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Review

Analysis and Applications of the Two Phases Closed Thermosyphon Technology in the Highways in Permafrost Regions: A Review

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Featured Application: This review concludes the advantages of heat pipe technology and its application in permafrost regions are summarized, which can also provide recommendations for permafrost protection measures.

Abstract: Permafrost spans approximately 23–25% of the land in the northern hemisphere, primarily found in Russia, Canada, USA, and China. Numerous engineering projects, particularly those related to transportation, are situated within these permafrost regions. Due to the impact of highway construction and global warming, the permafrost beneath the infrastructure is deteriorating, leading to significant damage. Two phases closed thermosyphon (TPCT) is a widely accepted green countermeasure against the problem in permafrost regions. Although it has been applied to prevent permafrost degradation, their application presents significant challenges on account of the stronger endothermic action of asphalt pavement. This paper focused on a review of the thermosyphon technology and application in the permafrost. Moreover, the article highlighted the excellent working performance of the TPCT that improves the stability of the infrastructures and prevents it degrading due its excellent efficiency in terms of heat transfer. The industrial applications of the TPCT were also summarized, along with their limitations. Ultimately, the findings presented in this paper can offer crucial insights for future TPCT design and development in permafrost areas.

Keywords: two-phase closed thermosyphon technique; permafrost region; analysis; applications

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1. Introduction

Permafrost is soil or rocks wherein the temperatures have remained 0 °C for at least two continuous years, and it spans approximately 23–25% of the land in the northern hemisphere, primarily found in Russia, Canada, USA, and China in Figure 1 [1]. In recent years, as a result of global warming, the average temperature in the permafrost regions has risen at about twice the rate of the rest of the world [2,3]. Meanwhile, the construction of highways will change the thermal stability of the permafrost and cause its degradation, such as the Alaska Highway in the United States, the trans-Siberian Highway in Russia, the Dempster Highway in Canada, and the Qinghai–Tibet Highway in China [4–7]. Therefore, it is a big challenge to build highway in a permafrost region, under the dual role of the above.

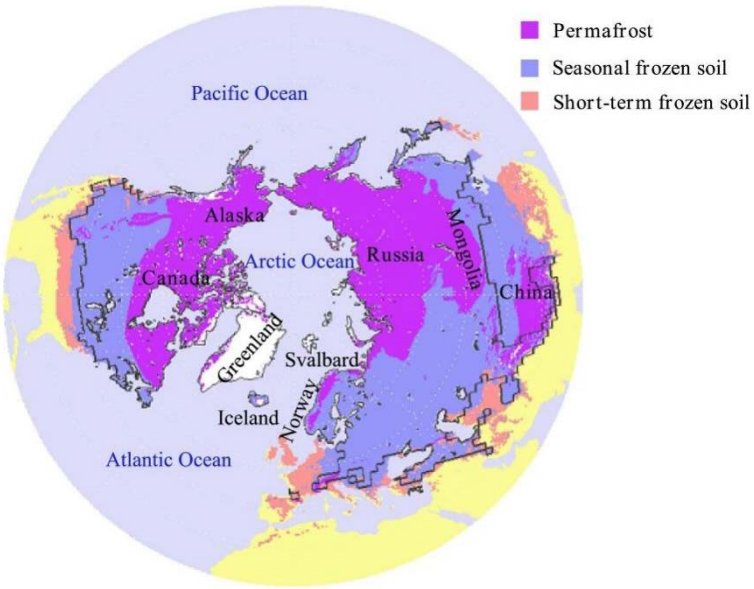


Figure 1. Distribution of permafrost in the northern hemisphere [7].

Over an extended period, scientists have been diligently striving to address the issue of damage to highway pavements in permafrost areas, and they have suggested numerous beneficial strategies [8–10]. The two-phase closed thermosyphon (TPCT) is one of the most efficient and cost-effective measures. The TPCT can prevent permafrost degradation to some extent and has been used in permafrost regions [11–14]. However, damage still occurs. As shown in Figure 2, the long cracks are still occurring with the applications of the TPCTs. Therefore, it is necessary to summarize the working principles and factors of TPCT and then design new appropriate measures.



Figure 2. The cracks on the roadbeds with TPCTs [13].

In view of the above, the paper is divided into two main sections: schematic analysis of the TPCT and applications. The first section includes the following: operating principles, factors affecting the operation of the TPCT. The second section lists the applications with special attention to the permafrost region, and the normal experimental and numerical approaches of applications of the TPCT.

2. Operating Principles of the TPCT

In the energy exchange systems, TPCT is an efficient heat transfer device without any external energy [15]. Usually, a TPCT consists of three parts, including the evaporator section, the adiabatic section, and the condenser section [16]. When it was applied in the highways in the permafrost region, the condenser section is exposed to the air and the evaporator section is inserted into the embankments. The evaporator section is placed under the condenser section. It can effectively transport a large amount of heat energy along the tube wall with a small temperature difference between the condenser section and the evaporator section [17,18].

The detailed working principle is shown in Figure 3 [19]. It mainly relies on the gas–liquid phase change of the internal work material and gravity reflux to transmit heat, the work material is accumulated at the bottom of the heat pipe, which can be liquid ammonia with low boiling point and environmental protection, etc. The evaporation section is in the lower half of the heat pipe, the condensation section is in the upper half of the heat pipe, and the adiabatic section is in the middle part. In the cold season, when the temperature of the evaporation section of the heat pipe is higher than the temperature of the condensing section, the heat pipe evaporation section of the workpiece is heated and evaporated into steam, under the action of differential pressure, the steam flows upward and rises to the condensing section, the exothermic condensation in the condensing section into a liquid, and then returns to the evaporation section under the action of gravity to complete the cycle of work. Through the constant vaporization of the mass of heat absorption—condensation and exothermic, a steady stream of heat pipe evaporation section occurs near the heat transfer to the condensing section. As long as there is a temperature difference between the condensing section and the evaporating section, the heat pipe will continue this cycle of heat transfer [11,20,21].

