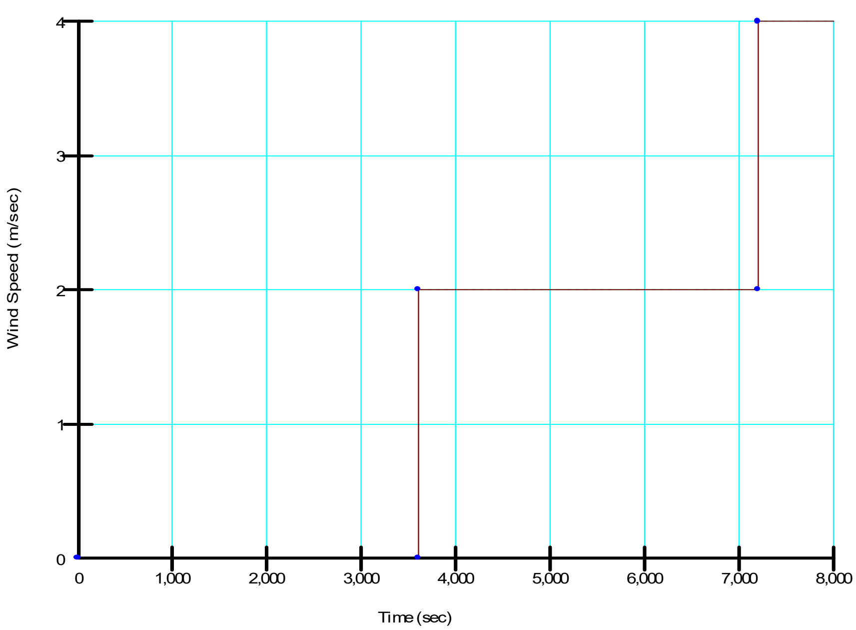

Figure 2. Wind speed as a function of time.

The response of the domain was simulated in three separate analyses that transitioned in accordance with the wind speed step function: first analysis modeled from 0 to 3600 seconds; second analysis modeled 3600 to 7200 seconds; and the third analysis from 7200 seconds to the end. An exponential time sequence was used for each analysis to capture the non-linear response of the boundary condition and domain (Define | Analyses).

The latent heat of fusion for water was set to 0.0 J/m3 in the project settings because the fluid did not freeze despite the temperature at the evaporator decreasing below the phase change value (Set | Units and Scale). Freezing was prevented during the experiment by circulating the fluid using a heat pump.

Results and Discussion

Figure 3 and Figure 4 show the simulated temperature at the evaporator surface (i.e. at the boundary condition) and the cumulative heat rate of the thermosyphon. The temperature drops rapidly at the onset of the analysis because of the large temperature difference between the air and the ground. The temperature reaches equilibrium near the end of the first analysis and then drops rapidly in the second and third analyses when the wind speed is increased. The temperature decrease at the evaporator surface on each subsequent increase in wind velocity is not as pronounced because: a) the convection heat transfer coefficient function is non-linear (Figure 1); and, b) the convective heat flux into the evaporator – which is calculated according to Newton's law of cooling – decreases as the evaporator surface temperature approaches the temperature of the air flowing past the condenser.

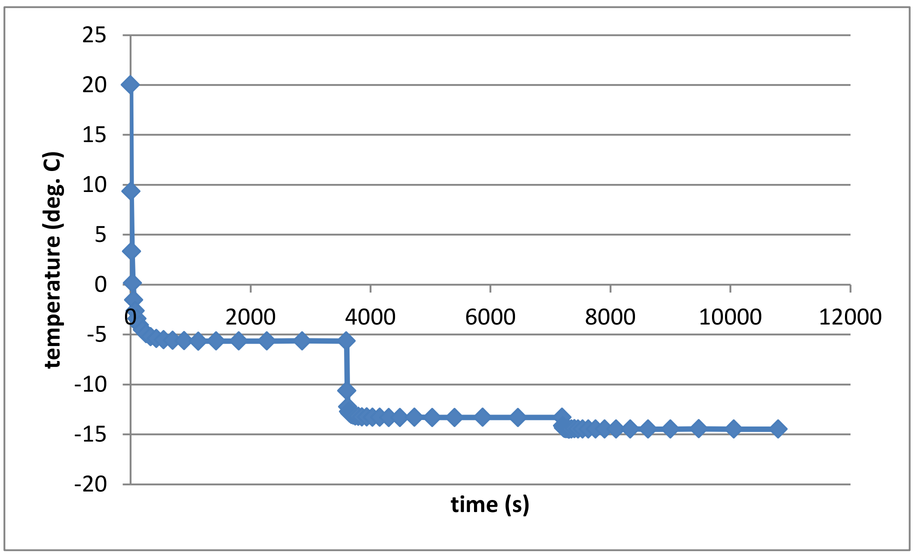

Figure 3. Simulated temperature at the evaporator surface.

