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Research Paper

Geotemperature control performance of two-phase closed thermosyphons in the shady and sunny slopes of an embankment in a permafrost region

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HIGHLIGHTS

- A model describing the process of air-TPCT-soil coupled heat transfer and heat conduction with phase change is developed.
- TPCTs can adjust the geotemperature under a permafrost embankment with shady-sunny effect.
- The ambient solar energy can be transferred into the foundation soil by TPCTs in the cold seasons.
- The working times and efficiency of TPCTs in the shady and sunny slopes are different.
- A permafrost embankment with bilateral TPCTs is better able to reduce the shady-sunny slope effect.

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ABSTRACT

Heat pipes are a widely-used technology for energy exchange in the world. One of the important issues in the future is how ground heat control can meet the demands of the environmental and engineering stabilities in cold regions. In this paper, a low-temperature gravity assisted heat pipe (two-phase closed thermosyphon, TPCT) is innovatively installed in an embankment with shady and sunny slopes to adjust the geotemperature of the underlying permafrost stratum. The geothermal conditions for three cases—an embankment without TPCTs, an embankment with unilateral TPCTs (UTPCTs), and an embankment with bilateral TPCTs (BTPCTs)—are assessed based on a three-dimensional heat transfer model considering the global warming. The model includes coupled air-TPCT-soil heat transfer and conductive heat transfer with phase change. The numerical results show that: (1) both the UTPCTs and BTPCTs can cool the permafrost stratum, but the UTPCTs aggravate the asymmetric geotemperature caused by the shady-sunny slope effect; and (2) the BTPCTs are better to alleviate the asymmetric geotemperature by controlling the working time and efficiency of the TPCTs under the two slopes. Consequently, the BTPCTs are a more effective engineering measure for embankments affected by the shady-sunny slope effect.

1. Introduction

Permafrost is soil or rock with a temperature below 0 °C for at least two consecutive years [1]. Permafrost includes perennial ground ice [1]. Permafrost regions constitute about 24% of the Earth's exposed land surface (Fig. 1), and 22.4% of China's land surface is permafrost regions [1,2]. Permafrost is, however, very sensitive to temperature changes caused by the existence of ground ice. Melting of ground ice in permafrost areas can produce uneven thaw settlement and can affect building stability [3,4]. One of the important future issues is how ground heat control can meet the demands of the environmental and engineering stability in cold regions.

The Qinghai-Tibet Plateau (QTP), with an average elevation of over 4000 m above sea level and an area of about 2.5×10^6 km^2 [4], contains the largest low-latitude permafrost region in the world, as shown in Fig. 1. Approximately 54.3% of the area of the QTP is permafrost [3]. Global mean temperatures have increased continuously since the industrial revolution according to the

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Nomenclature

h	heat transfer coefficient (W/(m^2·°C))
d	diameter (m)
L	length (m)
μ	dynamic viscosity (Pa·s)
η	heat exchange efficiency
C	volumetric heat capacity (J/m^3·°C)
λ	thermal conductivity (W/(m^2·°C))
Pr	Prandtl number
s_n	fin space (m)
b_n	fin height (m)
δ	fin thickness (m)
ε	dissipation rate of the turbulent kinetic energy
g	gravitational acceleration (m/s^2)
r	radius
y	y-direction
ln	napierian logarithm
c	specific heat capacity (J/(kg·°C))
bn	fin height (m)
V	wind speed (m/s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
q	heat flux (W/m^2)
p	pressure (Pa)
t	time (h)
A	area (m^2)
μ_t	dynamic viscosity of air (Pa·s)
l	latent heat of working fluid (J/m^3)
R	thermal resistance (°C /W)
Re	Reynolds number
T	temperature (°C)
x	x-direction
z	z-direction
k	turbulent kinetic energy

Subscripts/superscripts

H	height
$*$	equivalent
o	outer
c	condenser
e	evaporator
a	adiabatic
air	air
i	in
l	liquid
s	soil
f	frozen
u	unfrozen
sat	saturation
va	vapor

