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Research Paper

Field observations of cooling performance of thermosyphons on permafrost under the China-Russia Crude Oil Pipeline

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HIGHLIGHTS

- Mean annual oil temperatures of the CRCOP are higher than 0 °C and show a gradual warming trend.
- The permafrost underlying the CRCOP is degrading.
- Thermosyphon can cool the underlying permafros, depending on its number, spacing and working duration.
- A thaw bulb surrounding the pipe exists even in winter due to a higher oil temperature.

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ABSTRACT

The buried China-Russia Crude Oil Pipeline (CRCOP) traverses 441-km discontinuous permafrost zone and has been operating at positive oil temperature since 2011. The underlying permafrost is degrading and thaw settlement occurs in the trench. An instrumented site was established to monitor ground temperature and water content under the CRCOP to evaluate permafrost degradation and cooling performance of the thermosyphons installed near the pipe. Field observations show that: (1) mean annual oil temperatures are higher than 0 °C and show a gradual warming trend (average increase by 2 °C during the observation period from 2012 to 2016; (2) the active layer thickness (ALT) increases by 2.7 m and the deep (15–20 m) permafrost temperature, 2 m away from the uninsulated pipe, rises 0.2 °C from 2014 to 2017; (3) thermosyphon can cool the soils surrounding the pipe and effectively mitigate thawing of underlying permafrost depending on its number, spacing and working duration; and (4) a thaw bulb surrounding the pipe exists even in winter due to a higher oil temperature. Field observations provide a better understanding of permafrost degradation, cooling effect and design parameters of thermosyphons, and basic data for numerical validation, implications for other similar cold regions pipeline engineering.

1. Introduction

In permafrost regions, many engineering constructions and infrastructures have already been damaged by thaw settlement related to permafrost degradation [1]. For example, 85% of roadbed problems in permafrost regions along the Qinghai-Tibet Highway were caused by thaw settlement [2]. To ensure the thermal stability of permafrost soils, safe operation and integrity of the adjacent engineered infrastructures, various measures have been adopted to mitigate thaw settlement. One of the most widely used techniques in permafrost regions is thermosyphon, which can decrease ground temperature in cold environments utilizing the natural 'cold' energy without any artificial energy [3]. Lots of investigations have also verified that thermosyphons was an effective mitigation method to cool permafrost and protect the permafrost against thawing [4–7]. In addition, other techniques were combined with thermosyphons for improving the cooling effect and minimize the impact on the environment [8–9].

The China-Russia Crude Oil Pipeline (CRCOP), in operation since 2011, runs from Skovorodino, Russia, to Daqing, China. The Chinese portion of the CRCOP is 953-km long, crosses areas of 441 km

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discontinuous permafrost and 119-km warm and ice-rich permafrost. The 813-mm-diameter oil pipeline with a wall thickness of 11.9 mm is buried at a depth of 1.6–2.0 m depending on the varying geomorphic and permafrost conditions. For anti-corrosion, a three-layer polyethylene structure was applied, from outside to inside, including epoxy primer, synthetic adhesive coating and a polyethylene layer. Field surveys along the CRCOP revealed that warming and thawing of permafrost has led to significant surface subsidence within the trench in warm and ice-rich permafrost regions [10].

In recent years, comprehensive research approaches has focused on the interaction between oil pipeline and permafrost foundation soils. The pipeline-soil numerical models were developed to evaluate thermal influence of pipeline on permafrost foundation under different construction modes, thermal control techniques and ground conditions [11–13], to calculate the stresses and deformations of the pipeline induced by differential frost heave and thaw settlement [14,15], and to discuss the development of thaw bulb around the pipeline in permafrost regions [16,17]. Thermosyphons were also installed in warm and ice-rich permafrost sections along the CRCOP to avoid permafrost thawing and to ensure the stability of pipeline. However, few studies have been performed on cooling performance of thermosyphons installed near the buried warm oil pipeline. Wang et al. [18] suggested that thermosyphons could reduce the thaw penetration rates and extents, thus protecting the underlying permafrost from thawing. Fang et al. [19] pointed out that ground temperature near the thermosyphon could drop to −18 °C. In this paper, the monitored data including oil temperatures, ground temperatures and volumetric water contents are presented at an instrumented site consisting of four cross sections with or without thermosyphons, where the sporadic permafrost exists. The main purpose of this study is to identify the thermal regime of permafrost under the CRCOP, and to evaluate the cooling performance of the thermosyphons near the CRCOP due to warm oil pipeline.

2. Study site and monitoring method

2.1. Study site

The study site is located in sporadic permafrost regions (50°28′14.23″N, 124°13′31.75″E), approximately 0.6 km south of the Jiagedaqi pump station (Fig. 1). The mean annual air temperature (MAAT) from the Jiagedaqi Meteorological Station (during 1967–2015), about 8 km away from the study site, is −1.2 °C and the average annual precipitation is 524 mm. The mean annual ground temperature (MAGT) of natural undisturbed permafrost is about −0.7 °C, and the permafrost table is approximately 2.0 m deep. The geotechnical survey was carried out to show that the shallow strata consisted of peat, silty clay, gravel and weathered granite. The ground ice or a great amount of ice crystals were visible at the depth of −2.0 m to −8.0 m (Fig. 2). The ice content in the different sediments is shown in Fig. 2. The pipeline was uninsulated and buried about 1.6 m deep.

