

Article



Proposal of a New Method for Controlling the Thaw of Permafrost around the China–Russia Crude Oil Pipeline and a Preliminary Study of Its Ventilation Capacity

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Abstract: The China–Russia crude oil pipeline (CRCOP) has been in operation for over ten years. Field observation results have shown that a thaw bulb has developed around the CRCOP which expands at a rate of more than $0.8 \text{ m} \cdot a^{-1}$ in depth. In view of the deficits of existing measures in mitigating permafrost thaw, a new control method is proposed based on active cooling. According to the relationship between total pressure loss and the driving force of natural ventilation, the wind speed in a U-shaped air-ventilation pipe around the CRCOP is calculated. By analyzing the theoretical calculation and numerical analysis results, it is found that the influence of thermal pressure difference on the natural ventilation of the structure can be negligible, and the influences of resistance loss along the pipe and local resistance loss in the pipe are similarly negligible. Exhaust elbows greatly improve the ventilation performance of the U-shaped air-ventilated pipe. This study developed a novel structure around warm-oil pipelines in permafrost for mitigating thaw settlement along the CRCOP and other similar projects across the world.

Keywords: China–Russia crude oil pipeline; permafrost engineering; climate warming; thaw settlement; air-ventilated pipe; convective heat transfer

1. Introduction

With the further development and utilization of global oil and gas resources, the number of pipelines has increased at an unprecedented rate. However, when crossing permafrost regions, heat from a warm-oil pipeline is able to thaw permafrost around a pipeline [1]. Since permafrost is extremely sensitive to temperature, the thawing of permafrost around a pipeline may gradually reduce the bearing capacity of the pipeline's foundation [2].

When a pipeline crosses permafrost with different ice content and different geological landforms, differentiated thaw settlement may induce pipeline bending, breakages, and oil leakages. For example, for the Trans-Alaska Pipeline System, severely thawed permafrost in some segments has damaged the stability of the pipeline [3–5]. For the Norman Wells oil pipeline, thaw settlement induced by pipeline construction, water ponding on the right of way (ROW), and high oil temperatures have also threatened its operation. [6,7]. The



Citation: Cao, Y.; Li, G.; Wu, G.; Chen, D.; Gao, K.; Tang, L.; Jia, H.; Che, F. Proposal of a New Method for Controlling the Thaw of Permafrost around the China–Russia Crude Oil Pipeline and a Preliminary Study of Its Ventilation Capacity. *Water* **2021**, *13*, 2908. https://doi.org/10.3390 /w13202908

Academic Editor: Alexander Shiklomanov

Received: 17 August 2021 Accepted: 12 October 2021 Published: 16 October 2021

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). pipeline from Golmud to Lhasa on the Qinghai-Tibet Plateau in China was forced to be reconstructed as the pipeline warped and deformed because of frost heave, thaw settlement, and other disasters in permafrost regions [8]. A number of mitigation measures have been adopted to prevent thaw settlement in previous studies. For example, the input oil temperature was controlled in the Norman Wells oil pipeline in Canada to reduce thermal interaction between pipelines and permafrost [9]. Sawdust was used for thermal insulation on ice-rich steep slopes [9,10]. Other methods for controlling the thaw of permafrost applied in the Norman Wells oil pipeline also included: (1) a shallow buried depth, (2) a small pipeline diameter, (3) clearing the right-of-way in winter before construction, making maximum use of the previous cutlines, and (4) winter construction [9–13]. The Trans-Alaska Pipeline System in the USA was elevated by a thermal vertical support member system with thermosyphons in warm permafrost regions to prevent thaw settlement [4]. There is a better control effect of thawing settlement when the pipeline is elevated, but it has a higher cost [14–16].

