NUMERICAL ANALYSIS OF TEMPERATURE FIELDS AROUND THE BURIED ARCTIC GAS PIPELINE IN PERMAFROST REGIONS

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Based on one planned arctic natural gas pipeline engineering which will cross continuous, discontinuous, sporadic and non-permafrost areas from north to south, with different pipeline temperatures set, a thermal model of the interaction between pipeline and permafrost is established to investigate the influence of pipelines on the freezing and thawing of frozen soil around pipeline and thermal stability of permafrost. The results show that different pipeline temperatures influence the permafrost table greatly. Especially in discontinuous permafrost areas the permafrost table is influenced in both positive temperature and negative temperature. The warm gas pipeline of 5 ℃ could decrease the value of permafrost table about 1 to 3 times pipe diameter and aggravate the degradation of permafrost around pipeline; -1 ℃ and -5 ℃ chilled gas pipeline can effectively improve the permafrost table and maintain the temperature stability of frozen soil , but the temperature of soils below pipeline of -5 ℃ decreases obviously, which may lead to frost heave hazards. In terms of thermal stability around pipeline, it is advised that transporting temperature of -1 ℃ is adopted in continuous permafrost area; in discontinuous permafrost area pipeline could operate above freezing in the summer months with the station discharge temperature trending the ambient air temperature, but the discharge temperature must be maintained as -1 ℃ throughout the winter months; in seasonal freezing soil area chilled pipeline may cause frost heave, therefore pipeline should run in positive temperature without extra temperature cooling control.

Key words: natural gas pipeline;permafrost;coupled thermal-hydraulic modeling;pipe-soil heat exchange;numerical simulation;chilled transporting processes

1. Introduction

Permafrost regions, including arctic shelf and northern parts of North America and Siberia, are rich in natural gas resources. Oil and gas exploration, development and ensued pipeline construction have received increasingly more attention. The conventional techniques for pipeline design, construction and operation are facing great challenges in permafrost regions. The geological environment along the pipelines in permafrost areas is complex and the operation of buried pipeline has a great influence on the hydrothermal state of frozen soil around it, and the hydrothermal state change of frozen and melted soil directly affects its physical and mechanical properties, threatening the overall stability and structural integrity of the pipeline[1, 2]. Due to the differences in geological conditions, types of permafrost and landforms, the freezing-thawing process of the soil around the pipeline has significant non-uniformity, which determines the difference in the frost heaving and thawing of the soil. Pipeline, as linear project, will inevitably traverse different freeze-thaw deformation transition zones, and may be damaged due to excessive deformation caused by differential frost heave or thaw settlement [3, 4].

For crude oil pipeline, the key scientific questions are focused on the impacts of the heated pipeline on the thermal regimes of permafrost and series of creative and innovative designs such as thermosyphons for reducing thaw settlement were adopted in Trans-Alaska Oil Pipeline engineering. Being different from oil pipeline, gas pipelines in permafrost regions will face new problems and challenges in many areas because of different transporting media, gas flow temperature control and environmental protection.The most dangerous hazards would be potential differential frost heave and its impacts on pipeline deformation and integrity. There were examples such as frost heaving of the buried Norman Wells Pipeline in September 1997 and deformation of the Products Oil Pipeline from Golmud, Qinghai Province to Lhasa, Tibet Autonomous Region, China in June 2002 [5, 6]. Permafrost is one of the key components in the cryosphere, and is very sensitive to temperaure changes and anthropogenic disturbances. In order to put forward mitigation of frost hazards of buried gas pipeline in regions of frozen ground, the analysis of temperature field around the pipeline is the first step. There is one planned arctic natural gas pipeline engineering which will cross continuous, discontinuous, sporadic and non-permafrost areas from north to south. This article aims at establishing specific pipeline operating temperature ranges in three typical regions to prevent frost heave of the pipeline and long-term degradation of permafrost through numerical analysis. It is hoped that this new approaches can be inspired and envisioned for gas pipeline engineering in arctic and alpine permafrost regions.

