Proceedings of IWHT2013
2nd International Workshop on Heat Transfer Advances for Energy Conservation and Pollution Control
October 18-21, 2013, Xi'an, China

IWHT2013-013

Numerical simulation for coupling of temperature and water fields of frozen soil around buried oil pipeline in cold regions

Yu Zhao[1], Bo Yu[1,*], Guojun Yu[1], Wang Li[2]

1. National Engineering Laboratory for Pipeline Safety, Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, Beijing, 102249, P.R. China
2. PetroChina Southwest Pipeline Company, Chengdu, 610041, P.R. China

* Corresponding author: +86-10-89733849 (Tel & Fax), yubobox@vip.163.com (E-mail)

Abstract

Buried pipelines are one of the most economical and convenient methods for the transportation of large volume of crude oil, but when a pipeline goes through the cold regions, it may suffer severe frost damage. In this study, through establishing the governing equations of temperature and water fields for porous frozen soil, the water-heat coupled problem of frozen soil around buried hot oil pipeline in cold regions is systematically studied by means of numerical simulation. The temperature field, water content field and water migration diagram of frozen soil under different pipeline operation period can be obtained by pure heat conduction model and water-heat coupling model respectively. The present study also illustrates the influence of water field on temperature field of frozen soil as well as crude oil temperature along the pipeline. It can be concluded from the simulation results that it is the coupled interaction of temperature distribution and water migration that determine the ultimate status of frozen soil. The biggest water migration occurs in the soil area close to the buried oil pipeline where there is the largest gradient of temperature. And the change of thermal properties caused by the water migration turns out to be one of the most important factors affecting the temperature field of frozen soil.

Keywords: Frozen soil, Buried oil pipelines, Temperature field, Water field, Coupling

Nomenclature

c_o	Heat capacity of the crude oil [J/(kg·℃)]
c_j	Heat capacity of the jth layer, including insulation layer, steel wall and wax layer [J/(kg·℃)]
c_s	Heat capacity of the soil [J/(kg·℃)]
c_i	Heat capacity of the ice [J/(kg·℃)]
c_w	Heat capacity of the water [J/(kg·℃)]
D	The inner diameter [m]
f	Darcy friction coefficient
g	Gravity acceleration [m/s^2]
H_0	Pipeline buried depth [m]
H	Thermal influence region in the y-direction [m]
k	Permeability of the soil [m^2]
L	Half of thermal influence region in the x-direction [m]
L_i	Latent heat of water-ice phase change [J/kg]
P	Average pressure along the pipeline [Pa]
p	Moisture migration driving pressure [Pa]
q_0	Heat flux density of the crude oil along the pipeline [W/m^2]
r	Radial direction [m]
T_o	Temperature of the crude oil [℃]
T_j	Temperature of the jth layer, including insulation layer, steel wall and wax layer [℃]
T_s	Temperature of the soil [℃]
T_a	Temperature of the atmosphere [℃]
T_0	Temperature of the pipe inner wall [℃]
T_n	Temperature of the constant temperature layer [℃]
T_b	Freezing temperature of water in soil [℃]
T_p	Thawing temperature of ice in soil [℃]
u	Velocity of unfrozen water in the x-direction [m/s]
v	Velocity of unfrozen water in the y-direction [m/s]
V	Average velocity of the oil flow [m/s]
x	Horizontal direction [m]
y	Vertical direction [m]
Δz	Grid spacing in the axial direction [km]

