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Laboratory investigation of the heat transfer characteristics of a two-phase closed thermosyphon

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ABSTRACT

Two-phase closed thermosyphons (TPCTs) are widely used as heat transfer devices in engineering structures in permafrost regions to prevent freeze–thaw damage. In this paper, we reported on a laboratory experiment to study the heat transfer characteristics and working state of a TPCT installed in the soil based on the typical temperature conditions in the permafrost regions of the Qinghai–Tibet Plateau. The results indicated that when the temperature of the condenser section was lower than that of the evaporator section, and the negative temperature difference between the condenser and evaporator sections was beyond a critical temperature difference, the TPCT was active; otherwise, the TPCT was inactive. The critical temperature difference between the condenser and evaporator sections that was required for the TPCT to begin to work was defined as the "startup temperature difference". Furthermore, we found that the efficiency of the TPCT improved linearly with the negative temperature difference between the condenser and evaporator sections when the TPCT was working. In this study, the startup temperature difference of the TPCT was about −0.20 °C and the total thermal resistance was about 0.31 °C/W. These results provide a basis for future work evaluating and improving the performance of TPCTs used for embankment design in permafrost regions.

1. Introduction

Two-phase closed thermosyphons (TPCTs) are used as heat transfer devices in many engineering applications, including heat exchangers, solar energy conversion systems, and civil engineering projects, because they are simple devices that have easy operation and maintenance (Noie, 2005). TPCTs are used in engineering projects in permafrost regions in the USA, Canada and Russia (Yang et al., 2005); in China this technology has been widely applied to protect permafrost below embankments in cold regions, including the Qinghai–Tibet Railway and Highway. Field studies of embankments indicate that TPCT can effectively reduce underlying ground temperature and improve embankment stability in permafrost regions (Cheng et al., 2008; Li et al., 2003; Pan et al., 2003; Sun, 2005; Wang et al., 2005; Wu et al., 2010; Yang et al., 2005).

The cooling effect of the TPCT results from a "thermal semi-conduction effect" caused by vaporization and condensation of a fluid in a closed device that has an evaporator and a condenser. In an embankment application, the evaporator section is buried in the soil that makes up the subgrade, and the condenser section is above ground in the open air. When the temperature of the condenser section is lower than that of the evaporator section, and the negative temperature difference between the condenser and evaporator sections is beyond a critical temperature difference, the working fluid in the evaporator section absorbs external heat energy and vaporizes. The vapor rises to the condenser section because of the vapor pressure gradient. In the condenser section, the vapor is condensed on the wall, releasing latent heat, and the liquid returns down along the wall to the evaporator section under the influence of gravity. Otherwise, the heat transfer process stops. Thus, in a cycle of increasing and decreasing air temperature, when the TPCT is in a working state, heat energy from soil can be released through the TPCT; however when the TPCT stops working, no heat energy is transferred by the TPCT mechanism. Besides, a small amount of heat can only be exchanged between soil and air through conduction along the TPCT wall during the whole temperature change cycle.

Previous studies have focused on the cooling effect of the TPCT and its applications in cold regions engineering. Wu et al. (1996) tested convection heat transfer between a TPCT and air in a laboratory setting and showed that the heat transfer coefficient of a TPCT was related to the air temperature and outside wind speed. Pan and Wu (2002) studied how soil freezing expansion was restrained by TPCTs using numerical modeling, and Pan et al. (2003)'s study of the cooling radius and the temperature distribution of TPCT embankment in the Qinghai–Tibet Plateau concluded that the TPCT was effective in protecting permafrost

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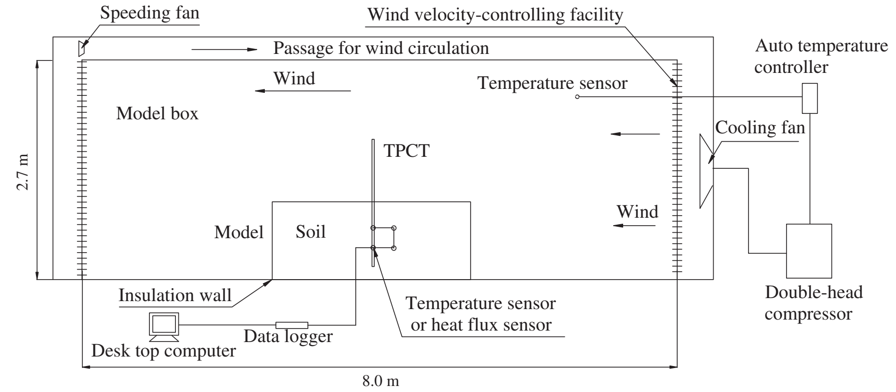

Fig. 1. Schematic of the experimental equipment.

and enhancing embankment stability. Wang et al. (2005) also drew the same conclusion by analyzing the working state and cooling effect of TPCT embankments of the Qinghai–Tibet Highway. Wu et al. (2010) found that combining a TPCT with insulation was a more effective way to decrease ground temperatures, based on the data collected on an embankment along the Qinghai–Tibet Railway.