2. Pipe-soil heat transfer calculation

2.1. Conventional methodology

Currently, closed-form analytical solution typically used in conventional hydraulic simulations are not an accurate representation of pipeline that is buried in permafrost and soils that are subjected to freeze and thaw cycles. Incongruously, the analytical solutions use a variety of simplied assumptions including soil having invariant soil thermal conductivity with no water/ice phase change, and an invariant “far-field” ambient soil temperature. These simplifications result in inaccurate pipe temperature predictions, which may have important consequences for arctic pipeline design where phase change and ground surface boundary conditions play a great role in governing pipe gas flow temperature [7].

2.2. Non-commercial software

Lacking any commercially available thermal-hydraulics modeling tools, several previous arctic pipeline projects developed their own thermal-hydraulics models to accurately predict flowing gas temperature. TransCanada PipeLines Ltd. (TCPL) developed a hydraulic simulator, Tempflo, which has been used and validated over the last 25 years. Northern Engineering and Scientific (NES) developed TQUEST, a state-of-the-art finite element heat transfer model for one, two and three dimensional heat transfer. However because of commercial considerations most of software mentioned above are proprietary to the private companys or parties participating into specific arctic pipeline designs or management [8, 9,10].

3. Model setup

In order to assess the thermal effect of pipelines on the freezing and thawing of frozen soil around pipeline and thermal stability of permafrost in continuous, discontinuous, sporadic and non-permafrost areas, a commercially available finite-element program COMSOL Multiphysics 5.4 was used.

3.1. Mathematical model

The thermal interaction between pipeline and frozen soil is an unsteady heat transfer process with phase transition. The differential control equation for temperature field is shown in Eq.(1).

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)=\rho C\frac{\partial T}{\partial t} \tag{1}$$

Where T is temperature. t is time variable. x and y are spatial variables. C is volumetric heat capacity of the soil. λ is thermal conductivity of soil. ρ is density of soil.

The heat capacity and thermal conductivity of the frozen and melted soil are different, and the severe phase transition of the frozen soil is mainly concentrated in a certain temperature range [$T_m \pm \Delta T$]. The expression of heat capacity and thermal conductivity are shown in Eq.(2) and Eq.(3).

$$C=\begin{cases} C_f & T<T_m-\Delta T \\ \dfrac{L}{2\Delta T}+\dfrac{C_u+C_f}{2} & T_m-\Delta T\le T\le T_m+\Delta T \\ C_u & T>T_m+\Delta T \end{cases} \tag{2}$$

$$\lambda=\begin{cases} \lambda_f & T<T_m-\Delta T \\ \lambda_f+\dfrac{\lambda_u-\lambda_f}{2\Delta T}\left[T-\left(T_m-\Delta T\right)\right] & T_m-\Delta T\le T\le T_m+\Delta T \\ \lambda_u & T>T_m+\Delta T \end{cases} \tag{3}$$

Where C_f and C_u represent the volumetric heat capacity of the materials at negative and positive temperatures, respectively. λ_f and λ_u are the thermal conductivity at negative and positive temperatures, respectively.

3.2. Domain geometry and material properties

Based on the planned arctic natural gas pipeline engineering which will cross continuous, discontinuous, sporadic and non-permafrost areas from north to south, with different pipeline temperatures set, a thermal model of the interaction between pipeline and permafrost was established. One-half of the study profile was used to reduce the computational effort because of the symmetry of the model shown as Fig. 1. In general, the pipeline with diameter 1016mm is to be buried 0.9 m deep along the route. Take numerical computational domain for continuous permafrost areas as an example, the upper layer, which consists of silty clay, is 0.5 m thick in the model. The layer of fine-grained soil in the model is 14.5 m thick. The vertical depth of the model is therefore 15m below the original ground surface. The horizontal width of the model extends 15 m perpendicular to the pipe axis. Fig. 1 shows the entire geothermal modeling domain representing the typical ROW cross-section described above. The highest temperature gradients within the modeling domain are near the pipe and downward from the ground surface. In these areas, a higher node/element mesh density was used. A constant snow thermal conductivity was used for all analyses. The physical parameters of the various typical soils for the model are summarized in Tab. 1.