α_a	Heat transfer coefficient at the ground surface [W/(m^2·℃)]
α_0	Heat transfer coefficient of the pipe flow [W/(m^2·℃)]
β_o	Expansion coefficient of the crude oil [℃$^{-1}$]
β_w	Expansion coefficient of the water [℃$^{-1}$]
θ	Circumferential direction
λ_j	Thermal conductivity of the jth layer, including insulation layer, steel wall and wax layer [W/(m·℃)]
λ_s	Thermal conductivity of the soil [W/(m·℃)]
λ_i	Thermal conductivity of the ice [W/(m·℃)]
λ_w	Thermal conductivity of the water [W/(m·℃)]
μ	Dynamic viscosity of unfrozen water [Pa·s]
ρ_o	Density of the crude oil [kg/m^3]
ρ_j	Density of the jth layer, including insulation layer, steel wall and wax layer [kg/m^3]
ρ_s	Soil density [kg/m^3]
ρ_i	Ice density [kg/m^3]
ρ_w	Water density [kg/m^3]
τ	Time [s]
ϕ	Porosity of the soil
φ	Water content in the soil pore
φ_0	Initial water content in the soil pore

1 Introduction

China is the third-biggest frozen soil country in the world where the distribution areas of permafrost and seasonal frozen soil occupy about 21.5% and 53.5% of the total area of the country respectively [1]. With the rapid development of international cooperation in oil and gas exploitation and utilization, taking advantage of the buried pipeline has already become the most important way of oil and gas transportation. However, when the underground pipelines go through the cold regions, the thaw and heave of frozen soil under the thermal effect of crude oil pipeline and ambient atmosphere may pose a serious threat to the safe operation of the pipeline [2-4].

The thawing and heaving process of frozen soil is a result of combined interactions between the temperature and water fields. In the whole process, there are complex heat exchanges between the frozen soil and buried oil pipeline as well as the atmosphere. To be specific, because the temperature of crude oil in the pipeline is usually higher than that of the surrounding soil, the heat input would increase the soil temperature and melt the ice in the porosity into liquid water. The phase change of solid ice and subsequent moisture migration under temperature gradient might have significant effects on the temperature and water distributions within the frozen soil. At the same time, due to the change of water content, thermal and physical properties of frozen soil, such as thermal conductivity and specific heat, also differ from the original values and would affect the heat transfer process directly [5]. Based on the above statements, it can be concluded rationally that the temperature and water fields influence each other and it is the coupling effect that determine the final status of frozen soil around buried hot oil pipeline in cold regions. Thus studying the coupling mechanism of temperature and water fields comprehensively has important practical significance to the construction and safe operation of hot oil pipeline buried in cold regions.

Since the late 1950s, the Soviet Union, North America, Northern Europe and other countries began the systematic research on the frozen soil. But most of the studies at that time based on the assumption that the soil contains almost no water, and the negligence of the influence deriving from the phase change and moisture migration limited the further applications of these research results. From then on, the effect of water field started to receive more attention among researchers. Penner [6], Williams [7] and Miller et al. [8] respectively carried out effective researches on the heat transfer and mass flow in the frozen soil, and put forward some complete theories. It is worth noting that in the year of 1973, Harlan [9] proposed the mathematical model of heat and mass transfer during the freezing of soil which made the study of frozen soil enter a new stage. Harlan's model firstly coupled the temperate and water fields through describing the moisture migration within the soil. On the basis of Harlan's work, Ling et al. [10] and Lai et al. [11] came up with the driving force of moisture migration in terms of water head and took the influence of water flow on the soil temperature into consideration. Flerchinger et al. [12] established the one-dimensional water-heat coupling model in the vertical direction which illustrated various influential factors involved in the process. Besides that, some researchers further put forward the mathematical model considering the effect of salt concentration in frozen soil [13]. In 1990s, scholars from home and abroad carried out more in-depth studies about the coupling of temperature and water fields in frozen soil, then extended the theoretical conclusions to solve various frost damage problems, for instance, roadbed, concrete dam and tunnel built in cold regions [14-18].

To the best knowledge of the present author, there are only a few reports in literatures about the coupling of temperature and water fields of frozen soil around buried hot oil pipeline in cold regions. Liang et al. [19] studied the temperature field of soil around the cold oil pipeline by means of numerical simulation, but when the pipeline is used to transport hot oil, the influence of oil temperature on the surrounding frozen soil can't be ignored. Zhang et al. [20] compared the temperature and water fields of frozen soil in various environments, but his research didn't consider the effect of moisture migration. Lu et al. [21] studied the heat transfer for a pipeline filled with crude oil in soil saturated with water during pipeline shutdown in winter and the results deeply reflected the coupling mechanism of temperature and water fields. Unfortunately, this numerical analysis didn't cover the situation of normal operation of hot oil pipeline.