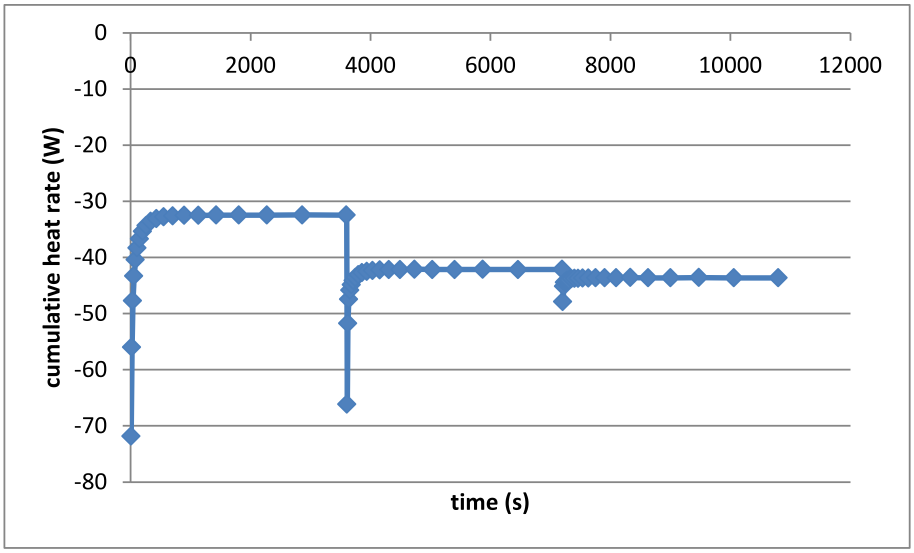

Figure 4. Simulated cumulative heat rate at the evaporator.

There are a number of heat transfer processes that are operating when a thermosyphon is functioning. All of these processes are characterized by a single measured coefficient: the overall heat conductance of a thermosyphon [W/°C]. As noted, however, the boundary condition is defined using a more generalized convection coefficient, h, although the convection heat transfer process is only strictly operative at the evaporator and condenser surfaces (note: natural or free convection occurs within the evaporator pipe).

It is therefore instructive to back-calculate the heat conductance for the thermosyphon. The heat rate (W) was graphed (Draw | Graph) and summed for all nodes along the boundary condition (Figure 2). The cumulative heat rate at every instant in time was multiplied by 2π to obtain the cumulative heat rate into the evaporator for a full revolution about the axis of symmetry (Figure 4). These values were in-turn divided by the temperature difference between the air and evaporator surface to obtain the conventionally measure heat conductance (Figure 5).

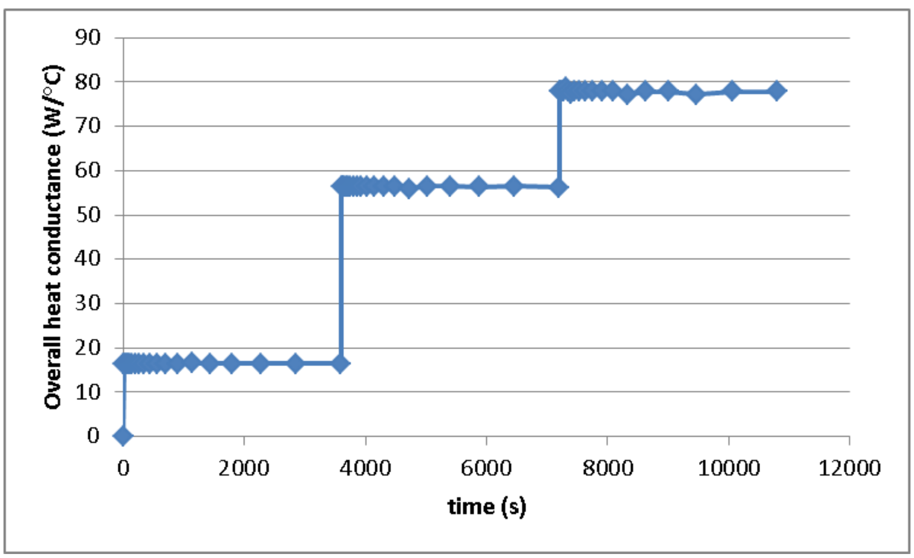

Figure 5. Simulated overall heat conductance of the thermosyphon.

As expected, the cumulative heat rate into the evaporator declines in accordance with temperature at the evaporator surface (Figure 3). In contrast, the overall heat conductance of the thermosyphon remains constant for any given wind speed and is in-keeping with input function, which was based on Equation 1. For instance, the overall heat conductance values between 0 and 3600 seconds and 3601 and 7200 seconds are $C = 16.5 + 26(0^{0.62}) = 16.5$ and $C = 16.5 + 26(2^{0.62}) = 56.45$ W/°C.

Summary and Conclusions

The objective of this example file was to demonstrate how to define a thermosyphon boundary condition in TEMP/W. The thermosyphon boundary condition is characterized by a convection coefficient h instead of the often measured or specified overall heat transfer conductance. The convection coefficient is simply obtained by dividing the overall heat transfer conductance by the surface area of the evaporator section. The simulated results can be verified by back-calculating the overall heat conductance by the temperature difference between the air and evaporator surface at any point during the simulation.

References

Haynes, F.D., and Zarling, J.P. 1988. Thermosyphons and foundation design in cold regions. Cold Regions Science and Technology, 15, 251-259. Elsevier Science Publishers B.V. Amsterdam.