Domestic studies in China on pipeline engineering in permafrost regions mainly focus on the China–Russia crude oil pipeline (CRCOP) [17–28]. The CRCOP has been in operation since January 2011, transporting crude oil at normal atmospheric temperature in a closed pipeline. The CRCOP starts from Siberia in Russia and ends in Daqing in China. It is 953 km in length in the Chinese territory, traversing 441 km of discontinuous permafrost in the Mohe–Jagdaqi area and 512 km of seasonally frozen soil (frozen depth > 1.5 m) in the Jagdaqi–Daqing section. It also traverses 119 km of warm permafrost and ice-rich permafrost, as well as 50 km of swamp. The diameter of the pipeline is 813 mm, with a 11.9 mm thickness (for pipelines in permafrost, the thickness ranges from 12.5–17.5 mm), and it has an 8 MPa design pressure. Since the pipeline crosses large areas of forests, wetlands, and villages in the Chinese territory, it is buried at a depth of 1.6–2.0 m to prevent natural disasters like forest fire.

Permafrost along the CRCOP is distributed near the southern boundary of a large permafrost region in Eurasia, which belongs to the ecosystem-protective Xing'anling-Baikal type of permafrost [29]. This type of permafrost is sensitive to environment variations and has low thermal stability [29,30]. At the same time, oil temperature monitoring has indicated that the maximum average monthly oil temperature at Mohe oil station reached 27.74 °C in 2020. In order to monitor the thermal regime of frozen soil around the pipeline in real time and provide early warnings, this article proposes a monitoring system consisting of pipeline–permafrost interactions along the CRCOP.

Additionally, problems of surface subsidence and ground cracks were also found in a geologic survey conducted in October 2011, as shown in Figure 1a. Moreover, water ponding on the ROW (see Figure 1b) was found in another survey in May 2016, which aggravated the risks of thaw-settlement disasters, urging mitigation measures to prevent the further development of thaw settlement.



Figure 1. (a) Natural ground surface subsidence along the CRCOP. (b) Water ponding on the ROW along the CRCOP.

Limitations also existed in previous preventive measures of thaw settlement. For example, the off-ground laying structure of the Trans-Alaska Pipeline System, as mentioned

above, is costly and unable to prevent forest fires. Fire safety is extremely significant for the CRCOP, since it traverses a large area of forests and villages [8]. Besides, insulation layers applied in other counterparts were also found to have limited effectiveness in numerical simulation analyses. Air-ventilation pipes, conducive to permafrost protection, have been widely applied in subgrade engineering in cold regions to improve road stability; however, such technology has not been applied in underground oil pipeline projects [31–35]. In this article, a new structure for pipeline thaw settlement prevention is proposed for the CRCOP. The ventilation capacity is considered a primary index of the convective heat transfer capacity of ventilation pipes in this paper; according to the theory of fluid mechanics, formulas for calculating the ventilation capacity are obtained. The ventilation capacity of the structure is verified, which provides a useful reference for operation optimization of the CRCOP and its counterparts.

2. Field Monitoring of Thermal Regime around the CRCOP

Figure 2 depicts the overall design of the on-site monitoring system, which was located in a patchy permafrost region (50°28′14.23″ N, 124°13′31.75″ E), 600 m to the south of the Jagdaqi pump station. The buried depth of the top of the CRCOP pipeline at this site is 3.0 m. The meteorological data were collected by a small-scale meteorological station (as shown in Figure 2c) developed by Campbell Scientific, Logan, UT, USA. Two boreholes (T1, T2) were made along cross-section 1-1. T1 was located 2 m from the horizontal pipeline center of the CRCOP and located on the ROW. The T2 hole was 16.6 m away from the central line of the pipeline, off the pipeline's ROW, which could be regarded as a borehole at an undisturbed site that does not experience the effects of the pipeline's heat. As shown in Figure 2b, there were 25 thermistor sensors (TS1–TS25) at T1 and T2, accordingly. The thermistor sensors (uncertainty \pm 0.05 °C) were developed by State Key Laboratory of Frozen Soil Engineering, and real-time data were collected every four hours by a Campbell Scientific datalogger CR3000.



Figure 2. The monitoring system for CRCOP–permafrost interactions. (a) Layout (b) Ground temperature sensors in boreholes. (c) Small-scale meteorological station layout.