Based on the previous research results, the present paper treats the frozen soil as one kind of porous media and implements numerical analysis for coupling of temperature and water fields in frozen soil during normal running of buried hot oil pipeline. Through comparing the calculation results obtained by pure heat conduction model and water-heat coupling model respectively, the paper describes the interaction mechanism between the two different fields and tries to figure out the crucial factors affecting the temperature of frozen soil and crude oil along the pipeline. The results of this study would offer beneficial guidance to the design, construction, operation and management of hot crude oil pipelines buried in cold regions.

2 Mathematical model & numerical method

2.1 Mathematical model

For the buried hot oil pipeline going through the cold regions, the complete description of the whole thermal system, which involves the oil transported inside the pipeline, surrounding frozen soil and ambient atmosphere etc., should contain the convective heat transfer of the oil in the pipeline, the heat conduction of wax layer, steel wall and insulation layer as well as the heat transfer in the frozen soil saturated with ice and water. This paper would obtain the oil temperature distribution along the selected oil pipeline and the corresponding temperature and water fields of frozen soil through numerical simulation. In the process, the balance of heat flux is used to couple the convective heat transfer in the pipeline and the soil heat conduction.

For simplicity of establishing and solving mathematical models, the following assumptions are proposed before the analysis: (1) the oil temperature at the cross-section of pipeline is assumed to be uniform, that is to say, the oil temperature is only the function of time and axial position; (2) according to the literature and engineering experience [22], the thermal influence region of the hot crude oil pipeline is within 10m, then the computational domain can be defined as shown in Fig. 1, where $-10m \le x \le 10m$ and $-10m \le y \le 0m$; (3) the axial temperature drop of frozen soil is small enough to be neglected, thus the heat transfer in the soil area can be assumed to be two-dimensional; (4) the soil anisotropy outside the pipelines is simplified as isotropy; (5) the moisture migration in the soil satisfies the Darcy law of seepage and the loss and supplement of water within the computational domain are not taken into consideration; (6) the water content change is thought to have no effect on the structure strength of frozen soil, that is to say, the shape of soil remains the same during the operation of pipeline; (7) the thermal properties, like heat conductivity, of the saturated frozen soil skeleton particles are assumed to be unchanged in the whole thawing and heaving process.

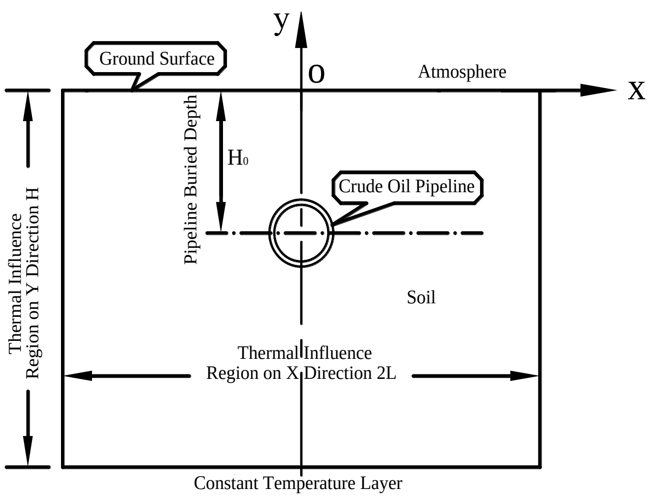


Fig. 1 Sketch of the buried hot crude oil pipeline

2.1.1 Governing equations for crude oil

Based on the assumptions listed above, the heat transfer equation of the oil flow in the pipeline can be obtained as follows:

$$c_o \frac{\mathrm{d}T_o}{\mathrm{d}\tau} - \frac{T_o}{\rho_o}\beta_o \frac{\mathrm{d}P}{\mathrm{d}\tau} - \frac{fV^3}{2D} = -\frac{4q_0}{\rho_o D} \tag{1}$$

where q_0 represents the heat flux transferring from the pipeline to the surrounding frozen soil in order to couple the heat transfer between the crude oil in the pipeline and the outside frozen soil.