2.2. Monitoring system

Four instrumented cross sections were established perpendicular to the pipeline at 20.0 m intervals. No. 1 Cross Section was constructed in 2014 and two 20-m deep boreholes were drilled (Fig. 3a). One is located on the right-of-way (on-ROW) 2 m away from the pipe, and the other is located at a natural undisturbed site 16.6 m away from the pipe. The thermistor cables (with an accuracy of ± 0.05 °C), developed and assembled by the State Key Laboratory of Frozen Soil Engineering (SKLFSE), were placed and the data were observed manually. Since October 2017, they have been recorded automatically. Observations showed that the active layer thickness (ALT) 2 m away from the pipeline had reached 6.9 m, and the pipe had experienced settlement of 1.4 m over the first four years of operation. Due to a larger thaw bulb and pipe settlement, ten 9-m-long thermosyphons were installed vertically 1.5 m away from the pipe centerline to cool the underlying permafrost with different numbers (one or two pairs of thermosyphons at different cross sections) and longitudinal spacings (1.3 or 1.4 m) in three cross section in 2015. As shown in Fig. 3b, the lower 6 m of each thermosyphon was buried in soils and the upper 3-m section was exposed to the air. The working fluid within them was ammonia, and the closed container was made of carbon steel. Some detailed parameters of thermosyphon are listed in Table 1. Correspondingly, three cross sections were instrumented in late June 2015 to investigate the cooling performance of thermosyphons. Nine boreholes 11–15 m deep were drilled 0.5, 1.5 and 2.5 m away from the thermosyphons (Fig. 3b). The thermistor cables were placed accordingly to monitor the ground

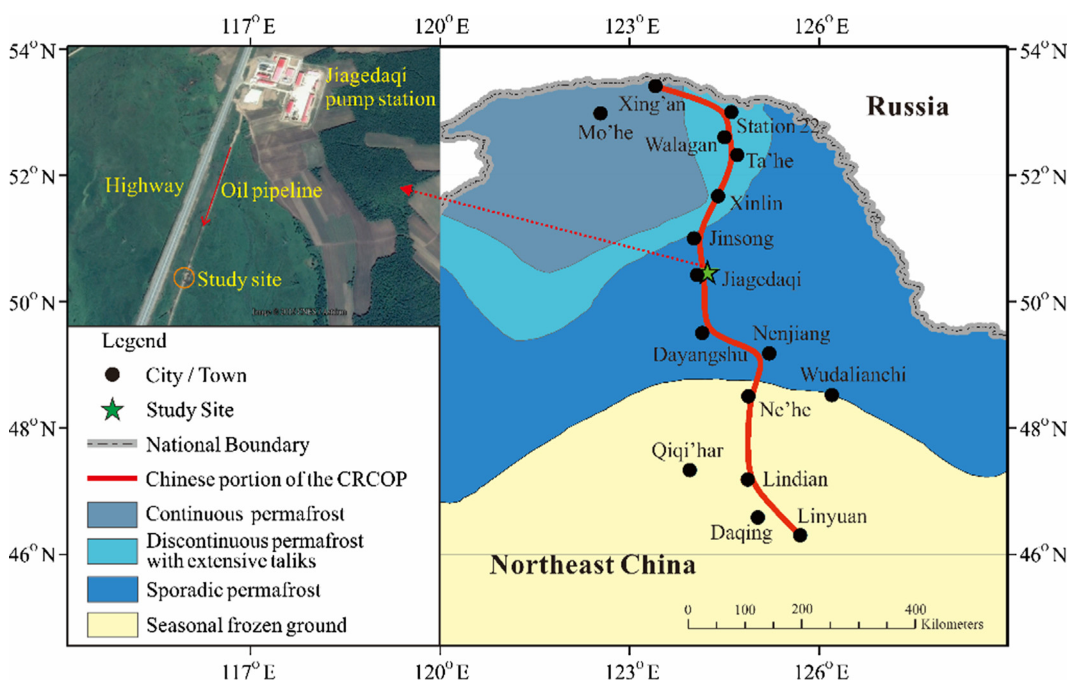

Fig. 1. Location map of the study site.

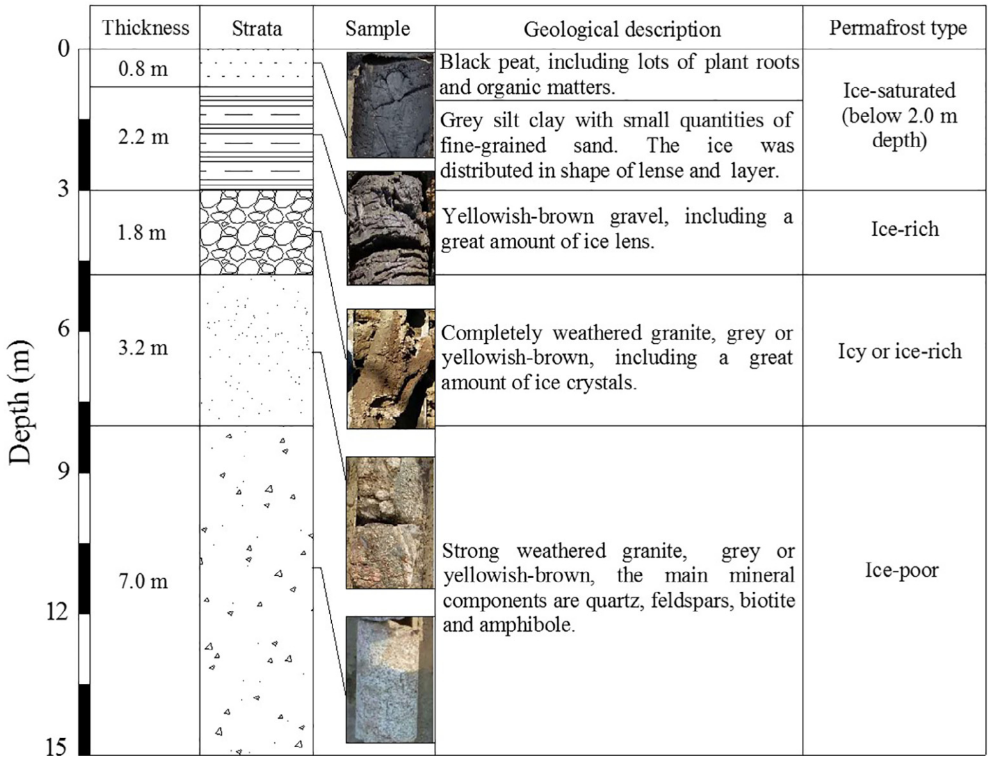

Fig. 2. Geotechnical survey characteristics at the study site.