Figure 3 depicts the ground temperature–depth profiles of boreholes T1 and T2 in cold seasons and warm seasons. It can be concluded from Figure 3a that, owing to pipeline heat, the ground temperature of T1 was remarkably higher than that of T2 in

cold seasons. Additionally, there was a thawing interlayer whose thickness was increasing during pipeline operation. It can be concluded from Figure 3b that the seasonal thawing depth of the T1 hole was significantly greater than that of T2 in warm seasons. The shaded area in red represents the thawed permafrost layer caused by pipeline heat in warm seasons, and it gradually increases with time. Figure 4 shows the variation process of the seasonal thawing depth of holes T1 and T2 with time in warm seasons, indicating the seasonal thawing depth of hole T1 has increased year by year in warm seasons but that, for hole T2, this value remained about 2 m. The seasonal thawing depth of hole T1 was 5.8 m in 2014, and 9.9 m in the warm seasons of 2019, with an average growth rate of 0.82 m \cdot a⁻¹. The buried depth of the pipeline top was 3.0 m in this area, and the thawing depth of hole T1 below the pipeline bottom reached about 6 m. The rapid thawing speed of permafrost around the pipeline brought great risks to its safe and stable operation; accordingly, protection and measures were required urgently to strengthen sections that experienced severe thawing and subsidence. Consequently, a new U-shaped air-ventilated pipe structure is proposed here based on this behavior. In the following section, theoretical and numerical analyses of the ventilation capacity of the U-shaped air-ventilated pipe structure are performed, which may provide a specific reference for its subsequent design and application.



Figure 3. Ground temperature-depth profiles of borehole T1 and T2 in (**a**) cold seasons and (**b**) warm seasons. The rectangles in grey represent the thawing interlayer in cold seasons, and the rectangles in red represent the thawed permafrost layer in warm seasons.



Figure 4. The seasonal thawing depth of holes T1 and T2 versus time.

3. Proposal of a New Control Method to Determine the Ground Thermal Regime

A new structure for pipeline thaw settlement prevention is proposed from the perspective of active cooling, which can be used not only for ground cooling around the pipeline but can also function as an underground support part for the pipeline. Its structure and working principle are illustrated in Figure 5, whose two main components, the support structure and the U-shaped air-ventilated pipe, are described in the following.



Figure 5. Schematic diagram of the proposed horizontal U-shaped air-ventilated pipe. (**a**) Axial side view and (**b**) sectional drawing.

The support structure is used for supporting the buried pipeline, which is composed of a supporting plate and four supporting legs (Figure 5). CRCOP is located on the supporting plate. The supporting legs, connected to the lower part of the supporting plate, lay in permafrost and are conducive to preventing pipeline settlement when the permafrost starts to thaw.

The U-shaped air-ventilated pipe (the cooling structure), shown in Figure 5b, is installed on the support plate for cooling. Dual elbows of the air-ventilated pipe are placed at different heights and the dual principles of cooling are adopted under different circumstances. On one hand, convection is mainly driven by thermal pressure (which varies in different dual elbows) when the wind speed is low. On the other hand, when the wind speed is high, the air intake elbows have a positive pressure and the air extraction elbows have a negative pressure; thus, forced convection is mainly driven by wind pressure. Additionally, a section of horizontal straight pipe was placed on both the air inlet and the outlet of U-shaped ventilated pipe for wind collection.

The two structures mentioned above perform collaboratively for thaw-settlement prevention. To meet different site requirements, such as different wind speeds and geological conditions, the structures could be combined with insulation layers to achieve a better cooling effect. An automatic temperature-control shutter (ATCS) made of a phase-change alloy was added to the mouth of the U-shaped ventilated pipe, as shown in Figure 6. The ATCS closes when the temperature exceeds 0 °C to ensure that hot air cannot enter the U-shaped ventilated pipe, thereby protecting the permafrost around the pipeline from thermal erosion. When the temperature is below 0 °C, the ATCS can open to ensure convective heat transfer between air in the pipe and any permafrost around the pipe, with which the surrounding air temperature could be fully utilized by the U-shaped ventilated pipe to achieve a better cooling effect [36].