2.1.2 Governing equations for wax layer, pipeline wall and insulation layer

$$\rho_j c_j \frac{\partial T_j}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_j r \frac{\partial T_j}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda_j \frac{\partial T_j}{\partial \theta}\right) \qquad j = 1,2,3 \tag{2}$$

Boundary condition:

$$\text{At } r = D/2, \ \lambda_1 \frac{\mathrm{d}T_1}{\mathrm{d}r} = -\alpha_0 \left(T_o - T_0\right) \tag{3}$$

2.1.3 Governing equations for frozen soil

2.1.3.1 Pure heat conduction model

If the moisture migration and latent heat of phase change are not taken into consideration, we can get the pure heat conduction model of frozen soil as follows:

$$\frac{\partial}{\partial \tau}\left[(\rho c)_s (1-\phi) T_s + (\rho c)_m \phi T_s\right] = \frac{\partial}{\partial x}\left(\lambda_m \frac{\partial T_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_m \frac{\partial T_s}{\partial y}\right) \tag{4}$$

where the density, specific heat and thermal conductivity in Eq. (4) are given by:

$$(\rho c)_m = (1-\varphi_0)(\rho c)_i + \varphi_0 (\rho c)_w \tag{5}$$

$$\lambda_m = (1-\phi)\lambda_s + \phi(1-\varphi_0)\lambda_i + \phi\varphi_0\lambda_w \tag{6}$$

where ϕ is the porosity of frozen soil, φ_0 is the original water content in the soil pore and λ_m is the comprehensive coefficient of thermal conductivity which remains unchanged during the calculation process without regard to the influence of water field.

2.1.3.2 Water-heat coupling model

According to the modern theory of frozen soil, the water field would change the temperature field to some extent. On one hand, the migration of moisture carries the heat with water flow and affects the soil temperature through natural convection. On the other hand, the water content change during the migration process would give rise to the change of thermal properties of frozen soil, such as heat conductivity and specific heat which have direct impact on the temperature field of frozen soil. Thus it is quite necessary to take the moisture migration and water distribution into account in order to obtain the water-heat coupling model as follows:

$$\frac{\partial}{\partial\tau}\left[(\rho c)_s(1-\phi)T_s+(\rho c)_m\phi T_s\right]+(\rho c)_w\varepsilon\left[\frac{\partial(uT_s)}{\partial x}+\frac{\partial(vT_s)}{\partial y}\right] \quad (7)$$
$$=\frac{\partial}{\partial x}\left(\lambda_m\frac{\partial T_s}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_m\frac{\partial T_s}{\partial y}\right)+\phi L_i\rho_i\frac{\partial(1-\varphi)}{\partial\tau}$$

where the density, specific heat and thermal conductivity in Eq. (7) are given by:

$$(\rho c)_m=(1-\varphi)(\rho c)_i+\varphi(\rho c)_w \quad (8)$$

$$\lambda_m=(1-\phi)\lambda_s+\phi(1-\varphi)\lambda_i+\phi\varphi\lambda_w \quad (9)$$

where s, w and i represent soil, water and ice respectively, and L denotes the latent heat of ice-water phase change. It is worth emphasizing again that, Eq. (6) and Eq. (9) only hold the feasibility when the porosity of saturated frozen soil is fulfilled with ice and water meanwhile the thermal properties of soil skeleton particles, ice and water keep constant in the thawing and heaving process.