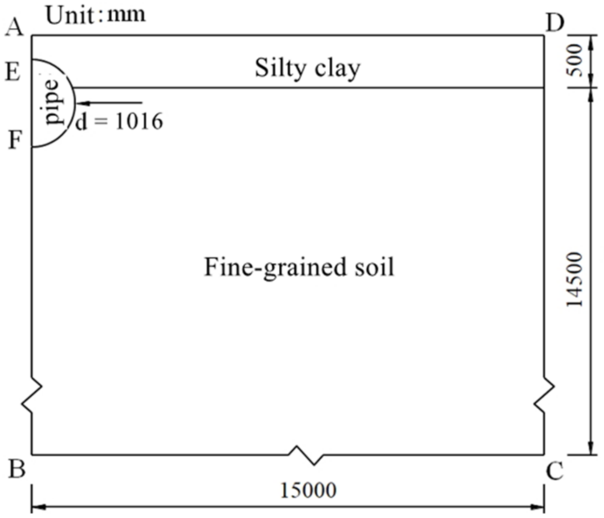


Fig.1 Numerical computational domain for continuous permafrost areas

Tab.1 Physical parameters of the various typical soils used for the proposed model

Parameter	ρ (kg/m^3)	w(%)	λ_f W/(m·K)	λ_u W/(m·K)	C_f J/(m^3·K)	C_u J/(m^3·K)	L (J/m^3)
Silty clay	170	500	1.20	0.4	2.30×10^6	3.89×10^6	283.9×10^6
Fine-grained soil	1300	30	2.21	1.13	1.92×10^6	2.87×10^6	152.0×10^6
Snow	250	-	$2.9\rho^2$	-	2.09ρ	-	-

3.3. Boundary conditions

3.3.1 Climate data

According to the actual air temperatures observed at meteorological stations, the air temperatures in the continuous, discontinuous, seasonal frozen ground areas can be expressed as sine functions using Matlab tools. The effect of climate warming were taken into account in the predictions and simulations. The air temperature along the route was assumed to warm by 0.02 °C per year according to numerous observations and projections from the past years. Three sine functions representing continuous, discontinuous, seasonal frozen ground areas are shown as Eq.(4), Eq.(5) and Eq.(6).

$$T = -10.89 - 15.61\sin\left(\frac{2\pi \mathrm{t}}{8760} + 1.01\right) + \frac{0.02\mathrm{t}}{8760} \tag{4}$$

$$T = -0.18 - 30.41\sin\left(\frac{2\pi \mathrm{t}}{8760} + 0.2\right) + \frac{0.02\mathrm{t}}{8760} \tag{5}$$

$$T = 3.89 + 10.97\sin\left(\frac{2\pi \mathrm{t}}{8760} + 1.36\right) + \frac{0.02\mathrm{t}}{8760} \tag{6}$$

3.3.2 Upper boundary condition

The upper boundary condition was set as the convective heat transfer between the ambient air and the natural ground surface, and the effect of the adherent layer and the insulation effect of snow cover were both considered. The coefficient of convective heat transfer between the ambient air and the natural ground surface was selected as 18 W/($\mathrm{m}^2 \cdot \mathrm{K}$).

3.3.3 Lower boundary conditon

A small temperature gradient 0.003 ℃/m was included at the bottom boundary. In addition, the geothermal heat flux is very small relative to the net heat flux from energy exchange at the ground surface.

3.3.4 Site boundary condition

The side boundaries are far enough away from the thermal disturbance of the ROW that there is no horizontal heat transfer at the sides of the modeling domain. The side boundaries were zero-flux boundaries.

3.3.5 Initial ground temperature

Long-term ground temperatures, as characterized by mean annual ground temperature (MAGT), are a result of heat energy exchange across the ground surface boundary. The initial temperature can be gained using a long-term numerical simulation according to the above boundary conditions without considering the effect of the climatic warming. In this paper, the initial temperature field was obtained by 100-year computation.