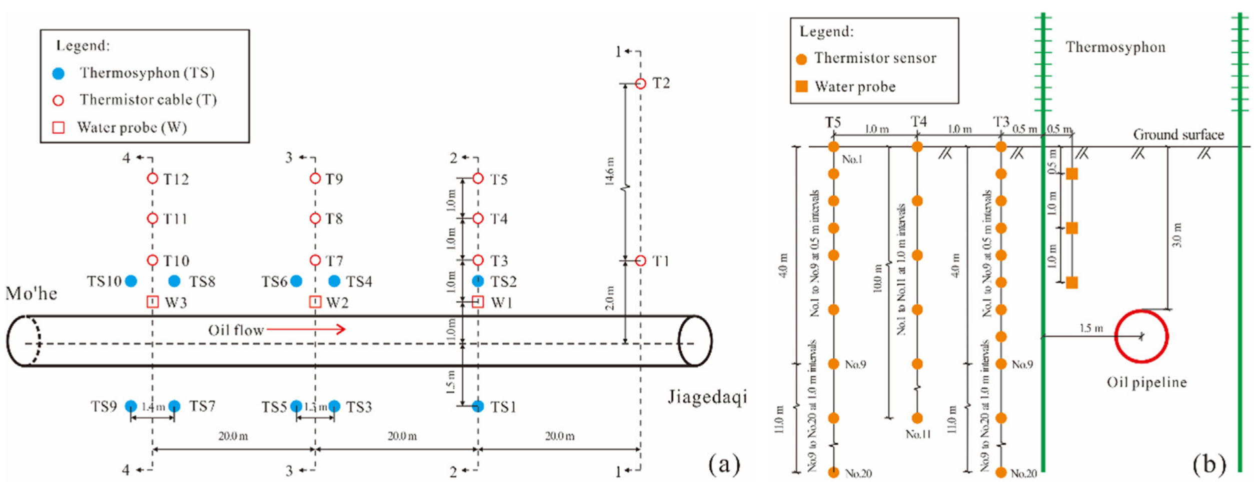

Fig. 3. Schematic figure of the monitored thermal and water content cross sections at the study site. (a) plane of the instrumented cross sections, (b) instrumentation of No. 2 cross section. Note: TS1–TS10, T1–T12 and W1–W3 indicate positions of thermosyphons, thermistor cables and water probes.

Table 1
Design parameters of the thermosyphons.

Parameter	Value	Parameter	Value
Length of condenser section, L_c	2.5 m	Fin thickness, δ	1.5 mm
Length of evaporator section, L_e	6.0 m	Fin height, h	25 mm
Outer diameter of tube, D	89 mm	Fin space, t	10 mm

temperatures. In addition, volumetric water content in soils was also monitored by time domain reflectometry (TDR) water probes (CS616, Campbell Scientific, Inc., USA). Nine water probes were embedded by excavating, 0.5, 1.5 and 2.5 m deep below the ground surface (Fig. 3b), and horizontally 1.0 m away from the pipeline axis (Fig. 3a). The ground temperature and volumetric water content were collected automatically every two hours by a data logger (CR3000, Campbell Scientific, Inc., USA) and stored.

3. Results and analyses

3.1. Oil temperature

The oil temperature at the study site was not directly measured. Thus, we used the outlet oil temperature obtained at Jiagedaqi pump station (0.6 km away from the study site) as a substitute. Fig. 4 shows the monitored outlet mean monthly oil temperature (MMOT) at Jiagedaqi pump station from May 2011 to March 2017. The MMOT recorded in this period ranged from 2.0 °C to 13.0 °C. This showed a remarkable rising trend probably due pumping at this station, climate warming, gradually increased ground temperature and inlet oil temperature. For example, it was 7.6 °C in 2016, significantly higher than

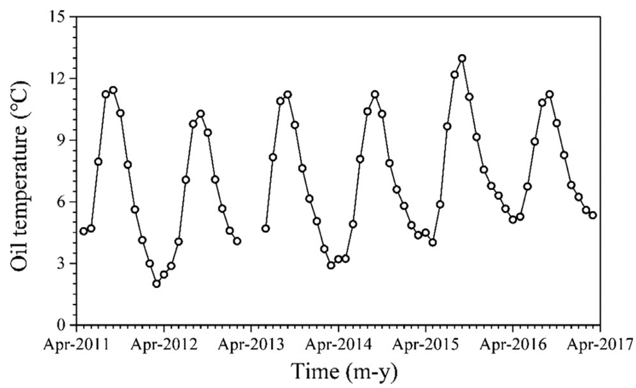

Fig. 4. Mean monthly oil temperature at the outlet of pipeline at the Jiagedaqi pump station.

the value of 5.6 °C in 2012.

3.2. Thermal effect of warm oil pipeline on the underlying permafrost without a thermosyphon

Fig. 5 shows the ground temperature profiles in the different boreholes in October of 2014 and 2017. Ground temperatures on-ROW without thermosyphon were substantially higher than at an adjacent natural site, particularly from the ground surface to −12 m deep. For example, the difference between ground temperature on-ROW and that at the natural site −2 m deep reached 6.2 °C in 2017. Ground temperatures on-ROW in 2017 increased significantly relative to 2014, particularly from −2 m to −8 m deep. Additionally, the natural permafrost table was almost unchanged (2.0 m) from 2014 to 2017, while the artificial permafrost table beneath the pipeline were noticeably deeper and increased by 2.7 m at a rate of 0.9 m/a over three years. Besides, the average ground temperature of the deeper permafrost (from −15 m to −20 m depth) underlying the pipe was 0.2 °C higher than that at the natural site, while the warming rate of ground temperature on-ROW was 0.02 °C/a from 2014 to 2017.