As shown in Eq. (7), the second term in the left hand of the formula reflects the influence of water field on temperature field of frozen soil. To get the velocity distribution of unfrozen water in soil, it needs to supplement the mass conservation equation and momentum conservation equation for unfrozen water in the porosity of soil as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (10)$$

$$\frac{\rho_w}{\varepsilon}\left[\frac{\partial(u)}{\partial\tau}+\frac{1}{\varepsilon}\frac{\partial(uu)}{\partial x}+\frac{1}{\varepsilon}\frac{\partial(uv)}{\partial y}\right]=\frac{1}{\varepsilon}\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{1}{\varepsilon}\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)-\frac{\partial p}{\partial x}-\frac{\mu}{k}u$$
$$\frac{\rho_w}{\varepsilon}\left[\frac{\partial(v)}{\partial\tau}+\frac{1}{\varepsilon}\frac{\partial(vu)}{\partial x}+\frac{1}{\varepsilon}\frac{\partial(vv)}{\partial y}\right]=\frac{1}{\varepsilon}\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{1}{\varepsilon}\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)-\frac{\partial p}{\partial y}-\frac{\mu}{k}v-\rho_w g\beta_w\Delta T_s-\rho_w g$$
$$(11)$$

In Eq. (7) and Eq. (11), the parameter ε is defined as:

$$\varepsilon=\phi\varphi \quad (12)$$

where φ is the water content in the porosity of soil and k stands for the soil permeability.

Due to the surface energy between frozen soil particles, not all the liquid water changed into solid ice and there remains certain amount of unfrozen water in the porosity of soil. The unfrozen water is not only the source of moisture migration in frozen soil but also the crucial parameter to affect the heat transfer performance of soil. According to the literature [1], the unfrozen water content φ keeps dynamic balance with the negative temperature of frozen soil and its value can be expressed and calculated as follows:

$$\varphi=\begin{cases}a|T_s|^{-b} & T_s<T_b\\ c|T_s|+d & T_b\le T_s<T_p\\ 1.0 & T_s\ge T_p\end{cases} \quad (13)$$

where $|T_s|$ is the absolute value of negative soil temperature, a, b, c and d are the empirical factors related to the soil properties. T_b and T_p represent the freezing point of water and thawing point of ice in the soil. Based on the relevant literatures and geological survey of China-Russia Crude Oil Pipeline (CRCOP), the present paper selects one kind of sandy soil, whose porosity is 0.3 and permeability is 3×10^{-11}m^2, to study. For this kind of soil, T_b, T_p, a, b, c and d are set to be -0.24℃, -0.02℃, 0.3917, 0.5541, -0.6195 and 1.0123 respectively. When the soil temperature is below the freezing point, the unfrozen water content presents exponential declining trend along with the temperature drop. And when the soil temperature lies between the freezing point and thawing point, the unfrozen water content has an approximate linear relationship with the negative soil temperature. After the soil temperature exceeds the thawing point, the porosity of soil is thought to be fulfilled with liquid water, in other words, $\varphi=1.0$.

Boundary conditions and initial conditions:

$$\text{At } y=0,\ u=v=0,\ \lambda_s\frac{dT_s}{dy}=\alpha_a(T_a-T_s) \quad (14)$$

$$\text{At } y=-H,\ u=v=0,\ T_s=T_n \quad (15)$$

$$\text{At } x=\pm L,\ u=v=0,\ \frac{\partial T_s}{\partial x}=0 \quad (16)$$

$$\text{When } \tau=0,\ u=v=p=T_s=0 \quad (17)$$

It is worth pointing out that since the loss and supplement of water in frozen soil are not taken into account, the velocity boundary conditions are all set to be 0 which is equivalent to assuming the moisture only migrates within the given area of frozen soil. In practice, the rainfall and snowfall in cold regions would increase the water content in the soil, and it is also quite possible that water in frozen soil flows in a larger area. In this paper, these influential factors are not considered.