3.3.6 Pipe temperature boundary condition

Pipe temperature boundary conditions should be obtained from hydraulics modeling. On the pipeline, significant Joule-Thomson cooling can occur as a result of gas pressure losses along the pipeline. To assess the effect on 30-year thaw or freezing depths on the pipe, three pipe temperature bounding cases 5 °C, -1 °C and -5 °C were considered. For convenience the relatively warm pipe temperatures at 5 °C, the relatively cold pipe temperatures at -1 °C and the relatively chilly pipe temperatures at -5 °C will be referred to as “warm pipe” , “cold pipe” and “chilly pipe”, respectively. The coefficient of convective heat transfer between the gas and the pipe wall was selected as 450 W/(m^2·K) .

3.3.7 Model validation

The geothermal model was calibrated such that it would reproduce appropriate soil temperature in undisturbed terrain. Take continuous permafrost area as an example. Fig. 2 show that the actual temperature agrees well with the analytic solutions. Therefore the forecast model and analysis system are sufficiently accurate to predict the temperature distribution along the pipeline route, and meet the requirement for engineering design.

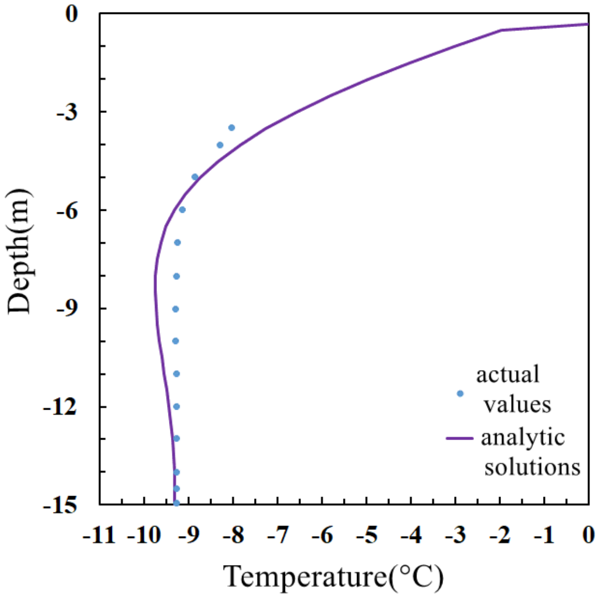


Fig.2 Comparison between actual values and analytic solutions

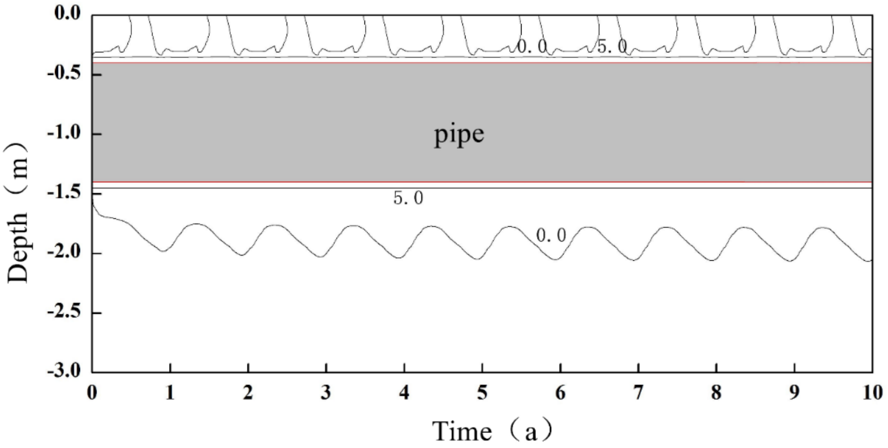
4. Results and discussion

4.1. Continuous permafrost area

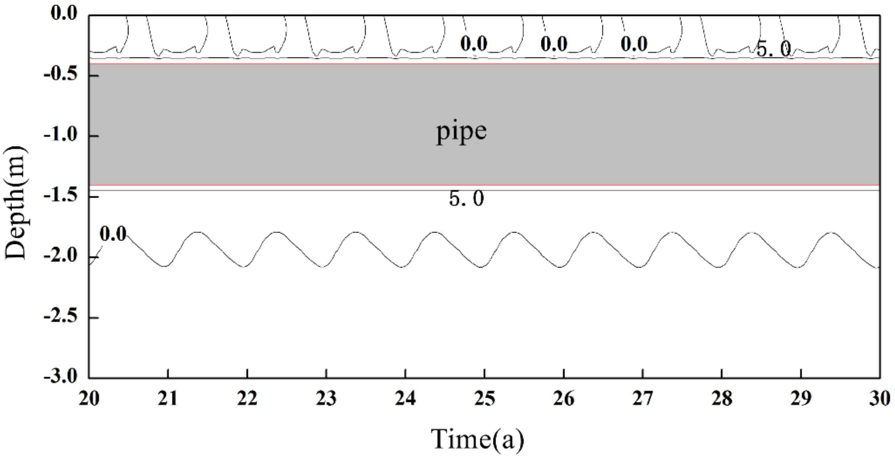
In continuous permafrost area the permafrost table of undisturbed terrain was calculated as 0.15 m and the whole pipe was below the active layer. The ground temperature on January 1 was selected as the initial ground temperature field, and the pipeline temperature was set to 5 ℃, -1 ℃ and -5 ℃ successively. Considering global warming, the thermal interaction calculations between pipe and soil for 30 years were conducted.

The ground temperature profiles in depths with different pipeline temperatures are shown as