Figure 6. Schematic diagram showing the cooling effect of the U-shaped air-ventilated pipe in (**a**) warm seasons and (**b**) cold seasons.

4. Theoretical Calculation of the Wind Speed in the U-Shaped Ventilated Pipe

Through convective heat transfer by cold air in the pipe, the U-shaped ventilated pipe takes away the heat of permafrost to achieve the purpose of ventilation and cooling. Since the ATCS is closed in the warm seasons, only the wind speed in the pipe when the shutter is open is analyzed. A simplified calculation diagram of the wind speed in the pipe is shown in Figure 7, where L1 and L2 are straight pipes in the horizontal section. According to the total pressure loss between the air inlet and outlet of the U-shaped air-ventilated pipe and the driving force of natural ventilation, the internal wind speed can be calculated.



Figure 7. Simplified calculation diagram for the U-shaped air-ventilated pipe.

4.1. Total Pressure Loss Calculation

The total pressure loss consists of two parts, as shown in Equation (1) [37]:

$$P_W = \sum P_y + \sum P_i \tag{1}$$

where P_W is the total pressure loss, $\sum P_y$ indicates the summed resistance loss along the U-shaped air-ventilated pipe, and $\sum P_i$ represents the summed local resistance loss of the U-shaped air-ventilated pipe.

4.1.1. Calculation of Resistance Loss along the Pipe

The resistance loss along the U-shaped air-ventilated pipe is shown in Equation (2) [37]:

$$P_{yi} = \frac{1}{2} \lambda_i \frac{l_i}{d} \rho_a u^2 \tag{2}$$

where P_{yi} is the resistance loss along the pipe, λ_i represents the coefficient of resistance loss along the pipe, and l_i indicates the pipe length.

Since the Reynolds number is $R_e = \frac{ud}{v} > 2000$, the air in the pipe flows in a turbulent state. Consequently, the coefficient of resistance loss along the pipe should be calculated, as shown in Equation (3):

$$\lambda_i = 0.11 \left(\frac{\zeta}{d} + \frac{68}{R_e}\right)^{0.25}$$
(3)

where *u* is the average wind speed in the U-shaped air-ventilated pipe, ζ indicates the equivalent roughness of the U-shaped pipe wall, and *v* represents the dynamic viscosity coefficient of the air in the pipe. By combining Equations (2) and (3), the resistance loss in the pipes can be obtained [37,38].

4.1.2. Local Resistance Loss

The local resistance loss of the U-shaped air-ventilated pipe is shown in Equation (4):

$$P_i = P_{i1} + P_{i2} (4)$$

where P_i is the total local resistance loss in the U-shaped air-ventilated pipe, P_{i1} represents the local resistance loss at the air inlet and elbow, and P_{i2} demonstrates the local resistance loss of the air outlet of the U-shaped air-ventilated pipe.

1

Local Resistance Loss at the Air Inlet and Elbow

The local resistance loss at the air inlet and elbow of the U-shaped air-ventilated pipe is shown in Equation (5):

$$P_{i1} = \frac{1}{2}\xi_i \rho_a u^2 \tag{5}$$

where ξ_i is the local resistance loss coefficient. Four 90° elbows, each of which has a curvature radius of 1.5 times the diameter and a local resistance coefficient of about 0.17, are distributed in four places in the U-shaped ventilation pipe structure. Besides, the entrance of the U-shaped vent pipe is regarded as a circular section with a diameter of *d* reduced from the infinite plane, and the local resistance loss coefficient can be taken as 0.5, accordingly [37].

Local Resistance Loss at the Air Outlet

The local resistance loss of the air outlet is shown in Equation (6):

$$P_{i2} = P_{i1} + \frac{1}{2}\rho_a u^2 \tag{6}$$

where $\frac{1}{2}\rho_a u^2$ is the dynamic pressure loss. The local resistance loss of the air outlet consists of the dynamic pressure loss and the local resistance loss calculated by Equation (5). Additionally, the local resistance loss coefficient of the air outlet of the U-shaped air-ventilated pipe is taken as 0.5 [37].

