IOP Conference Series: Materials Science and Engineering

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IOP Conf. Series: Materials Science and Engineering **507** (2019) 012017 doi:10.1088/1757-899X/507/1/012017

Roadway embankment stabilization on permafrost using thermosyphons with Y-shaped evaporators

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Abstract. Constructing surface facilities on permafrost soils is a substantial engineering challenge. Moreover, evading thaw-settlement on roadway embankments is not an easy task due to the shifting thermal regime of underground soil because of seasonal temperature variations. Of all engineered cooling solutions available to stabilize permafrost, thermosyphons have attracted many researchers because of the benefits of using this cooling method compared with other methods. In this paper, we describe the optimization of thermosyphons with a Y-shaped evaporator. The cooling effects were compared with those of a conventional parallel design. The optimal spacing between thermosyphons for both the parallel design and the proposed Y-shaped design are documented.

1. Introduction

Permafrost is soil that is at or below the freezing point of water (0°C) for two or more years. Permafrost is a major problem in high-latitude regions such as the Arctic and Antarctic. This soil will thaw in a shifting thermal regime. Stabilizing thaw-settlement on roadway embankments in permafrost zones is a highly technical engineering challenge. Roadway embankments are one of various engineering structures affected by thawing permafrost. Thermosyphon cooling is a passive cooling method widely used in cold regions to avoid thaw-settlement in permafrost [1–5]. Our main interest in this research is the evaporator, which is buried in the soil at a certain known depth. The evaporator absorbs heat from the surrounding soil and delivers it to the condenser where the heat is ejected to the atmosphere. There is growing interest in designs that improve the performance of the evaporator section in thermosyphons. The classic design of the evaporator section in a thermosyphon consists of pipes of simple parallel shape, and this design has been used widely [2, 6, 7]. In our research, we employ a Y-shaped design to improve the parallel evaporator.

The Y-shaped tree design is depicted in figure 1. We have compared the evaporator performance of the classic design (straight evaporators placed parallel) with the Y-shaped design. The net volume occupied by the pipes in the evaporator is fixed in all designs for a fair comparison.

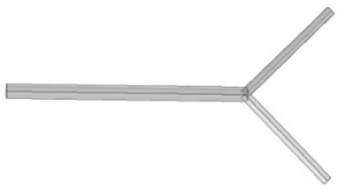

Figure 1. Y-shaped architecture

2. Mathematical model

The geometry of the roadway embankment model is adopted from a highly cited paper [8]. The roadway embankment dimensions are shown in figure 2. This model consists of a highway embankment with a driving surface width of 6 m and height of 2.5 m. The lower boundary is 9 m beneath the pavement surface, and the outer vertical boundary is 17 m from the centerline. Due to the symmetry, we can only consider the half portion of the model. We are interested in finding the optimal spacing between two neighboring thermosyphons by minimizing the volume-averaged temperature. We will consider that the road is of infinite length and that the thermosyphons are installed equidistantly in the direction perpendicular to the plane. By varying the width of the model (the spacing between two neighboring thermosyphons), the minimum volume-averaged temperature is sought. The width resulting in the minimum volume-averaged temperature is the optimal spacing. The outer surfaces of the evaporator, which are buried in the solid, are modeled as isothermal. This assumption is reasonable because the flow in the pipes is intense and the convective heat transfer coefficient in the pipes is very high. The boundary of the entire volume is modeled as adiabatic. The solid is initially at temperature (T_s), which is higher than the temperature of the pipes (T_p). In time, due to the temperature difference, heat transfer occurs between the ground soil and the pipes, and the cooled zone grows around the evaporator.

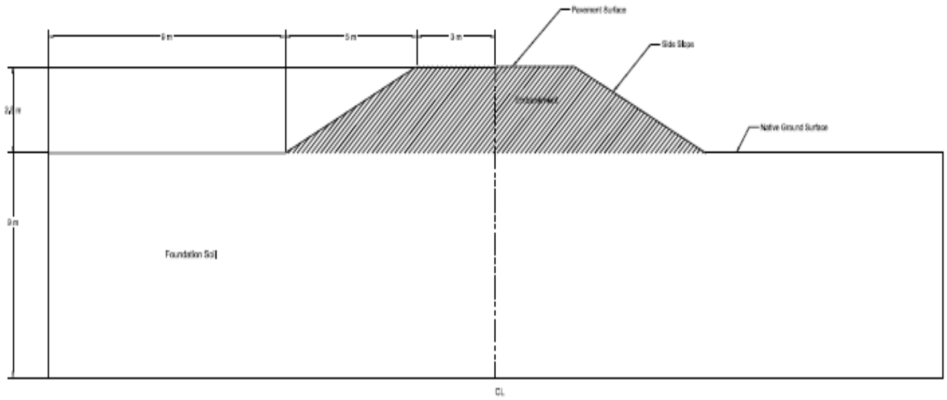

Figure 2. Model embankment geometry

The Y-shaped design (figure 1) has the following dimensions:

$$L_1 = 3m, \text{ and } L_2 = \frac{L_1}{3} \quad (1)$$

All of the pipe cross sections are round. The minimization of fluid flow resistance calls for a particular sequence of diameter sizes, and the round shape holds for both laminar and turbulent flow. The diameters of the pipes in Fig. 1 are sized relative to one another, according to the Hess-Murray rule [9],

$$\frac{D_i}{D_{i+1}} = 2^{1/3} \quad (i = 1, 2, 3\ldots) \quad (2)$$

The conservation of energy in the solid that surrounds the branch structures is governed by

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (3)$$

where α is the thermal diffusivity of the solid, and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$, where *x, y, z* are the coordinates of the model. For greater generality, we determine the temperature field in terms of the dimensionless variables.

$$(x_*, y_*, z_*) = \frac{x,y,z}{V^{1/3}} \quad (4)$$

$$t_* = \frac{\alpha t}{V^{2/3}} \tag{5}$$

$$\theta = \frac{T_p - T}{T_p - T_s} \tag{6}$$

where t and V denote the time and volume, respectively. Eq. (3) can be written in terms of the dimensionless variables as

$$\frac{\partial \theta}{\partial t_*} = \frac{\partial^2 \theta}{\partial x_*^2} + \frac{\partial^2 \theta}{\partial y_*^2} + \frac{\partial^2 \theta}{\partial z_*^2} \tag{7}$$

The initial boundary conditions are

$$\frac{\partial \theta}{\partial x_*} = 0 \; at \; x_* = 0 \text{ and } 17; \quad \frac{\partial \theta}{\partial y_*} = 0 \; at \; y_* = 2 \text{ and } -6;$$

$$\text{and } \frac{\partial \theta}{\partial z_*} = 0 \; at \; z_* = 0 \text{ and } W \tag{8}$$

$$\theta = 1 \quad \text{at } t_* = 0 \tag{9}$$

The simulation is initiated from t_*= 0, where the heat is transferred from the solid to the pipes. The objective is to find the effective volume-averaged temperature with different designs. As the t_* value increases, the volume-averaged temperature of the embankment approaches that of the pipe temperature (T_p). At a fixed non-dimensionalized time at $t_* = 1$, we compute the effective volume-averaged temperature:

$$\theta_{avg} = \frac{T_p - T_{avg}}{T_p - T_s} \tag{10}$$

3. Simulations: Y-shaped vs. conventional design

The heat transfer process was simulated as transient heat conduction by using a computational package, COMSOL Multiphysics [10]. Figure 3 depicts examples of the simulations at $t_* = 1$. The value in the color temperature bar indicators is the non-dimensionalized time. As can be seen in figure 3, the left panel shows the straight evaporator (conventional design); the right panel shows a Y-shaped evaporator. In the vicinity of the evaporator, temperatures are low due to the cooling provided by the thermosyphons. Therefore, the embankment and the soil under it are well protected from the possibility of thawing permafrost.

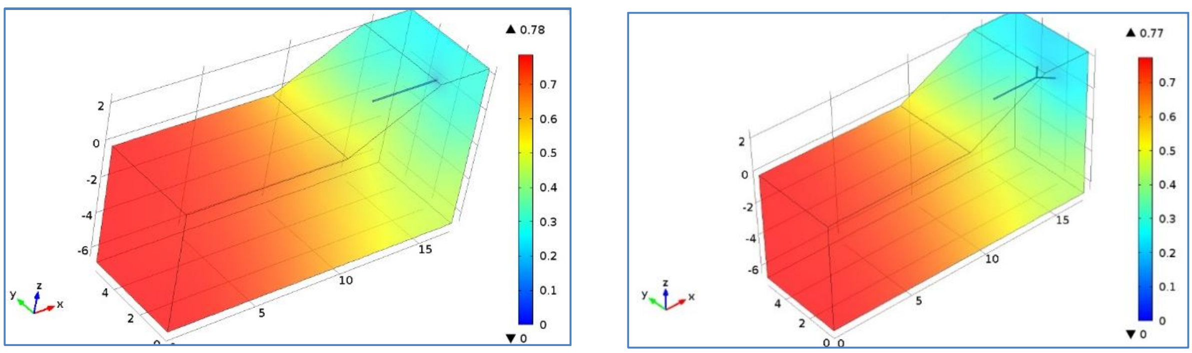

Figure 3. Simulation results for the conventional (left) and Y-shaped (right) designs at an optimum width of 5.5 m