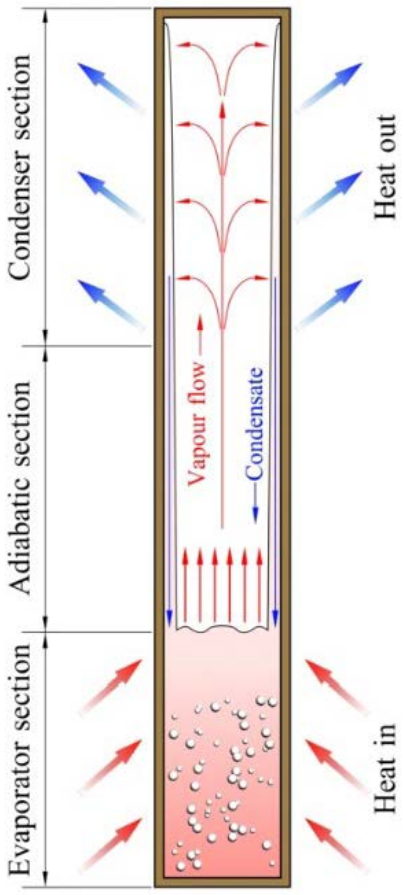


Figure 3. The detailed working principle of the TPCT [22].

In addition, the concept of equivalent thermal resistance [23] is mentioned in order to facilitate the calculation and simulation of heat pipes. When the heat pipe works in the roadbed in the permafrost zone, its thermal resistance includes the thermal resistance between the air and the wall of the condensing section R_f, the thermal resistance of the wall of the condensing section R_{cw}, the thermal resistance of the liquid film of the condensing section R_{cl}, the thermal resistance of the adiabatic section R_a, the thermal resistance of the liquid film and the pool of liquid in the evaporating section R_{el}, the thermal resistance of the wall of the evaporating section R_{ew}, the thermal resistance between the soil and the wall of the pipe R_s, respectively. As illustrated in Figure 4, T_a, T_{co}, T_{ci}, T_{cl}, T_{el}, T_{ei}, T_{eo}, and T_s are the air temperature, the wall temperature outside the condensing section, the wall temperature inside the condensing section, the liquid film temperature in the condensing section, the liquid film temperature in the evaporating section, the wall temperature inside the evaporating section, the wall temperature outside the evaporating section, and the soil temperature, respectively.

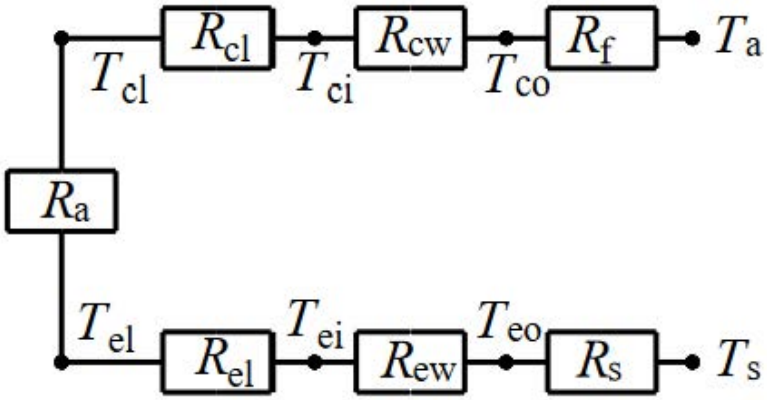


Figure 4. The circuit diagram of TPCT's resistance.

3. Factors Affecting the Work of the TPCT

In permafrost TPCT engineering, the heat transfer performance of TPCT is the decisive factor to keep the subgrade permafrost in a frozen state. In 1942, Gaugler put forward the principle of TPCT. In 1965, Cotter put forward a more complete TPCT theory for the first time, which laid the foundation for the future research work of TPCT theory. Since then, many scholars have carried out a lot of research work on the heat transfer performance of TPCTs [24–26]. It has been shown that the heat transfer performance of TPCT is mainly affected by the properties of the TPCT itself: the work fluid [22,27–30], the liquid filling rate [31–35] (the ratio of the work mass volume to the volume of the evaporating section of the TPCT), the length-to-diameter ratio [15,36,37] (the ratio of the length of the evaporating section to the inner diameter of the TPCT), and the geometrical shape [38,39], as well as by the other factors: the angle of the inclination of the TPCT [13,40–43], the ratio of the effective length of the TPCT [18,44] (the ratio of the effective lengths of evaporating), and external environmental factors [23] including wind speed [41], etc., are also considered. The following is a selection of five important factors.

3.1. Working Fluid

Kanji Negishi et al. [27] investigated the heat transfer coefficients of the heat pipe with different filling volumes and different work materials (water and ethanol) at different tilting angles of the heat pipe. It was found that the total heat transfer efficiency of the heat pipe with water as the work material was higher than that of the heat pipe with ethanol as the work material. Ma et al. [28] investigated the effect of eight work materials on the heat transfer performance of heat pipe and found that the heat transfer performance of the heat pipe with R245fa/R152a as the work material was the best for the evaporation section at temperatures ranging from 35 to 95 °C and the condensation section at temperatures

ranging from 20 °C. Engin Gedik [22] found that the best heat transfer performance of heat pipes with three different media (water, ethanol, and ethylene glycol) was achieved under different ambient conditions. From the above studies, it was found that the heat transfer performance of the heat pipe is not only affected by the working medium, but also by the ambient conditions.

3.2. Filling Ratio

The heat pipe filling rate is the ratio of the volume of the work mass inside the tube to the volume of the evaporating section of the heat pipe. Payakaruk et al. [31] found that the heat pipe filling rate has no effect on the ratio of the heat flow at different angles and vertically. Wang and Ma [32] found that the optimum angle of inclination of the heat pipe varies with the filling rate and ranges from about 20° to 50°.Emami et al. [33] found the highest heat transfer efficiency for a heat pipe tilted at 35% for three types of aspect ratios at 60° for different filling rates and length-to-diameter ratio and different angles of inclination. Elmosbahi et al. [34] found that the best heat transfer performance was achieved when the volume of methanol in the heat pipe was about 2/3 of the volume of the evaporation section.