4.2. Calculation of Structure Driving Force for Natural Ventilation

The driving force of natural ventilation in the U-shaped air-ventilated pipe consists of two parts, as shown in Equation (7):

$$P_F = P_{FH} + P_{FW} \tag{7}$$

where P_F is the driving force of natural ventilation in the U-shaped air-ventilated pipe, P_{FH} is the thermal pressure difference and P_{FW} is the wind-pressure difference. Both the two constitute the total pressure difference between the inlet and outlet of the U-shaped air-ventilated pipe. The thermal pressure difference P_{FH} and the specific composition of the wind-pressure difference P_{FW} are introduced below.

4.2.1. Thermal-Pressure Difference Calculation

The thermal pressure difference is caused by the inconsistent air density inside and outside the U-shaped air-ventilated pipe, where a greater air-density difference will lead to a greater height difference between the air inlet and outlet elbow, and a greater thermal pressure difference. The specific calculation is shown in Equation (8):

$$P_{FH} = (\rho_0 - \rho_a) gh_1 \tag{8}$$

where P_{FH} is the thermal differential pressure, ρ_0 is the air density in the pipe, ρ_a represents the air density outside the pipe, *g* depicts the acceleration of gravity, and h_1 is the height difference between the air inlet elbow and air outlet elbow of the U-shaped air-ventilated pipe (as shown in Figure 7).

4.2.2. Wind-Pressure Difference Calculation

Since the U-shaped air-ventilated pipe is equipped with an air inlet elbow and an air exhaust elbow, the different directions of the two result in a wind-pressure difference, which provides the driving force for natural ventilation of the U-shaped air-ventilated pipe structure as [37]:

$$P_{FW} = \rho_0 \left| K_1 (V_1 cos \beta)^2 - K_2 V_2^2 \right|$$
(9)

where K_1 and K_2 are the wind-load shape coefficients of the air inlet and outlet, V_1 and V_2 are the wind speed of air inlet and outlet, respectively, and β is the angle between the wind and the air inlet of the U-shaped air-ventilated pipe [37].

4.3. Calculation of the Wind Speed in the Pipe

According to the equivalent relationship between the total pressure loss and the pressure difference on both sides, the internal wind speed can be calculated as:

$$P_W = P_F \tag{10}$$

where P_W represents the total pressure loss between the air inlet and outlet of the U-shaped air-ventilated pipe and P_F is the driving force of natural ventilation in the U-shaped air-ventilated pipe.

Through the analysis shown in Sections 4.1 and 4.2, by combining Equations (1)–(10), the wind speed in the pipes can be calculated by Equation (11):

$$u = \sqrt{\frac{\rho_0 \left[K_1 (V_1 \cos \beta)^2 - K_2 V_2^2 \right] + 2 \left(\rho_0 - \rho_a \right) g h_1}{\rho_a \left(1 + \sum_{i=1}^n \xi_i + \frac{\lambda \sum_{i=1}^n l_i}{d} \right)}}$$
(11)

5. Ventilation Performance Analysis of the U-Shaped Air-Ventilated Pipe

5.1. Calculation Parameters and Boundary Conditions

The CRCOP was adopted in this study to verify the ventilation performance of the U-shaped air-ventilated pipe. Through the k- ε model of the computational fluid dynamics module in the finite-element software, the wind speed in the U-shaped air-ventilated pipe was calculated using the finite-element method. The wind-speed boundary conditions were determined using data obtained by small meteorological monitoring stations arranged at Jagdaqi along the CRCOP (as shown in Figure 2c) and were calculated according to Equations (12) and (13). The geometric model of the numerical simulation is shown in Figure 8.

$$V_{x/1.5} = 1.52 + 0.43 \sin\left(\frac{2\pi t_h}{8760}\right) \tag{12}$$



Figure 8. Geometric model used in the numerical calculations.