The warm pipe dissipated heat into the surrounding soils throughout the entire year, resulting in the higher ground temperatures on-ROW. In addition, the construction disturbance also contributed to ground temperature rising such as on-ROW vegetation clearing and pipeline installation. The higher oil temperature is the primary factor

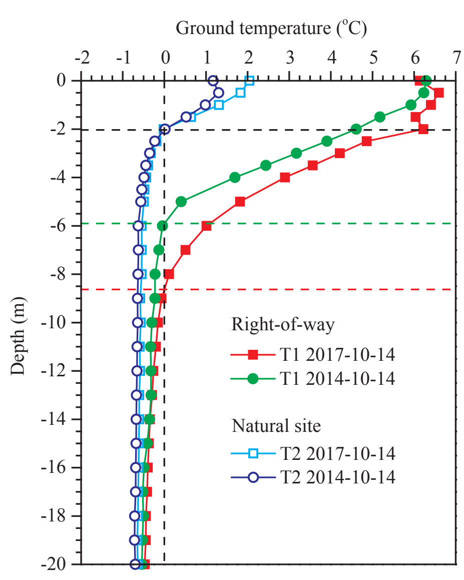

Fig. 5. Ground temperature profiles on-ROW (T1) without a thermosyphon and at the adjacent natural site (T2) recorded in October of 2014 and 2017.

causing permafrost warming and thawing. Therefore, the mitigative measures should be adopted to minimize thawing of underlying permafrost and thaw settlement of the pipeline.

3.3. Cooling performance of thermosyphons on underlying permafrost

Fig. 6 shows the ground temperature profiles in the boreholes T3, T7 and T10 in cold seasons. Ground temperatures in the borehole T1 are also depicted together as the reference values to analyze the cooling performance of thermosyphons. Boreholes T3, T7 and T10 are all 0.5 m away from thermosyphons. It could be seen in Fig. 6 that, the ground temperatures of the upper 6-m-thick soil layers near thermosyphons were much lower than those without thermosyphons, indicating that thermosyphons worked better and had great cooling effect in winter. For instance, the ground temperature at the depth of −3 m in the borehole T3 near thermosyphon was 2.1 °C lower than that in borehole T1 without thermosyphon on January 22, 2016. The best cooling effect was found at No. 3 cross section in borehole T7, which had two pairs of thermosyphons at a shorter longitudinal spacing of 1.3 m. On February 13 of 2017, the ground temperature at a depth −3 m measured from borehole T7, T10, T3 reached −2.6, −2.2, −0.4 °C, about 4.1, 3.7, 1.9 °C lower than that without thermosyphon. In summary, thermosyphon had a marked cooling effect on the foundation soils surrounding the pipe, particularly on soil layers around the evaporator section, and its cooling effect significantly depended on the number and longitudinal spacing of thermosyphon.

Ground temperatures along the Nos. 2 and 3 cross sections were used to evaluate the impacts of number of thermosyphons on the cooling effects. Time series of ground temperatures at the depths of −0.5, −1.5, −2.5, −4.0 and −6.0 m in boreholes T3 and T7 are shown in Fig. 7. Ground temperatures with two pairs of thermosyphons in borehole T7 were lower than those with one pair of thermosyphons in borehole T3, and the remarkable difference occurred in winter when thermosyphons worked. For example, the maximum difference was about 3.8 °C at −4.0 m depth and 1.9 °C at −0.5 m depth in late January of 2016. Apart from the ground temperature difference, the freezing dates of soils at different depths near two pairs of thermosyphons were earlier than those near one pair of thermosyphons. For example, the soil at −6.0 m depth in borehole T7 started to freeze on December 2, 2015, whereas that occurred two months later in borehole T3. Additionally, due to best cooling capacity of two pairs of thermosyphons, the ground temperatures at different depths were all lower than those with one pair of thermosyphons even in summer, except for the location of −4.0 m depth.

The ALTs at instrumented cross section with different numbers of the thermosyphons were gained from the ground temperature observations based upon the depth of 0 °C isotherm. Fig. 8 presents ground temperatures as a function of time and depth in boreholes T3 and T7. Overall, the ALTs from boreholes T3 and T7 has been increasing slowly for the last two years, but the different increasing rates were observed after installing the thermosyphons. The ALT increased by 1.1 m (ranging from 9.4 m to 10.5 m) in borehole T3 and 0.9 m (ranging from 8.0 m to 8.9 m) in borehole T7 in October of 2015 and 2017, respectively. The ALT increased at a rate of 0.90 m per year in borehole T1 (Fig. 5), while it increased 0.55 m per year in borehole T3 and 0.45 m per year in borehole T7, due to the cooling effect of thermosyphons during the monitored period. In addition, in borehole T3 (Fig. 8a), there was a layer of thawed soils, namely thaw bulb surrounding the pipeline. However, the soil layers were almost fully frozen in borehole T7 (Fig. 8b). This indicated that two pairs of thermosyphons had better cooling effect on the surrounding soils.