2.2 Numerical method

Considering the symmetry of soil area, take half of the area as the computational domain and establish the geometric model on it. An Advancing Front Method (AFM) is used to generate the unstructured triangular grids for the computational domain (as shown in Fig. 2). The whole domain is divided into many non-overlapping grids and each grid corresponds to one node. Because there is always large gradient of temperature near the oil pipeline, denser grids are deployed around the pipeline so as to increase the numerical accuracy in the following calculation. The temperature distributions and variation of natural convection with time are obtained by solving the model utilizing the SIMPLE algorithm based on collocated unstructured grid.

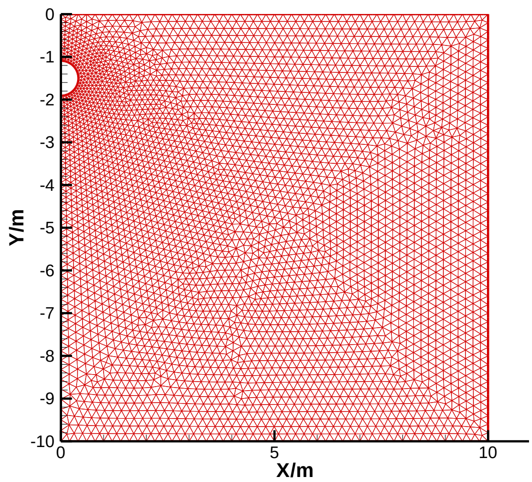


Fig. 2 Unstructured grids of the frozen soil

Figure 3 shows the grids used in the axial direction of the pipeline. The method of thermal characteristic line is employed to describe the unsteady flow and obtain the oil temperature distribution along the pipeline. The heat transfer between hot oil pipeline and surrounding frozen soil is coupled by means of balancing the release and adsorption of heat along the interface in an iterative procedure.

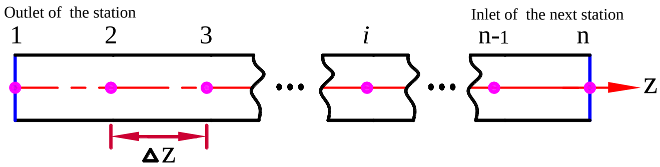


Fig. 3 Grids of the pipeline

3 Computation and result analysis

3.1 Temperature and water fields of frozen soil

In order to compare the calculation results of pure heat conduction model and water-heat coupling model, a typical hot crude oil pipeline and corresponding parameters are first selected and listed below. That is, the outer diameter of the crude oil pipeline is 813mm and the thickness of the steel wall is 11mm. The length of the pipeline is 100km from the outlet of one pumping station to the inlet of next pumping station; the buried depth of pipeline is 1.5m; the temperature of the ambient atmosphere and the constant temperature layer are -5℃ and -2℃ respectively. The throughput of the selected oil pipeline is 1000×10^4t/a and its outlet temperature is 55℃. The thickness of the wax layer and that of the insulation layer are 10mm. Thermal properties of soil, water, ice, crude oil and three-layer structure of the pipeline are shown in Table 1.

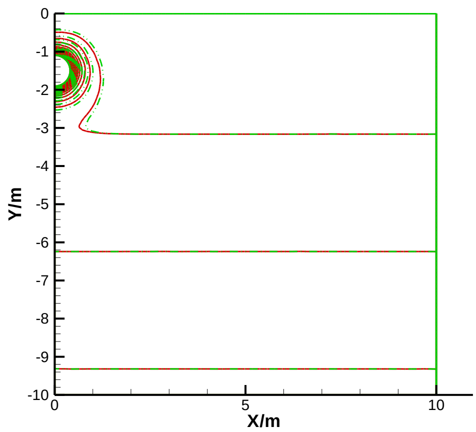
Table 1 Thermal properties

Name	Thermal Conductivity (W/m·℃)	Specific Heat (J/kg·℃)	Density (kg/m^3)
Soil	1.82	982	1800
Water	0.55	4200	1000
Ice	2.22	1930	910
Crude oil	0.13	2100	850
Steel wall	48	465	7840
Wax layer	0.18	2000	920
Insulation layer	0.025	1380	45