According to the power law of wind profiles in atmospheric surface layers [32], the variation law of wind speed in the height direction is shown below:

$$V_{x/y} = V_{x/1.5} \left(\frac{y}{1.5}\right)^{\alpha}$$
 (13)

where $V_{x/1.5}$ and $V_{x/y}$ are the wind speed in the *x* direction at heights of 1.5 m and *y* above the ground surface, respectively [32]; α is the power law exponent, and it can be taken as 0.16 by the field test.

According to the theoretical calculations and analysis of the wind speed in the U-shaped air-ventilated pipe given in Equation (11), and compared with the numerical simulation results, the correctness of both results was verified. The calculated parameters produced by both methods are shown in Table 1.

Diameter of U-Shaped Ventilation Pipe (m)	Curvature Radius (m)	Length of the Horizontal Section (m)	Air Inlet Height (m)	Dynamic Viscosity Coefficient of Air (Pa·s)	Equivalent Roughness Rate (mm)	Air Density (kg⋅m ⁻³)	
0.219	0.3285	0.2	1.8	$1.81 imes 10^{-5}$	0.046	Air in pipe	Air outside pipe
						1.2201	1.228

Table 1. Calculated parameters.

5.2. Comparative Analysis of the Theoretical Calculation and Numerical Simulation Results

Figure 9 depicts a comparison of the theoretical calculation results and numerical calculation results. It can be seen that they are basically consistent. In particular, when the wind speed is small, the difference is also small; meanwhile, larger wind speeds lead to slightly increasing differences.



Figure 9. Comparative analysis of the theoretical calculation results and numerical calculation results.

To conclude, the consistent overall trends of the two show that the theoretical calculation and numerical simulation results in this study meet the accuracy requirements, and the theoretical calculations can be suitably used to evaluate the cooling and ventilation capacity of the U-shaped air-ventilated pipe.

5.3. Influence of the Thermal-Pressure Difference and Exhaust Elbow on the Wind Speed in the Pipe

Figure 10 shows wind-speed variation curves in the pipe without considering thermal pressure differences or the effects of the exhaust elbow. When ignoring the thermal pressure difference, the average wind speed in the pipe is almost consistent with the theoretical wind speed, indicating that the impact of the thermal pressure difference has little effect on the wind speed.



Figure 10. Variation law of the wind speed as a function of different influencing factors.

Moreover, without the exhaust elbow, the wind speed is obviously lower than the theoretical wind speed, because the wind-load shape coefficient of the air outlet is different. Without the exhaust elbow, in the high wind speed season, the wind speed in the pipe decreases by about 20%, while in the season with low wind speeds, the difference between the two is only about 15.4%.

5.4. The Influence of Resistance along the Pipe and Local Resistance on the Wind Speed in the Pipe

Figure 11 presents wind-speed-time variation curves obtained by theoretical calculations without considering resistance loss along the pipe or local resistance loss. When ignoring local resistance loss and resistance loss along the pipe, both simulated wind speeds are greater than the theoretically calculated values. In seasons with high wind speeds, the wind speed without considering local resistance loss is slightly higher than when the along-way resistance loss is ignored. During the low wind speed season, the wind speeds of the two are basically consistent. The impact of local resistance loss on the wind speed in pipe is slightly greater than that of resistance loss along the pipe, which is caused by numerous U-shaped air-ventilated pipe bends and relatively few straight pipe sections, resulting in a slightly large local resistance loss.



Figure 11. Annual variation of wind speed considering resistance loss along the pipe and local resistance loss.

5.5. Influence of the Pipe Diameter and Horizontal Section on the Wind Speed in the Pipe

Figure 12 shows the influence of the U-shaped air-ventilated pipe diameter and horizontal section length on the wind speed in the pipe at the maximum wind speed. The wind speed in the pipe increases with an increase of pipe diameter, and the growth rate increases first and then decreases. When the pipe diameter is increased to 0.3 m, the average wind speed in the pipe increases to $1.06 \text{ m} \cdot \text{s}^{-1}$, and when the pipe diameter is increased to 0.5 m, the maximum wind speed is $1.12 \text{ m} \cdot \text{s}^{-1}$. Accordingly, in the design of the U-shaped air-ventilated pipe, and considering the convenience of installation and construction, its diameter should not exceed 0.3 m.