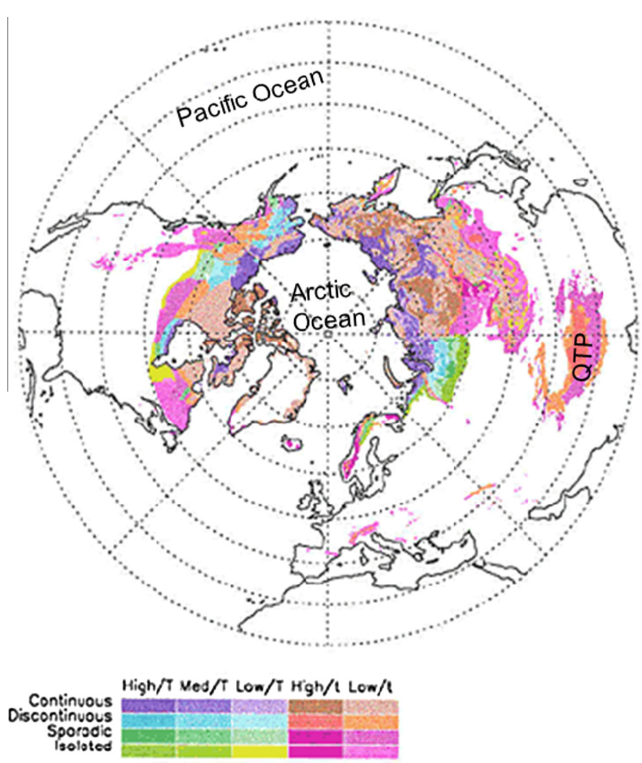

Fig. 1. Distribution of permafrost and ground ice in the Northern Hemisphere. "High (>20%)", "Med (10–20%)", and "Low (<10%)" refer to ice content, and "T (>5–10 m)" and "t (<5–10 m)" refer to thick and thin overburden, respectively. QTP represents the Qinghai-Tibet Plateau. *Source:* Zhang et al. [2]; Image courtesy International Permafrost Association.

Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) and the Paris Climate Agreement of December 2015 [5]. However, a 4 °C warming will likely occur over the QTP over the next 100 years [4]. To date, many different engineering projects have traversed the permafrost areas of the QTP, e.g. the Qinghai–Tibet Railway (QTR), the Qinghai–Tibet Highway (QTH), and so on. Unfortunately, climate warming has accelerated the thawing of permafrost and has caused damage to engineering structures [3,7]. The two-phase closed thermosyphon (TPCT), as an active geothermal control technology, has been widely used in these engineering projects to cool the permafrost stratum and protect the permafrost from thawing.

The TPCT is a wickless heat transfer device with highly efficient energy-transfer capacity, which requires no external power supply [8,9]. TPCTs have been widely used in many applications [8–11], e.g. the petrochemical industry [12], solar energy utilization [13–16], nuclear power engineering [17], and cold regions engineering [18–21], due to their simple structure and eco-friendly advantages.

Several studies have shown that TPCTs perform well in cooling permafrost embankments because the ground heat extracted from the soil by the TPCTs in cold seasons is much more than the ambient heat energy transferred into the soil in warm seasons [8,18,20]. TPCTs are usually inserted vertically into the shoulders of an embankment along the road direction, as depicted in Fig. 2a and b. On the QTP, the south-facing slope (sunny slope) often absorbs much more solar energy than the north-facing slope (shady slope) [22–25]. As a result, the transverse geotemperature distributions under the two slopes are asymmetric, which is called the "shady-sunny slope effect". The difference in the geotemperatures under a permafrost embankment can cause uneven deformation and even longitudinal cracking [24,25]. To adjust the asymmetric geotemperatures under an embankment with shady and sunny slopes, both unilateral TPCT embankments (UTPCT embankments; Fig. 2a) and bilateral TPCT embankments (BTPCT