Recently, numerical studies have been performed to predict and evaluate the long-term thermal stability of TPCT-protected embankments in permafrost regions. Liu et al. (2004) analyzed the cooling effect of a TPCT system on a permafrost roadbed using an approach that modeled the TPCT as a line with an approximate heat flow. Wen et al. (2005) analyzed the temperature characteristics of the embankment protected by the combination of both insulation and TPCTs in permafrost regions by utilizing the same simplification of the TPCT. Similarly, based on the heat flow characteristics of TPCTs derived from field observations, Yang et al. (2006) used a numerical approach to study the cooling effect of TPCTs with different inclination angles for embankments along the Qinghai–Tibet Railway. Using a more complex modeling approach, Zhang et al. (2011) studied the thermal characteristics of a TPCT-protected embankment along the Qinghai–Tibet Railway using a coupled heat transfer model of air–TPCT–soil for the TPCT embankment based on heat transfer theories.

Generally speaking, the cooling capacity of a TPCT and its general application as an approach to enhance embankment stability have been the primary foci of research to date. However what is less well understood are the heat transfer processes and performance characteristics for a TPCT used to reduce ground temperatures in cold regions. In the work reported here, we studied the heat exchange characteristics of a TPCT by analyzing the temperature and heat transfer rate changes of a TPCT model in a laboratory setting. Better understanding of the performance of TPCTs will be helpful in the future design of TPCT embankments in permafrost regions.

2. Experimental design

The experimental work took advantage of a custom-designed cold regions engineering laboratory that was set up for scale model simulations. The experimental equipment consisted of four parts: a model box, a temperature controlling system, a ventilation system and a data acquisition system (Fig. 1). The model box was insulated and has inner dimensions of 8.0 m × 1.84 m × 2.7 m (length, width and height). The temperature control system was composed of a double-head compressor and an automatic temperature controller with a temperature sensor. The ventilation system was composed of cooling fans, speeding fans, wind velocity-controlling facilities and a passage for wind circulation. The wind direction was parallel to the longitudinal direction of the model box. The data acquisition system included temperature sensors, heat flux sensors, a data logger and a desk top computer.

The experimental model for the TPCT is shown in Fig. 2. The cross-section of the model was 2.5 m × 1.0 m along the longitudinal direction

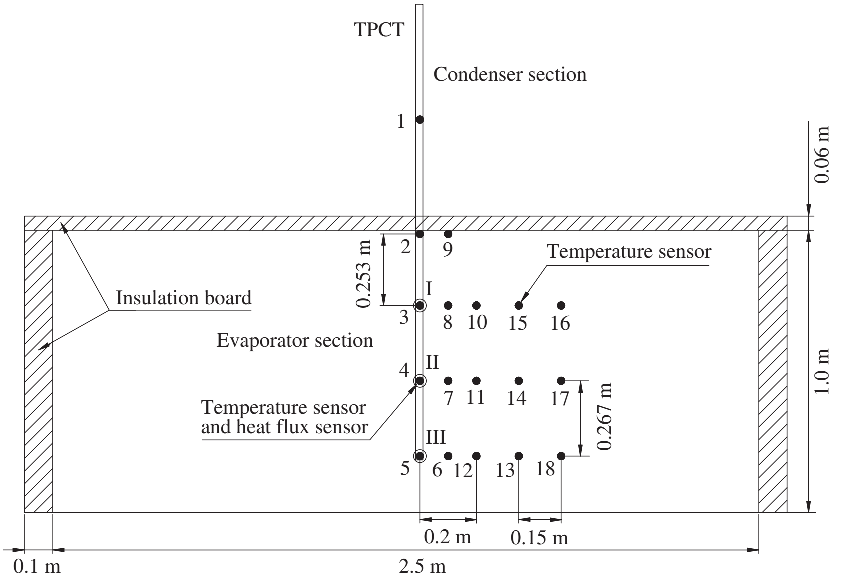

Fig. 2. Schematic of the experimental model for TPCT.