In the perennial permafrost region, under negative temperature, the influence of liquid filling rate on the heat transfer performance of heat pipe is less studied. In the Alaskan pipeline [45], when the heat pipe is not in operation, the height of liquid ammonia is controlled to be about 0.3–0.6 m. Zhang et al. [15] investigated the heat transfer performance of a heat pipe with a liquid filling rate of 65% at low temperatures and found that the total thermal resistance was at a minimum at an inclination angle of 20°.

3.3. Inclined Angle

Pei et al. [40] conducted indoor tests by modeling heat pipes with inclined angles of 50°, 70°, and 90°. It was found that the ground temperature control efficiency of the heat pipe was the highest when the heat pipe was inclined at 70°. Haynes et al. [46] found that the heat transfer performance of the heat pipe increased with the increase in the inclined angle of the evaporation section at low temperatures, wind speeds of 0–5.2 m/s and heat pipe evaporation section angles of 0°–12°. Therefore, if the inclined angle of the heat pipe is used reasonably, the cooling performance of the heat pipe can be improved, and then the heat pipe spacing can be increased, the cost of the project can be reduced, or different inclined angles of the heat pipe can be adjusted to the sunny and shady slope effect.

3.4. Ambient Conditions

Haynes et al. [47] found that the heat transfer performance of the heat pipe increased with the increase in wind speed at low temperatures, wind speeds ranging from 0 to 5.2 m/s, and the angle of the evaporating section of the heat pipe ranging from 0° to 12°. Zhang et al. [43] found through indoor experiments that, when the heat pipe started to work, the efficiency of the heat pipe had a linear relationship with the temperature difference between the evaporating section and the condensing section. Therefore, the heat pipe works more efficiently under the lower temperature and higher wind speed.

3.5. Geometric Shape

In the permafrost region, depending on the shape of the TPCT, TPCTs can be approximately classified into straight TPCTs (straight or slant insert) [48], L-shaped TPCTs [38], horizontal TPCTs [14], hairpin TPCTs [49], and TMD-5 type [50]. In China, USA, and Canada, the evaporation section of the TPCT tends to be straight, with an adjustable tilt angle and without fins, while the condensing section is a straight pipe with fins. In Russia, a TPCT named TMD-5 has 12 vertical fins in the condensing section and aluminum cross-sections welded to the evaporating section to increase the cooling area and stiffness of the TPCT. Numerical calculations showed that after five years of operation, the thermal influence range of the TMD-5 was double that of a smooth round tube in the evaporation

section. Subsequently, the cooling capacity of the TIP obtained by modifying the TMD-5 was increased by a factor of 1.6 compared to the TMD-5. In the range of applications, straight TPCTs are suitable for most projects, such as pile foundations, road foundations, and shallow tunnel sections [7]; L-shaped TPCTs can be used for wide road foundations [12]; horizontal TPCTs are mainly used for houses and airports [30]; hairpin foundations are used in road foundation projects [49]; and TMD-5 is mainly used for pile foundations in Russia [50].

4. Applications of the TPCT

Currently, the TPCT has been widely used in the permafrost region to ensure the thermal stability of various types of foundations, such as the highways [12,16,51,52], railways [53–55], tunnels [56], oil, and gas pipelines [57], tower foundations [58], dams [59,60], and other engineering apparatuses. In this paper, we pay attention to the applications in the highways and railways.

4.1. Highways

Xu et al. [49] monitored an integrated temperature control system consisting of hairpin TPCTs (Figure 5) and ventilated shoulders on the Alaska Highway, which is a high-temperature permafrost region that is particularly sensitive to temperature, and the construction of the highway would disrupt the original geothermal equilibrium of the ground air, which was found to be functioning well after one year of operation through the on-site monitoring data.

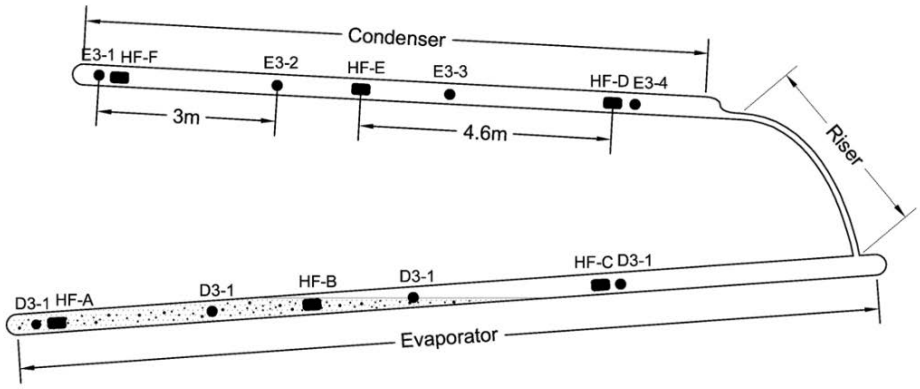


Figure 5. The harpin TPCT with the sensor [49].

In China, TPCT was firstly applied to damaged highway culverts. Nearly 2000 straight and diagonally inserted TPCTs were used to mitigate severe longitudinal cracks and melt subsidence in the Chumar River section of the Qinghai–Tibet Highway from 2002 to 2004 [61]. Wu et al. [51] analyzed the characteristics of the ground temperatures in the same horizontal and vertical directions based on the observations of the TPCT test section of the Qinghai–Tibet Highway from 2004 to 2012. Through indirect calculations, it was found that the TPCT transfers about 1200 MJ to 1500 MJ of heat per year, transferring more energy in the first few years, and gradually stabilizing the heat transferred by the TPCT over time. Yu et al. [52] found that the TPCT could effectively cool the submerged multiyear permafrost of the roadbed, and that the optimal cooling effect of the TPCT was located in the middle of its evaporation section. Wang et al. [61] analyzed the ground temperature characteristics, temperature field morphology, and the freezing and thawing process of TPCT roadbed based on nearly 11 years of field monitoring data of the TPCT roadbed test project on Qinghai–Tibet Highway, estimated the horizontal heat gain and loss condition near the TPCT under the influence of the roadbed's yin and yang slope effect, and concluded that the long-term cooling effect of the bi-lateral TPCT roadbed was stronger than that of the unilateral TPCT roadbed, and that the diagonally inserted TPCT roadbed was stronger than that of the straight-inserted TPCT roadbed.