The descriptions above indicated that the thermosyphons could reduce the thawing rate of the underlying permafrost, and their cooling effect was enhanced with an increasing number. However, even two pairs of thermosyphons could not completely remove heat from warm pipeline, resulting in a thin layer of thawed soil in borehole T7 relative

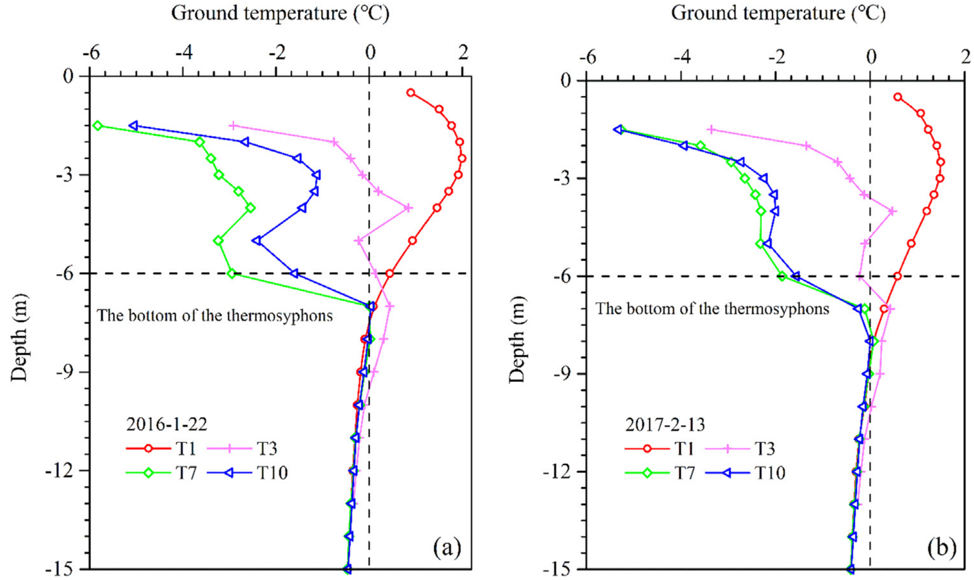

Fig. 6. Ground temperature profiles in boreholes T1, T3, T7 and T10: (a) 2016-1-22; (b) 2017-2-13.

to borehole T3 (Fig. 8).

3.4. Thermal and hydrological process of foundation soils

The water content in soils varies with periodical freezing and thawing. Fig. 9 shows the changes in ground temperature and volumetric water content at different depths in boreholes T7 and W2 to analyze their interactions. As shown in Fig. 9a, the amplitude of temperature wave decreased with increasing depth. The ground temperature at a depth of −0.5 m changed from 19.1 °C to −13.6 °C and ranged from 1.1 °C to −3.0 °C at a depth of −6 m. Additionally, the freezing time of the upper soil layers became earlier than the lower soil layers. For instance, the freezing time at depth of −0.5 m was one month earlier than that at depths of −1.5, −2.5, −4 and −6 m.

As shown in Fig. 9b, the variations in volumetric water content at depths of −0.5 and −1.5 m were observed with freezing and thawing of soil layers. For example, the soil at a depth of −0.5 m depth began to freeze in late October of 2015 and thaw in early May in 2016. Correspondingly, the volumetric water content decreased abruptly from 44% to 10% in 2015 and then increased when soil was thawed in 2016. This variation indicated that the volumetric water content was controlled by the freeze-thaw process. Another abnormal phenomena was that the water content at a depth of −2.5 m was less changed with an average of 48%. It increased slightly in summer and it decreased slightly in winter. The reason was that a thaw bulb around the pipe always existed upon pipeline operation where the water always kept thawed. Because the water content sensors and thermistors were not placed at the same distance away from warm pipeline (at a distance of 1 m between them, Fig. 3(a), the times soil temperature and volumetric water content varied were inconsistent, particularly at a depth of −2.5 m.

Fig. 10 provides the variations in ground temperatures with time and depth 1.5 m (T8) and 2.5 m (T9) away from thermosyphons. The ALT in borehole T8 was about 1.0 m larger than that in borehole T9, which in borehole T8 moved upward from −7.4 m in July 2015 to

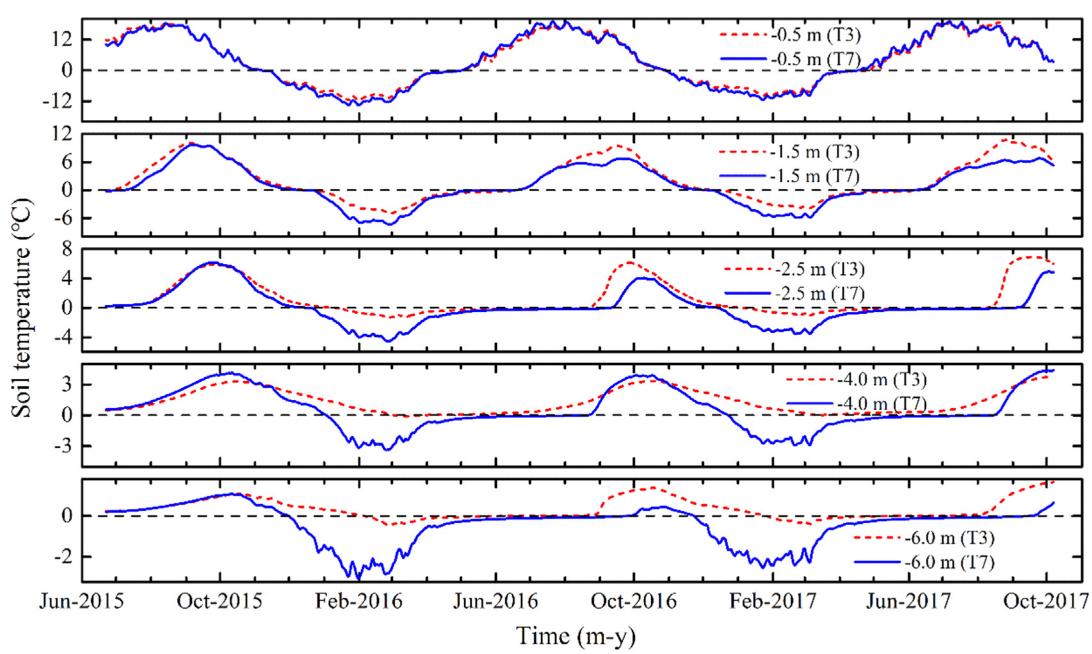

Fig. 7. Time series of soil temperatures at different depths in boreholes T3 and T7.