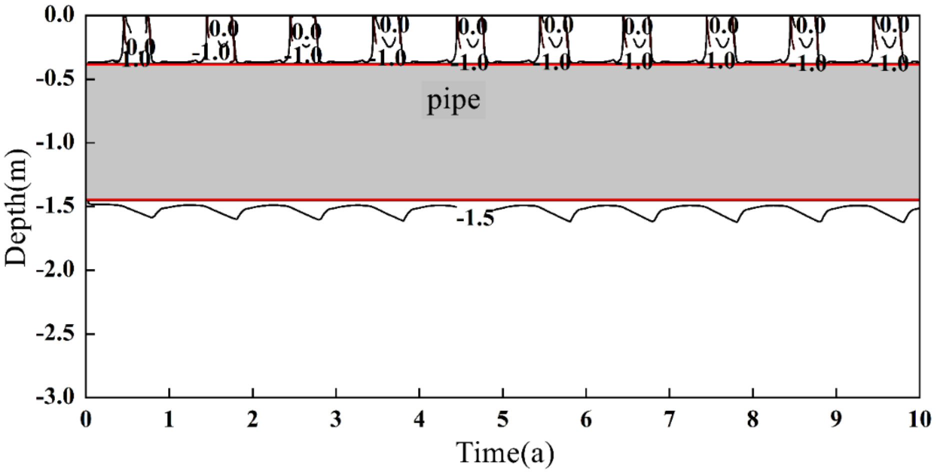
Fig. 3. The red line represents the position of the top and bottom of the pipe, and the gray filler represents the section of the pipe. According to Fig. 3 (a) and (b) for warm pipe case, high pipe temperature had great influence on the soil under the pipeline which was always in a positive temperature state, and the melting range kept increasing. In the 10th year, the melting depth of permafrost reached to 2.0 m, between the 20th year to 30th year, the melting tended to flatten and in the 30th year, the melting depth reached to 2.2 m. Under the combined action of the external air temperature and the pipe temperature, the active layer above the pipe deepened to about 0.3 m compared with the natural ground. As shown in Fig. 3 (c) and (d), for cold pipe case the soil temperature above the pipe was not affected obviously. The soil under the pipeline was always in a negative temperature state, and the ground temperature at the depth of 1.50 m has been maintained at about -1.5 ℃ for 10 years. It can be seen that when the pipeline temperature is -1 ℃, the frozen soil temperature was less affected. As shown in Fig. 3 (e) and (f), for chilly pipe case the soil temperature around the pipe decreased obviously and the depth of active layer reduced to 0.12 m. The influence of pipe temperature on soil was stronger than that of ambient air temperature. The soil under or above the pipe were always in a negative temperature state, and the ground temperature at the top and bottom of pipe maintained at about -5 ℃. In addition, Fig. 3 indicated that, no matter whether the pipe was at positive temperature or negative temperature, the temperature distribution of the soil above the pipe reached the stable state in the first 10 years, while the temperature distribution of the soil under the pipe needed longer time to reach the stable state.