High-grade highways have the structural characteristics of "wide, thick and black" and strong heat absorption, heat storage, and heat gathering effects, which pose a greater threat to the stability of perennial permafrost roadbeds. Many scholars have carried out a series of research on the thermal stability of high-grade wide roadbeds [7]. Lai et al. [38] and Dong et al. [62] designed an L-shaped TPCT-block gravel berm-insulated panel composite roadbed in order to achieve the purpose of maintaining the thermal stability of a wide high-grade highway in a permafrost zone while protecting the underlying permafrost. In order to verify the cooling effect of the new TPCT composite roadbed, an indoor model test was carried out, and the test results preliminarily proved the effective cooling ability of this roadbed, and it was found that the air temperature remained negative in most parts of the roadbed after the end of the positive temperature period, remaining around −0.4 °C. Zhang et al. [39] conducted a wide test roadbed in the Beiluhe area of the Qinghai–Tibetan Plateau monitoring and comparatively analyzed an L-shaped TPCT-insulation board-block gravel berm composite roadbed and an unprotected roadbed as a control. The longitudinal length of the L-shaped TPCT-insulation board-block gravel berm composite roadbed was 16.5 m, the top surface width was 15.9 m, and the asphalt pavement width was 11.5 m, with four lanes in both directions. After about 4 years of monitoring, compared with the unprotected roadbed with no protection measures and roughly the same direction, it is obviously found that the L-shaped TPCT-insulation board-block gravel berm composite roadbed not only solves the sunny and shady slope effect of the unprotected roadbed, but also lifts up the upper limit of the perennial permafrost under the roadbed, effectively cools down the underlying perennial permafrost, and enhances the thermal stability of the wide roadbed in the perennial permafrost area. In addition, the Gonghe–Yushu Expressway in Qinghai Province is the world's first high-altitude and high-cold permafrost highway (Figure 6a), and in order to protect the stability of the roadbed in the perennial permafrost development of the Chalaping area, the first phase of the project used nearly 4000 TPCTs [8].



Figure 6. Application of TPCTs in Permafrost regions.

However, the application of the TPCT roadbed in the highway still has different degrees of problems. Wang et al. [61] investigated the Qinghai–Tibet Highway and found that 30.8 km of heat pipe roadbed had a disease rate of 35%, among which 10% was serious disease. The main diseases of heat pipe roadbed are longitudinal cracks, and there are also corrugated roadbed, transverse cracks, and other diseases. The main cause of the diseases is the uneven distribution of mechanical properties of the roadbed caused by the uneven temperature field.

4.2. Railwanys

In 1978, TPCTs were used on the Hudson Bay Railway in Canada to stop the degradation of perennial permafrost and thus stabilize the roadbed. Through five years of monitoring data, it was found that it was feasible for TPCTs to control the thawing and sinking of roadbeds in high-temperature discontinuous perennial permafrost zones [63]. TPCTs are mainly inserted vertically or at a certain angle diagonally in the shoulder or foot of slope position in the construction of the Qinghai–Tibet Railway (Figure 6b), and their application mileage exceeds 34 km, and many TPCTs are used in the operation and

maintenance process of the Qinghai-Tibet Railway. Depending on the height of the railway roadbed, the length of TPCTs is divided into 7 m, 9 m, and 12 m. Wu et al. [64] found that the upper limit of perennial permafrost was consistently lifted after the use of composite measures of TPCTs and thermal insulation boards in the roadbed of the Qinghai–Tibet Railway. Hou et al. [53] added block gravel slopes and TPCT composite reinforcement measures to the high temperature and high ice content section of the Qinghai–Tibet Railway. The results showed that the upper limit of perennial permafrost was further lifted for the roadbed without an insulation board, and the yin–yang slope effect was weakened; the upper limit of perennial permafrost was lifted to the vicinity of the insulation board for the roadbed with the insulation board, and the thawed interlayer disappeared after two freeze–thaw cycles. Ma et al. [48] found that the composite roadbed structure of inline TPCT-block gravel berms could solve the roadbed diseases of Qinghai–Tibet Railway and mitigate the settlement of the embankment. In addition, the TPCT is also used in the transition section of the Qinghai–Tibet Railway to alleviate the phenomenon of "jumping car at the bridge".

Along the railway line of Qaidam–Muli, high-temperature swampy permafrost is widely developed, and the high-temperature, high ice-content permafrost section is more than 35 km. According to the meteorological observation data along the railway line of Qaidam–Muli, the low average air temperature in winter and the negative temperature in summer that promotes the work of TPCTs, coupled with the high average annual wind speed, provide favorable climatic conditions for the work of TPCTs [65]. Therefore, about 20,391 TPCTs were used in a 20 km long permafrost subgrade with a longitudinal and transverse spacing of 3.0 m, and the design parameters were strengthened on the sunny slopes [66]. By comparing the upper limit of permafrost in the TPCT section with that in the non-TPCT section, the TPCTs can effectively reduce the road base temperature after one year of construction, and the upper limit of permafrost was found to be elevated by 1.5 m relative to the natural borehole ground temperature. In addition, Chen et al. [67] observed the ground temperature of the TPCT section in Chaiwu Railway, and took the ground temperature drop of 0.5 °C in the middle of the TPCT evaporation section as the criterion for determining the effective cooling range of the TPCT, and used the annual minimum temperature and the annual average temperature as the basis for division, and found that the effective cooling radius of the TPCT was 4.5 m and 2.4 m. Therefore, the design spacing of TPCT of Chaiwu railway is in the range of TPCT cooling, and the TPCT roadbed can effectively cool the frozen soil roadbed and improve stability. In order to rectify the freezing and thawing disaster of the roadbed in the perennial permafrost area of the Yalin Line in the northeast region, TPCTs and thermal insulation materials were used, and the upper limit of man-made permafrost was found to be significantly raised after rectification.