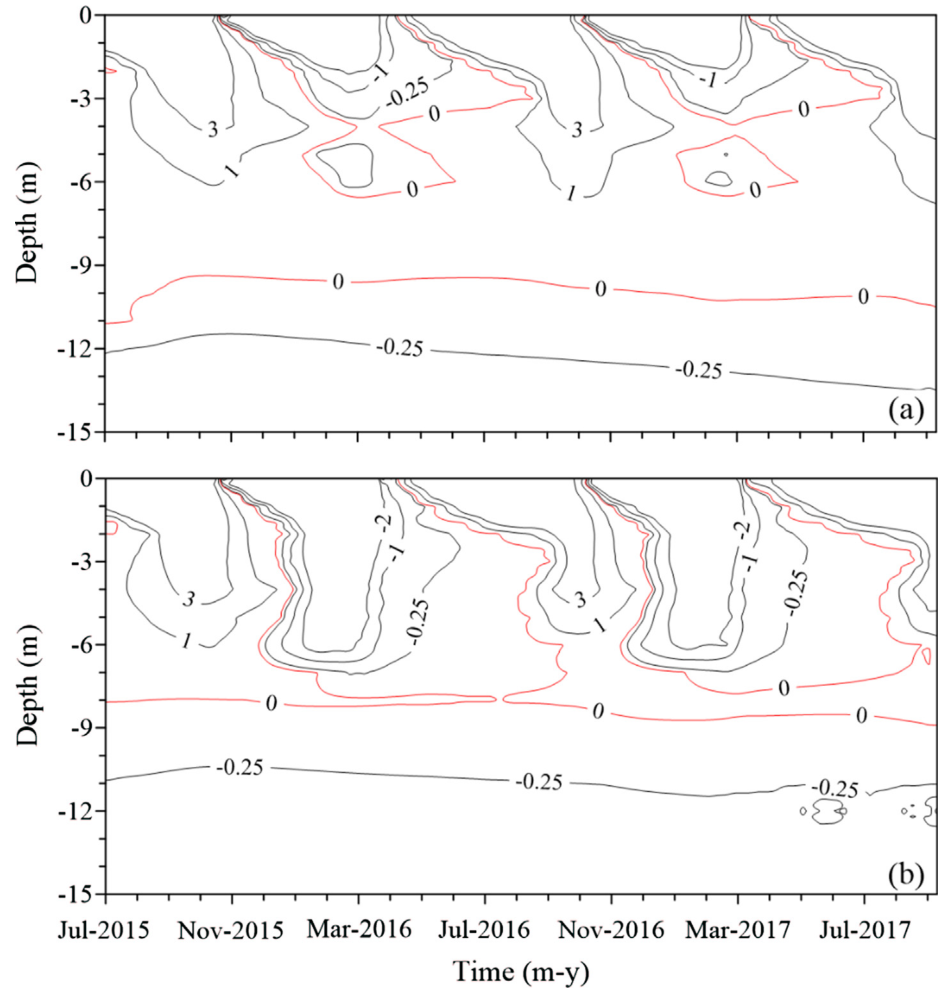

Fig. 8. Ground temperatures as a function of time and depth in boreholes T3 (a) and T7 (b), respectively.

−5.3 m in July 2017 due to the cooling effects of thermosyphons. However, in borehole T9 it gradually deepened from −4.4 m in July 2015 to −6.4 m in July 2017. In addition, the −0.25 °C isotherm in borehole T8 dropped from −10.6 m July 2015 to −12.0 m in July 2017 at a increasing rate of 0.7 m/a, while it raised by 1.6 m (ranging from −9.6 m to −11.2 m) at a rate of 0.8 m/a in borehole T9. The aforementioned results suggested that the thermal disturbed range of the warm pipe was greater than 4.0 m after 6 years of operation, and the cooled range of two pairs of thermosyphons had been above 1.5 m in the lateral direction after 2 winters of operation.

4. Discussion

4.1. *Causes for permafrost thawing under the pipeline*

The soil layers under the uninsulated pipe without a thermosyphon showed a higher temperature and faster thawing rates than those at an adjacent natural site (off-ROW) after the pipeline's construction and operation, which were primarily caused by following factors. Firstly, the construction disturbance related to the ROW clearing and pipeline trenching led to the change in ground temperatures and drainage patterns, resulting in warm or/and thawing of permafrost on ROW [20]. Meanwhile, ground subsidence would inevitably follow thawing because permafrost contained massive ground ice (Fig. 2). Then a great amount of surface water gathered in the settled trench forming water ponding in summer (Fig. 11), which infiltrated to the permafrost table and accelerated thawing [21]. Previous studies have also identified that the undisturbed topsoil was heated by the water percolation due to summer precipitation [22], and the disturbed depth of water infiltration exceeded 3.1 m in the foundation backfill of a power transmission tower foundation in a permafrost terrain [23].

Secondly, the warm oil was the key factor for permafrost degradation on-ROW. The MMOT kept above 0 °C (2–13 °C from 2011 to 2017) in permafrost regions, even in winter (Fig. 4). Therefore, the heat dissipated from the warm pipe continuously entered the underlying permafrost. As a result, the thaw bulb formed around the pipe, and the ground water flowed in thaw bulb in some slope terrains along the pipeline. The flowing ground water increased ground temperature and expanded the size of thaw bulb gradually.