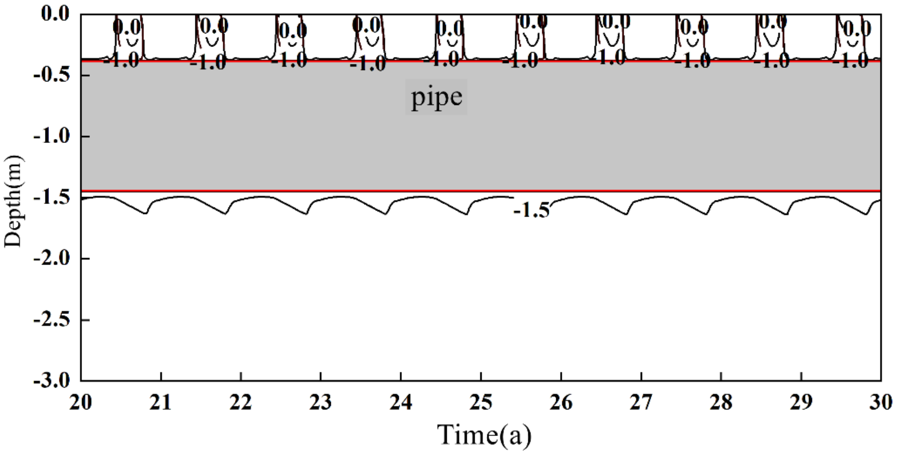
(a) PT=5.0 ℃, 0-10 a



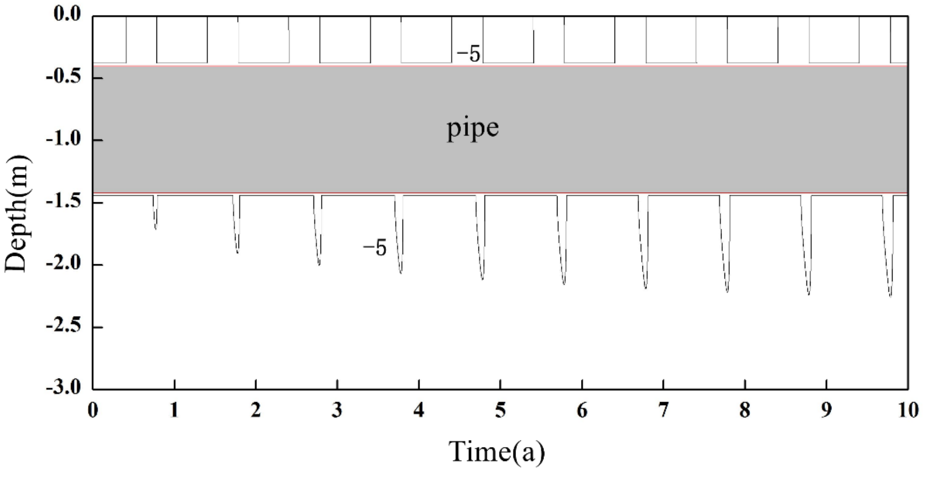
(b) PT=5.0 ℃, 20-30 a



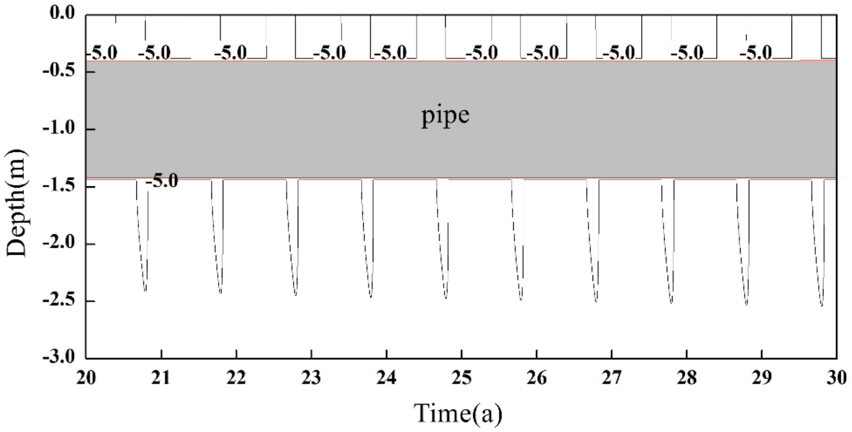
(c) PT=5.0 ℃, 0-10 a



(d) PT=5.0 ℃, 20-30 a



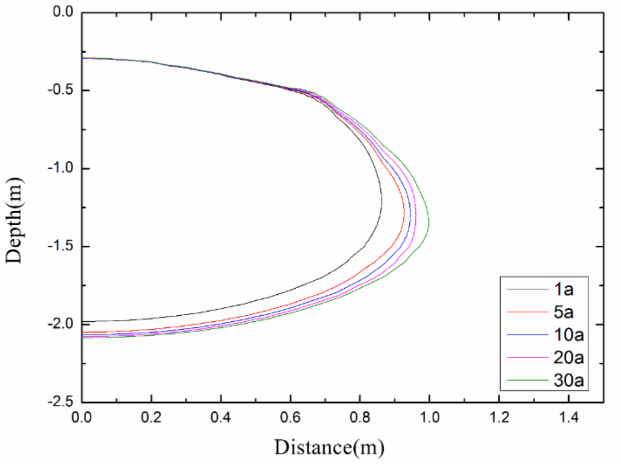
(e) PT=5.0 ℃, 0-10 a



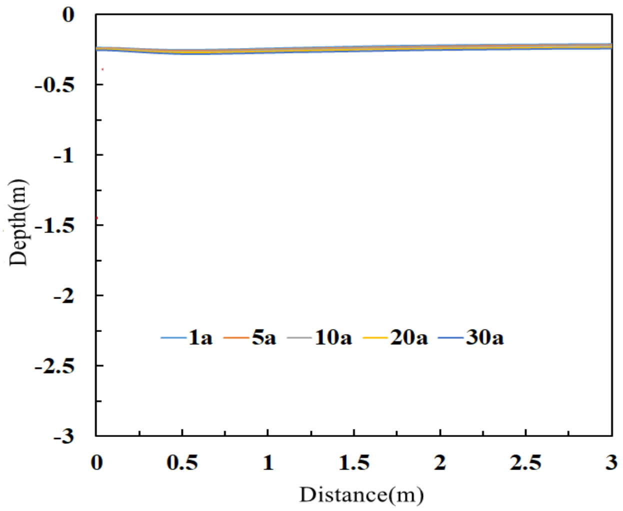
（f）PT=5.0 ℃, 20-30 a

Fig. 3 The ground temperature profiles in depths with different pipeline temperatures

Fig. 4 depicts the expected long-term thaw or freezing depths on the pipe in the continuous permafrost terrain under different pipe temperature after thermal modeling. As shown in Fig. 4(a), for warm pipe case, along with time, the melting depth of permafrost gradually deepened, reaching 2.2 m in the 30th year, and the melting depth has exceeded the bottom of the pipe. Compared with the natural permafrost, the melting depth has deepened by 2.05 m, which is about twice the diameter of the pipe. The thaw affected zone extended horizontally about 0.5 m beyond the edge of both sides of the pipe. The maximum melting depth of the pipe occured in the refreezing season, when the surface layer of the frozen soil was in the freezing state, while the soil around the pipe was in the melting state. As shown in Fig. 4(b), when the pipe temperature was -1 ℃, the maximum melting depth near the pipe did not reach the top of the pipe within 30 years, and the artificial permafrost table was maintained at about 0.24 m. Compared with the natural ground, permafrost table was reduced by about 0.09 m due to the pipeline operation, and the whole pipe was still under the active layer. Tab. 2 shown that the time when the soil refreezed to the artificial permafrost table. Obviously, the time when the frozen soil refreezed to the permafrost table was the same every year (around late August), indicating that when the pipeline temperature was -1 ℃, the pipeline operation has little influence on the frozen soil.