It is worth mentioning that TPCTs are also used in seasonal permafrost zone to eliminate frost heave, and Gao et al. [54] used heated TPCTs to manage the frost heave disaster of high-speed railway subgrade in seasonal permafrost zone, and based on the working mechanism of the TPCTs, they established a coupled heat transfer models between heated TPCTs and the fill soil, and compared and analyzed the calculation results with the on-site monitoring data, which proved the reasonableness of the model. The simulation results show that the heated TPCT can regulate the temperature distribution inside the roadbed, thus weakening the frost damage of a high-speed railway roadbed in seasonal permafrost zone.

5. Performance Evaluation of the TPCT

To further evaluate the work performance of the TPCT, in situ observations [68,69], laboratory tests and numerical simulations are three normal and efficient ways to predict future changes in highway embankments with TPCTs in permafrost regions.

5.1. In Situ Observations

In situ observation in TPCT embankments is crucial for understanding their performance and effectiveness in different climatic conditions, particularly in permafrost regions [70,71]. For example, Figure 7 shows the plane distributions of the observation system and Figure 8 presents the cross-sections of the two embankments. Zhang et al. [71] firstly established an innovate spatial thermal-deformation observation system and evaluates the spatiotemporal thermal-deformation characteristics of a composite embankment with LTPCTs on a permafrost slope. It provides valuable data for understanding the performance of TPCT embankments in permafrost regions. Wang et al. [72] suggested that L-shaped TPCTs should be adopted in the remedial engineering to ensure the cooling effect and reduce the differential settlement of the embankment. It provided valuable data for understanding the performance of TPCT embankments in permafrost regions. Zhou et al. [57] evaluated the influences of protective measures, including an insulation layer and TPCT, on the thermal and mechanical response of frozen soils and buried pipelines. It provided valuable insights into the mitigation of permafrost degradation and ensuring pipeline safety in permafrost. Wang et al. [70] provided a comprehensive analysis of the thermal characteristics and the cooling effect of TPCTs based on the Zhangling–Mohe highway TPCT test section in Da Xing'anling Mountains. It also discussed the limitations of using existing TPCTs in high-latitude permafrost regions of China and presented potential improvements. Yu et al. [73] presented long-term monitoring data for a road section of the Qinghai–Tibet highway before and after installing the TPCTs.

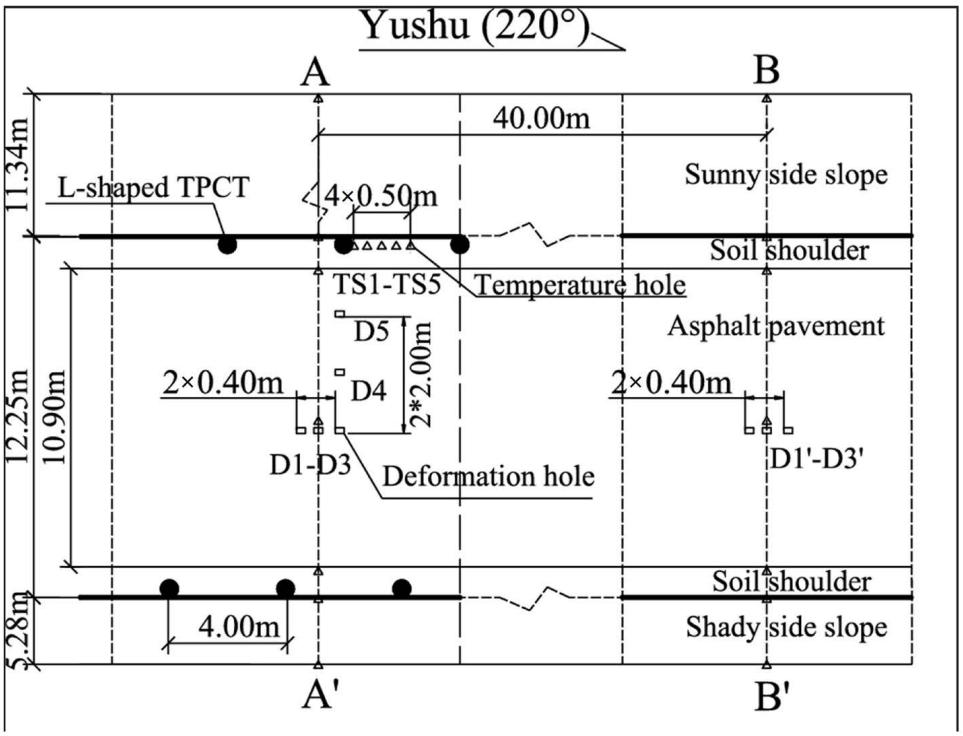


Figure 7. The plane distribution in the observation system of the two embankments [71]. Composite embankment (AA′ cross section); Contrast embankment (BB′ cross section).

In conclusion, in situ observation is vital for understanding the performance of TPCT embankments, assessing their cooling effects, evaluating their impact on infrastructure stability, and guiding potential improvements.