Figure 4 shows the computed volume-averaged temperature with respect to the width of the embankment structure. Both Y-shaped and conventional parallel designs make a U-shaped curve, which implies that there is an optimal width for maximum cooling performance from the equal-volume occupied evaporators. The optimal width is formed at approximately 5.5 m for both designs. In other words, a thermosyphon performs best when it is installed an equal distance of 5.5 m apart from neighboring thermosyphons. When the distance (W) is reduced to 2 m, the average temperature rises to 0.604 and 0.594 for the parallel and Y-shaped design, respectively. That value also becomes greater than the minima when the distance between two neighboring thermosyphons is greater than 5.5 m.

In a comparison of the Y-shaped and conventional designs, the proposed Y-shaped structures transfer the heat much better than the classic evaporator model. Improvements are made by changing the classic design to the proposed Y-shaped design: the minimum averaged temperatures are 0.577 for the conventional design and 0.556 for the Y-shaped design. The Y-shaped design results in a 3.6% improvement.

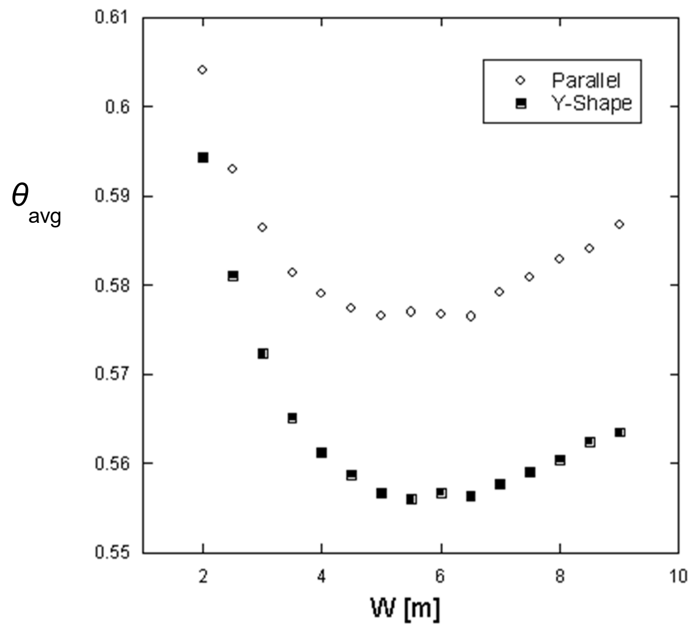

Figure 4. Comparison of volume-averaged temperature with respect to width for Y-shaped and parallel (classic) shaped evaporators

4. Conclusion and future work

In this paper, we propose a Y-shaped configuration to improve the heat transfer performance of thermosyphons used for roadway embankment stabilization on permafrost. We successfully analysed the thermal performance of the different architectures located in a conducting medium. The simulations computed the volume-averaged temperature for various cases. For fair comparison, the volume fraction of the evaporator was maintained at a fixed value for all cases studied. Our findings show that there is an optimal distance (width) between two neighboring thermosyphons.

We found that the Y-shaped configuration performs better than the classic design, as shown in figure 4. The optimum spacing was determined to be 5.5 m. The volume-averaged temperature (θ_{avg}) for Y-shaped structures produced an improvement over the conventional ones with about a 3.6% increase.

The improvement stems from the Y-shaped bifurcation. This design provides more effective heat transfer between the evaporator and ground soil. In future work, we will study higher bifurcation level designs (figure 5 shows an example of a two-bifurcation level design), as well as the effect of the branch length at each level. The angles of bifurcations will be numerically evaluated.

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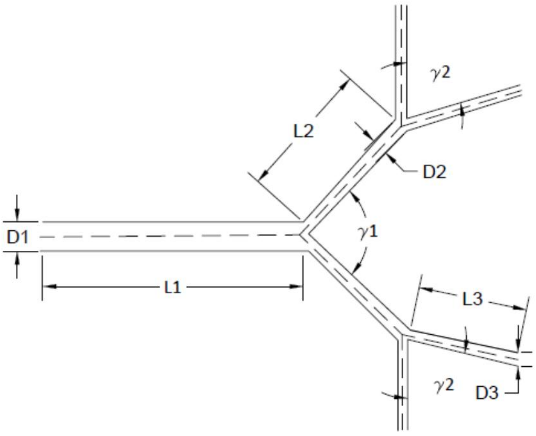

Figure 5. Tree structure lengths and branch angles

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