Thirdly, a layer of sand and gravel soil was placed over the settled trench for maintenance. The ground surface temperature was increased by reducing vegetation coverage [21]. In Fig. 5, the permafrost at a natural site was warmed about 0.1 °C from 2014 to 2017, indicating that climate change also resulted in permafrost warming.

As mentioned above, many factors led to permafrost thawing and thaw settlement including ROW vegetation clearing, trenching, warm oil temperature, surface water infiltration, ground water flowing and climate warming. At this monitoring site, the top of the buried pipe declined from −1.6 m (design buried depth in 2011) to −3.0 m during installing of thermosyphons in March 2015. Although a large pipe settlement has occurred in the past 7 years, the pipe is still secure because it had a better flexibility and did not exceed its settlement limits. In addition, the deeper soil layers consisting of the gravel and weathered granite are ice poor and thaw stable, which having a high bearing

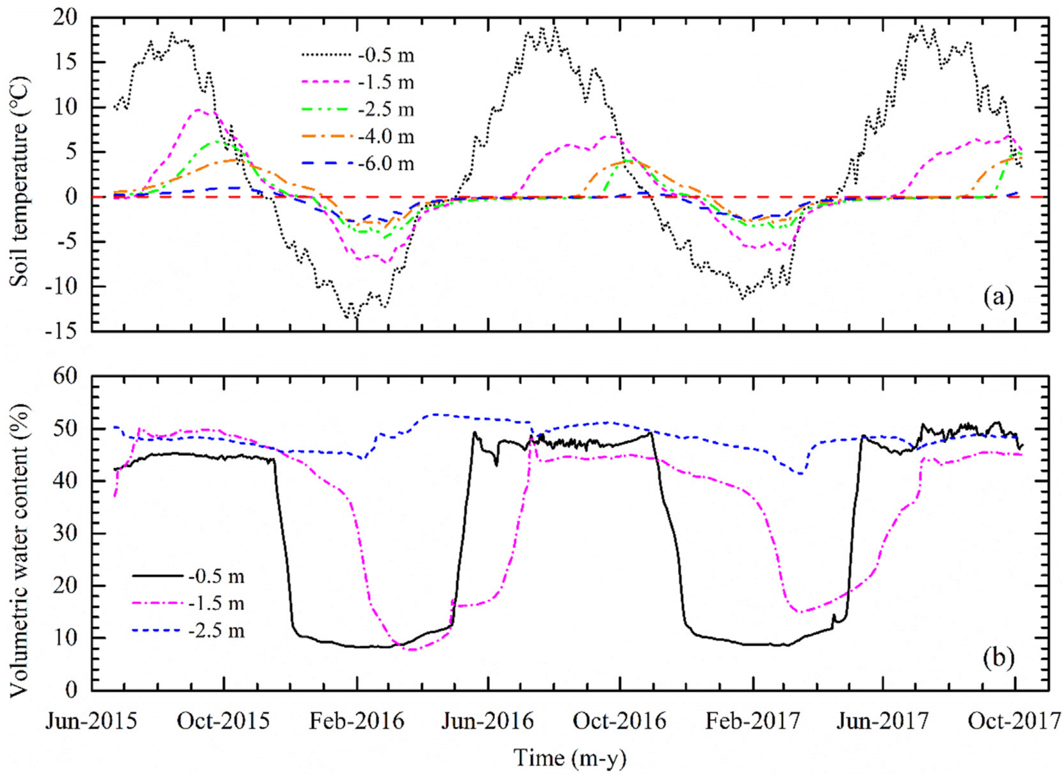

Fig. 9. Time series of soil temperature (a) and volumetric water content (b) at section No. 3.

capacity (Fig. 2). The strain-based design criteria, therefore, should be considered for a larger displacement of pipe [24].

4.2. Reasons for thermosyphons to less cool the underlying permafrost

Concerning the cooling performance of thermosyphons and their influencing factors, the monitored adjacent data proved that they could effectively reduce the ground temperatures around their evaporator section. This finding is meaningful because it offers valuable references for preventing thaw-related hazards along the CRCOP and the other similar permafrost pipelines. However, a thaw bulb still occurred around the pipe even if two pairs of thermosyphons have worked over 2 winters with a small spacing of 1.3 m. The permafrost table has not raised to the expected elevation (Figs. 8 and 10). Therefore, thermosyphons still need more time to cool the soils surrounding the pipe. The long-term monitoring of the cooling performance of thermosyphon is also needed.

In addition, pore water flow in soils can weaken the cooling effect of thermosyphons on underlying permafrost. In Fig. 8b, a thawed layer occurred in borehole T7 0.5 m away from thermosyphons and 2.0 m away from the pipeline. The unfrozen ground water can flow in the thawed layer along the pipeline driven by water head even in winter. The accumulated surface water in trench in summer may infiltrate into the thawing front and carry some heat into soils weakening the cooling effect of thermosyphons. Some investigations have showed that the ground and surface waters carried lots of heat into the underlying permafrost and thawed it [25].

As described above, the cooling effect of thermosyphons depended on number, spacing, water flow and working duration. According to the previous studies, some other factors also affected their cooling effect such as burial depth, inclination angle, working fluid, ratio of condenser length to evaporator length, diameter, climatic conditions (air temperature and wind speed) geological conditions and combination with insulation materials [26–29].

Therefore, the parameters and efficiency of thermosyphons need to be studied further and improved in future to ensure the best cooling effect on permafrost underlying the CRCOP. Correspondingly, the desired ground temperature, the heat from the warm oil pipeline and flowing water in the thaw bulb must be estimated to optimize their design parameters [18,30]. Besides, the stress and deformation of the pipe should be measured to evaluate the pipeline integrity and long-term cooling effects of thermosyphons. For this purpose, some steel rods were mounted on the pipe for settlement observation along the second line of the CRCOP. In addition, some new mitigative methods need to be developed to effectively prevent the permafrost degradation and enhance the stability of pipeline according to the engineering and permafrost characteristics.