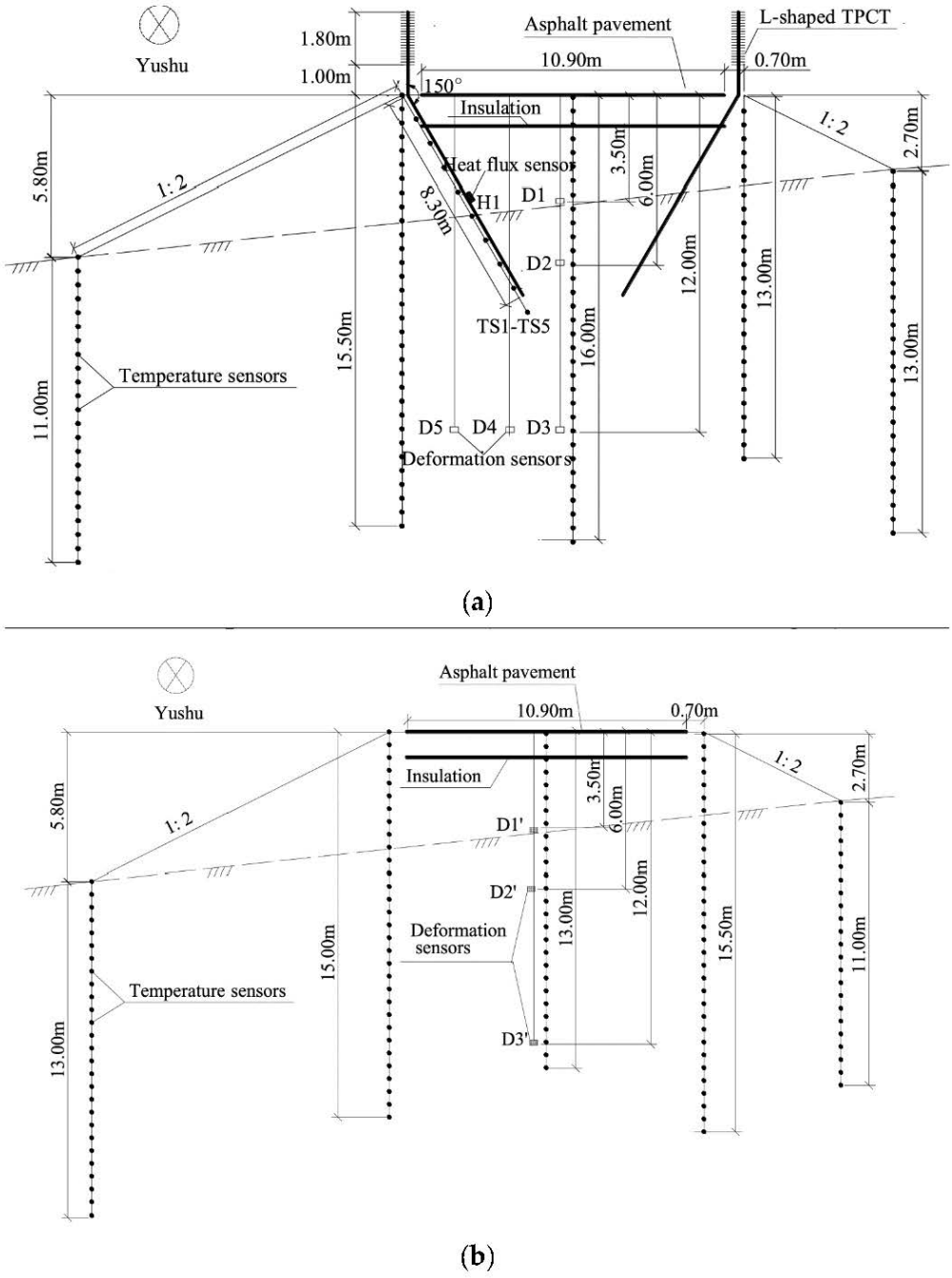


Figure 8. The cross-sections of the two embankments [71]. (**a**) Composite embankment (AA′ cross section in Figure 7); (**b**) Contrast embankment (BB′ cross section in Figure 7).

5.2. Laboratory Tests

The laboratory test serves to examine the stability of the roadbed and the related performance of the TPCT by reducing the real embankment structure by a similar ratio, so that the real environmental conditions can be simulated in a shorter time inside the experimental model box. The common experimental box is shown below in Figure 9 For evaluating the working performance of the TPCTs, numerous tests have been performed.

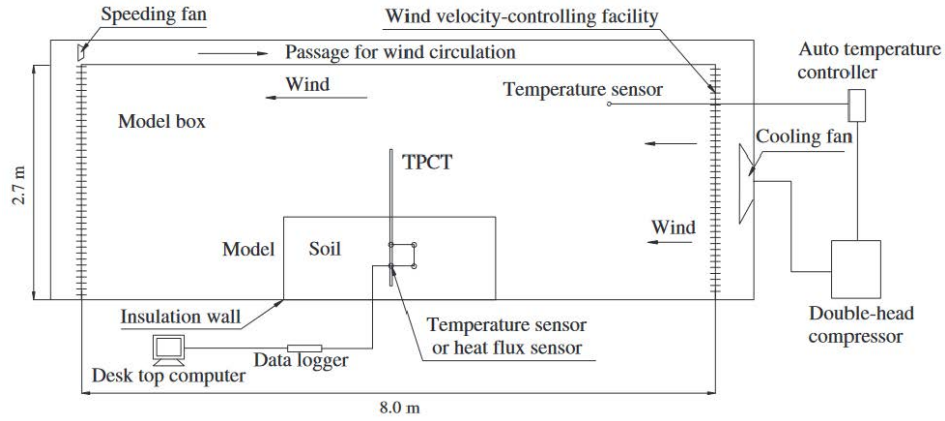


Figure 9. Schematic of the experimental equipment [15].

Lai et al. [38] presented an L-shaped thermosyphon with crushed-rock revetment and insulation. The results indicate that the combined measures can keep the thermal stability of large-width embankment in cold regions. Pei et al. [40] conducted a series of experiments to explore the geo-temperature control process. The optimal inclined angle with efficient control ability is 70 °. Zhang et al. [15] found that the TPCT has a significant thermal semi-conduction effect and it can work efficiently with the startup temperature difference of about −0.2 °C. Yan et al. [16] indicated that the TPCTs can effectively cool down the embankment center and prevent it from degrading. Pei et al. [14] also designed a self-adaption TPCT which has a better ability to solve the side-slope faces and severe environment.

Generally, the experiments test can enable rapid test results to be obtained than the observation. But its results may not be reliable. Therefore, we need the numerical simulations to check it in a few years' time.