Figure 12. Analysis of the variation law of the maximum wind speed in the U-shaped air-ventilated pipe as a function of the (**a**) pipe diameter and (**b**) horizontal section length.

Figure 12b depicts a variation curve of the wind speed in the U-shaped air-ventilated pipe as a function of the horizontal section length. Because an increase in the horizontal section length increases the overall resistance loss along the pipe, the wind speed decreases as the horizontal section length increases. In the absence of any horizontal sections, the average wind speed in the pipe is about $1 \text{ m} \cdot \text{s}^{-1}$. Consequently, when designing the U-shaped air-ventilated pipe, the horizontal section length should be minimized as possible, where an ideal length is about 0.1 m.

6. Conclusions

The CRCOP has been in operation for over 10 years [22]. Disasters such as surface subsidence and ponding in pipe trenches have occurred in some areas. A comprehensive permafrost thermal state monitoring system has been established in the Jagdaqi area along the CRCOP to provide real-time early warning for the safe and stable operation of the pipeline. In order to solve the problems associated with pipeline thawing and subsidence, a composite structure consisting of a U-shaped air-ventilated pipe, which takes into account the underground pipeline support and provides cooling and temperature reduction of

the permafrost around the pipeline, was proposed in this work. Regarding the CRCOP as the research topic, and using the wind-speed boundary conditions monitored on site, theoretical and numerical analyses of the U-shaped air-ventilated pipe were conducted. Based on the results of these analyses, the following conclusions are drawn.

- In 2014, the seasonal thawing depth near the pipeline in Jagdaqi along the CRCOP reached 5.8 m; in 2019, the seasonal melting depth near the pipeline reached nearly 10 m. This represents a growth rate of about 0.84 m·a⁻¹, threatening the safe and stable operation of the pipeline;
- (2) The U-shaped air-ventilated pipe structure has a good ventilation capacity. Wind-pressure difference is the driving force for the natural ventilation of the U-shaped air-ventilated pipe structure. Since the density differences between the inside and outside of the pipe are little, the effect of the thermal pressure difference on the ventilation in the U-shaped air-ventilated pipe is negligible.
- (3) The effect of local resistance loss on the ventilation in the pipe is similar to that of resistance loss along the pipe. This similarity is mainly due to the numerous bends along the U-shaped air-ventilated pipe.
- (4) In the design of the U-shaped air-ventilated pipe, and considering the convenience of installation and actual requirements, the pipe diameter is recommended to be about 0.3 m. Since the horizontal section of the U-shaped vent pipe will lead to increased resistance loss along the pipe, resulting in a reduction of the average wind speed in the pipe, the horizontal section length of the U-shaped vent pipe should be reduced as possible, where an ideal length is about 0.1 m.

Author Contributions: Conceptualization, Y.C.; methodology, Y.C.; software, Y.C.; validation, Y.C. and G.W.; formal analysis, Y.C.; investigation, Y.C., G.W., D.C., K.G., L.T., H.J. and F.C.; resources, G.L.; data curation, G.L.; writing—original draft preparation, Y.C.; writing—review and editing, Y.C.; visualization, G.W.; supervision, G.L.; project administration, G.L.; funding acquisition, G.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA2003020102), the National Natural Science Foundation of China (No. 41672310) and the Research Project of the State Key Laboratory of Frozen Soils Engineering (Nos. SKLFSE-ZY-20 and SKLFSE201913).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Acknowledgments: We are grateful for grants from the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA2003020102), the National Natural Science Foundation of China (No. 41672310) and the Research Project of the State Key Laboratory of Frozen Soils Engineering (Nos. SKLFSE-ZY-20 and SKLFSE201913).

Conflicts of Interest: The authors declare no conflict of interest.

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