5. Conclusions

The cooling performance of thermosyphons on the foundation soils at an instrumented cross section along the CRCOP was analyzed using the measured ground temperatures and volumetric water contents. Some preliminary conclusions are drawn as follows:

(1). The CRCOP operated at year-round positive oil temperature and brought substantial heat into the underlying permafrost, resulting in its warming and thawing. The ALT increased by 2.7 m and the deep (15–20 m) permafrost temperature rose 0.2 °C from 2014 to 2017. The higher oil temperature was the key factor.

(2). Thermosyphons significantly cooled the soils around them in cold seasons, and lowered the developing rate of artificial ALT obviously. Different cooling effects significantly occurred and depended on the number of thermosyphon. Two pairs of thermosyphons had the better cooling effect than one pair for the upper 6-m soil layers with a lower ground temperature and an earlier refreezing date.

(3). The change in volumetric water content was affected and controlled by freezing and thawing in subsurface soils. The thaw bulb surrounding the pipe always existed even though the foundation

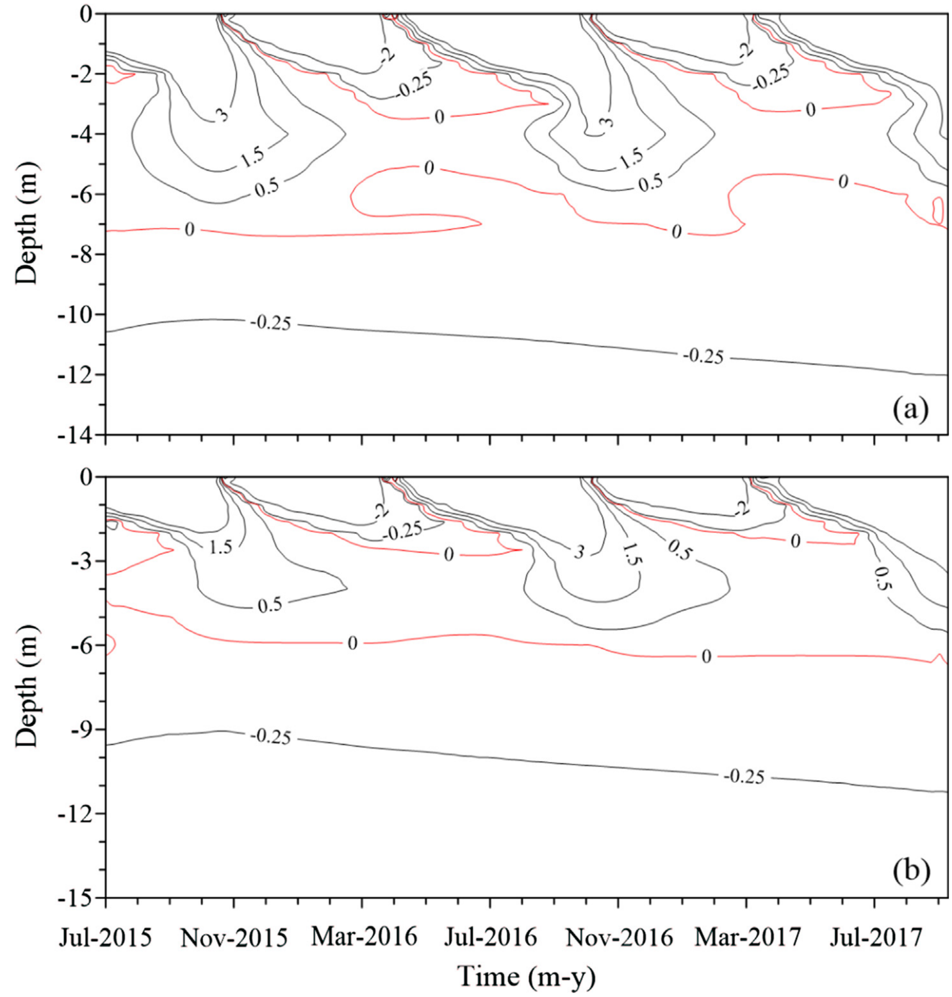

Fig. 10. Ground temperatures as a function of time and depth in borehole T8 (a) 1.5 m away and in borehole T9 (b) 2.5 m away from the thermosyphons at the No. 3 cross section.

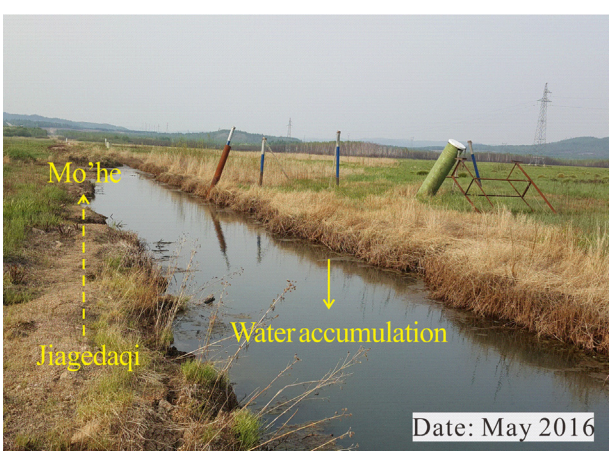

Fig. 11. Water accumulation in the trench in the wetland.

soils were cooled by thermosyphons in winter. The thermally affected region of warm oil pipeline expanded to more than 4.0 m, and the cooled scope of thermosyphons was over 1.5 m in the lateral direction.

Acknowledgements

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