5.3. Numerical Simulations

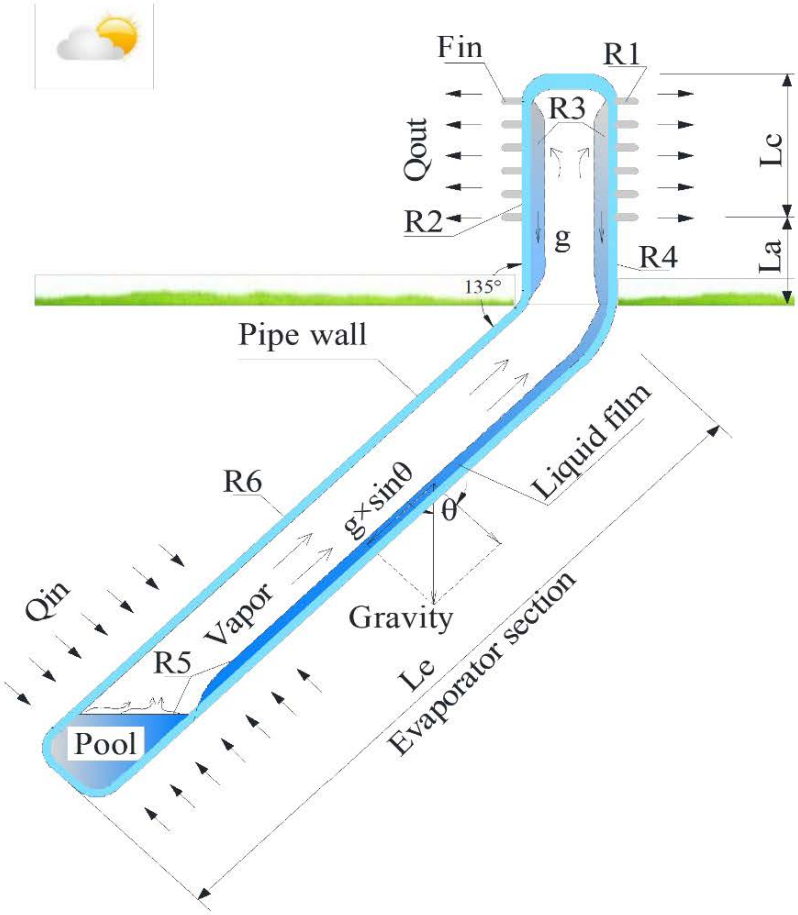
Numerical simulations have a lot of advantages over the two methods above. These can set different conditions and predict the future. For the complex systems, such as the thermal-mechanical stability of the embankment, it is necessary to use simulations.

For theoretical analyses, several methods have been proposed for TPCT embankment. Including the linear heat flux method [74], the equivalent thermal resistance method [75], and the air–TPCT–soil-coupled heat transfer model [12,76]. Currently, the air–TPCT–soil coupled heat transfer model has been the most widely used model in permafrost engineering. Thus, we pay attention to the air-TPCT-soil coupled heat transfer model.

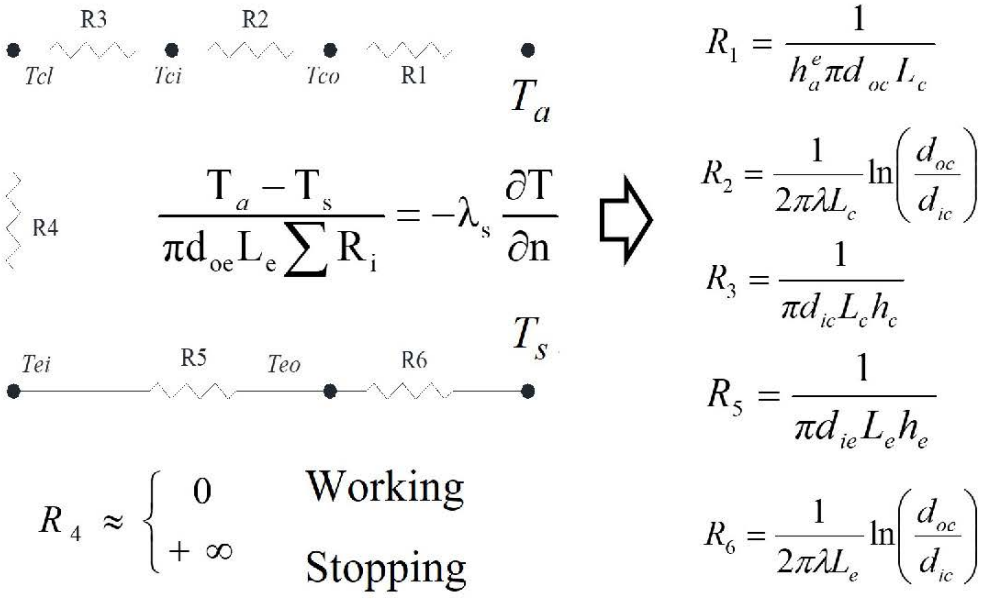
Zhang et al. [76], on the basis of the thermal resistance method (in part 2), considered the coupled heat transfer process of the heat pipe with the atmospheric environment and the surrounding soil, established the coupled heat transfer mechanism between the heat pipe and the surrounding perennial permafrost environment and air, and established the equations for the calculation of the thermal resistances of each part of the TPCT. Pei et al. established the theoretical model of coupled air–TPCT–soil heat transfer considering the effect of inclination angle, which are shown as follows (Figure 10).

Then, the numerical simulation of heat transfer based on the actual temperature difference to regulate the start/stop of heat pipes was written. The new written procedure overcome the previous time regulation method which cannot accurately simulate the working process of the heat pipe defects, to achieve the efficient simulation of the TPCT.

Table 1 lists the different structure of TPCTs including the vertical, the L-shaped, and the horizontal TPCT, and its evaluation method published in the literature. In the 'method' column, the numbers 1, 2, and 3 mean observation, laboratory test, and numerical simulation, respectively.



(**a**)



(**b**)

Figure 10. The effective thermal resistance of the TPCT [12]: (**a**) The distributions of the thermal resistance; (**b**) The formula of the thermal resistance.

Table 1. The structure and evaluation method of the TPCTs.