(a)PT=5.0 ℃



(b)PT=-1 ℃

Fig. 4 Thawing and freezing front with different pipeline temperatures

Tab.2 Depth of the artificial permafrost table with corresponding time (PT=-1 ℃)

Time	1 a 236 d	5 a 236 d	10 a 236 d	20 a 236 d	30 a 236 d
Depth	0.23 m	0.24 m	0.24 m	0.25 m	0.25 m

4.2. Results summary

Depth of the artificial permafrost table with different pipeline temperatures in continuous permafrost area and discontinuous permafrost area and freezing front with different pipeline temperatures in seasonal frozen soil area are summaried in Tab. 3 and Tab. 4.

Tab.3 Depth of the artificial permafrost table with different pipeline temperatures (m)

Parameters	Depth of natural permafrost table (m)	Pipe temperature (℃)	1 a	10 a	20 a	30 a
Continuous permafrost area	0.15	5.0	1.9	2.0	2.2	2.2
		-1.0	0.24	0.24	0.24	0.24
		-5.0	0.12	0.12	0.12	0.12
Discontinuous permafrost area	1.64	5.0	2.5	3.5	4.0	4.4
		-1.0	0.37	0.37	0.37	0.37
		-5.0	0.32	0.32	0.32	0.32

Tab.4 Depth of freezing front with different pipeline temperatures(m)

Parameters	Depth of freezing front (m)	Pipe temperature (℃)	Location	1 a	10 a	20 a	30 a

Seasonal frozen soil area	1.30	5.0	pipe above	0.1	0.1	0.1	0.1
			pipe below	-	-	-	-
		-1.0	pipe above	0.4	0.4	0.4	0.4
			pipe below	2.4	2.8	2.8	2.8
		-5.0	pipe above	0.2	0.2	0.2	0.2
			pipe below	2.8	3.9	4.0	4.0

5. Conclusion

Some preliminary conclusions can be drawn on the basis of the above numerical simulations and discussions.

(1) In the arctic region, due to the great difference in atmospheric environment temperature, the active layer of natural ground in the continuous permafrost area is 0.15 m in depth, while the one in the discontinuous permafrost area is 1.64 m in depth. Because the pipeline is located within active layer in the discontinuous permafrost area, the operation of the pipeline will greatly affect the permafrost table.

(2) In the continuous permafrost area, the cold gas pipeline with -1 ℃ can effectively protect the permafrost, causing little disturbance to the permafrost environment. The warm gas pipeline with 5 ℃ positive temperature aggravates the permafrost degradation process, resulting in an increase of permafrost table. Compared with the pipe temperature with -1 ℃, the -5 ℃ pipe temperature can effectively increase the artificial permafrost talbe, however, the temperature of the soil decreases significantly, which may lead to the occurrence of frost heaving hazards. In the seasonal frozen soil area, the cold gas pipeline will cause the freezing of the soil around the pipeline which will affect the safe operation of the pipeline and the permafrost environment.

(3) Through a large number of numerical simulation analysis, the basic control line of the pipeline operating temperature in each frozen region is basically determined. It is recommended to adopt -1 ℃ for continuous permafrost area. In the discontinuous permafrost area, the temperature of

-1 ℃ is adopted in winter, and the discharge temperature of the compressor station can be close to the atmospheric temperature in summer. In seasonal frozen soil areas, it is suggested pipeline run without extra temperature cooling control.

(4) From the perspective of time dimension, the freezing-thawing disaster is concentrated in the early stage of pipeline operation. In this stage, deformation monitoring of the pipeline should be carried out. From the perspective of regional dimension, the disasters are concentrated in the transition zone of permafrost in the discontinuous permafrost region.

Nomenclature

T −temperature, [℃]

t −time, [s]

C −volumetric heat capacity of the soil, [℃]

C_f −volumetric heat capacity of the materials at negative temperatures, [J/m^3·K]

C_u −volumetric heat capacity of the materials at positive temperatures, [J/m^3·K]

λ_f −thermal conductivity at negative temperatures, [W/(m·K)]

λ_u −thermal conductivity at positive temperatures, [W/(m·K)]

ρ −density of soil, [kg/m^3]
L −latent heat of phase change, [J/m^3]
w −mass water content, [%]

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