Reference	Structure	Methods	Performance
[52]	Vertical TPCT	1, 3	Cooling is evident but causes pavement cracks.
[58]	Vertical TPCT	1, 3	Threatens the stability and develops deformation.
[11]	Vertical TPCT	3	Decreases the temperature, increases mechanical strength.
[77]	Vertical TPCT	3	Adjusts the temperature of embankment with shady-sunny effect.
[66]	Vertical TPCT	1	Cools the embankment, keeps the thermal stability.
[78]	L-shaped TPCT	3	Effective in cooling permafrost, but duration limited.
[38]	L-shaped TPCT	2	Keeps the thermal stability with the combined measures.
[79]	L-shaped TPCT	3	Works in cold seasons, cools embankment core efficiently.
[12]	L-shaped TPCT	1, 3	Extends the horizontal cooling extent under embankment.
[80]	L-shaped TPCT	3	Controls permafrost degradation rate by reducing heat absorption
[68]	L-shaped TPCT	1	Improves the long-term service performance.
[71]	L-shaped TPCT	1	Cools the embankment but may cause longitudinal cracks.
[81]	L-shaped TPCT	3	Considers the installing position of the TPCT.
[20]	Inclined TPCT	3	Eases permafrost degeneration, cools down permafrost.
[13]	Inclined TPCT	3	Reveals the cause of longitudinal crack on TPCT.
[16]	Inclined and L-shaped TPCT	2	Cools down the embankment center, prevent it thawing.
[14]	Horizontal TPCT	1, 2	Reduces horizontal temperature difference, increases heat control distance
[69]	Horizontal TPCT	1, 3	Doubles the contact surface, reduces heat flux difference.
[54]	Heating TPCT	3	Reduces the freezing depth and evaluates the railway.

6. Limitations of the TPCT

The limitations of the TPCT includes its own limitations and problems that arise in applications.

First section: Although TPCTs are effective transfer devices, there are some limits, including viscous, sonic, dry-out, boiling, flooding, and geyser boiling.

(1) The sonic limits are mentioned in theory, but never observed.
(2) The viscous limit is that the pressure difference is smaller than the viscous force, the vapor cannot move and the viscous limit is reached [82].
(3) The dryout limit occurs at a small working fluid. For the continuous circulation of the two phases, there is a minimal mass of working fluid. When the available mass is smaller than the minimum, the bottom of the evaporator will dry out [83,84].
(4) The boiling limit: when it occurs, there is a transition from nucleate boiling to film boiling, which will greatly increase the risk of the TPCT damage.
(5) The flooding limit: the latent heat of vaporization of the working fluid is necessary in controlling the flooding limit. Once the axial heat fluxes are higher than the radial heat fluxes, the upward vapor will prevent the liquid from going back to the evaporator. Meanwhile, the evaporator will dry out [85,86].
(6) The geyser boiling limit: this is an unstable phenomenon [87]. Khazaee et al. [88] examined geyser boiling in two TPCTs with different diameters (15 and 25 mm) and a length of 1000 mm. The results of the experiment showed that the period of geyser boiling decreased as the heat load and aspect ratio increased.

Considering the above limit, when using TPCTs, it is more important to pay attention to the conditions of its use and choose the appropriate optimal design ratio to meet the higher engineering needs.

Second section: the TPCTs were successful in the highways, and can significantly cool the roadbeds and enhance the permafrost thermal stability. However, there are several limits listed below.

(1) The cooling range of the TPCTs is limited, and the effective cooling range is about 2.4 m [89].
(2) The asymmetric geotemperature distribution under the roadbeds caused by the TPCTs can affect their stability [14]. The area is near the TPCTs where the temperature is

lower than the rest of the area which causes the frost heaven in winter. Then, in summer, the thawed depth is uneven, which causes the sliding down at the shoulder.

(3) The installation holes around the TPCTs were uncompacted [7]. They will settle after the freeze–thaw cycle. The water from the rain will fill these holes and accelerate the damage process of the roadbeds.

Thus, it is necessary to optimize the better performance structure to meet these needs.

7. Future Development of TPCTs

Lower heat loss, higher transfer efficiency, longer work time, and less economic cost are the objectives of the evolution of TPCTs. With global warming and the requirement of improving high-efficiency structures, expectations for stable a TPCT structure are increasing. Based on the evaluation of the cooling performance for the TPCTs structure, the following research directions are proposed:

1. The utilization of the latent heat of the working fluid: TPCT cooling generally uses liquid convection heat transfer. By combining the two-phase heat transfer of the working fluid with the utilization of its latency, the cooling capacity can be improved.
2. Optimization of the design of the TPCT: according to the needs in engineering, the inner channel design of the TPCT should be optimized to reduce the flow resistance and ensure the uniformity of roadbeds' temperature distributions.
3. Establishment of the ventilation ducts: The ventilation ducts can improve the convection heat transfer efficiency, and then improve the cooling performance of the TPCT roadbeds. An external air system can also be installed.
4. Installation of the solar generator: The improvement of the TPCT with the addition of a solar generator can lead to the long-term use of solar energy to operate the TPCT.
5. Update of the materials: Currently, the material of the TPCT is stainless steel. Improving the corrosion and frost resistance of the material may lead to its longer-term use and reduce the cost.

8. Summary

With the construction of the highways in permafrost regions, the requirements for stability have been pushed to a new level. The TPCT as an efficient transfer device has been widely applied to cool the roadbeds. The effective cooling performance of the TPCT is essential to decrease the deformation and the error of the roadbeds. In this paper, the summary of the advance and application of the TPCT has been performed through the following work.

1. The detailed introduction of the operation of the TPCT is presented. The factors of the TPCT mainly include the working fluid, inclined angle, filling ratio, ambient conditions, and geometric shape. Recent developments in each of these factors are also discussed.
2. The application of the TPCT mainly in the highways in the permafrost region is presented. The numerical performance of the different TPCT structure is also discussed. The vertical TPCT is the most common technique but may cause cracks in the pavement. The L-shaped TPCT can cool the center temperature well. However, the sunny and shady slope influence will be increased. The horizontal TPCT can meet the required geotemperature distribution criteria.
3. The limits of the TPCT have been listed. Firstly, for the TPCT itself, there are viscous, sonic, dry out, boiling, flooding, and geyser boiling limits. Secondly, for the engineering application, the limit includes the cooling range, asymmetric geotemperature distribution, and the installation holes.
4. The future development of TPCT is predicted as follows: we will mainly consider updating the latent heat of the working fluid, optimizing the design of the TPCT, establishing ventilation ducts, installing a solar generator will be installed, and updating the materials.

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