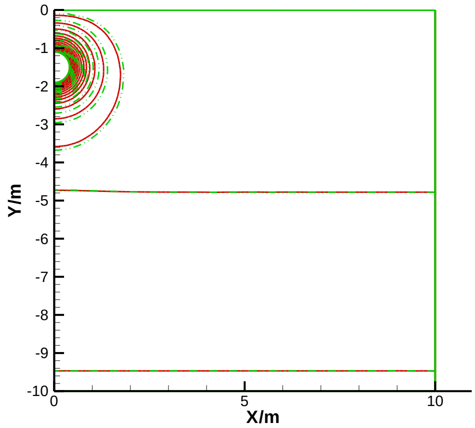
Based on the mathematical models and numerical method demonstrated above, program code is developed in FORTRAN95 language. By running the computing program under the given conditions of pipeline and relevant parameters, following results and analysis can be obtained (as shown in Figs. 4-6).

For the initial soil temperature is below the freezing point, most of the soil area are in frozen state which means the water content of soil is at a relatively low level. When the hot oil pipeline is running normally, the temperature of crude oil in the pipeline is higher than that of surrounding soil and the heat is transferred from oil to soil via the three-layer structure of pipeline. Frozen soil absorbs the heat to make the ice in the porosity melt and become liquid water. As a result of this, the water content in frozen soil increases and thermal properties of soil changes correspondingly to affect the whole heat transfer performance. Under the gradient of temperature, unfrozen water also starts to migrate within the porosity of soil.

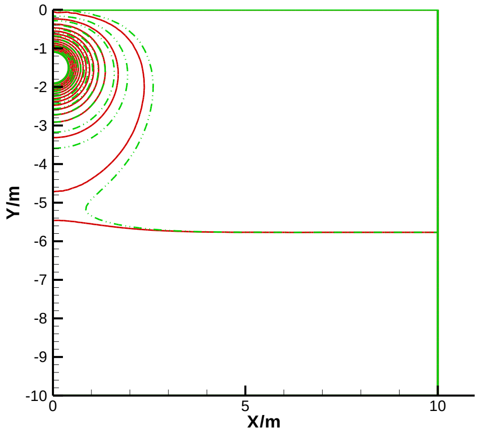
The comparisons between soil temperature fields obtained by pure heat conduction model and heat-water coupling model under different pipeline operation periods are illustrated in Fig. 4. The red solid line represents the results calculated by the water-heat coupling model while the green one denotes the results of pure heat conduction model, and the two different temperature fields become more obvious apart gradually. When the pipeline is running 50 hours, the difference between two soil temperature fields is relatively small because the thawing of ice is not as severe enough as to have apparent effect on the soil temperature field. After the operation period of 150 hours, the two soil temperature fields differ from each other significantly and the thermal affected area of hot oil pipeline expands more slowly when the water-heat coupling model is employed in the calculation. The cause of this phenomenon has a close relationship with the comprehensive thermal conductivity of frozen soil. Generally speaking, the heat conductivity of soil enhances with the increase of the water content, because the liquid water holds a higher heat conductivity than the air which occupies the porosity of soil initially, thus when the water content in soil increases which means water replaces air in the porosity, it is rational to conclude that the comprehensive heat conductivity of soil would increase. Different from the common case, there are two phases, water and ice, exist in the saturated frozen soil pore and the heat conductivity of ice is no doubt bigger than that of water. Therefore, after absorbing the heat released from the hot oil pipeline, the ice would melt into water which has poor heat conductivity and the whole heat conductivity of soil would decrease. And in the process of melting, the solid ice needs to absorb additional latent heat from the surrounding environment to further slow the heat transfer in the soil area and make the soil temperature obtained by water-heat coupling model is lower than that got by pure heat conduction model in the same location of computational domain. In addition, due to the lower temperature of ambient atmosphere, the soil above the oil pipeline has a tendency to freeze thus the difference between the two temperature fields in there is relatively small. On the contrary, the soil beneath the pipeline reflects the difference more apparently.



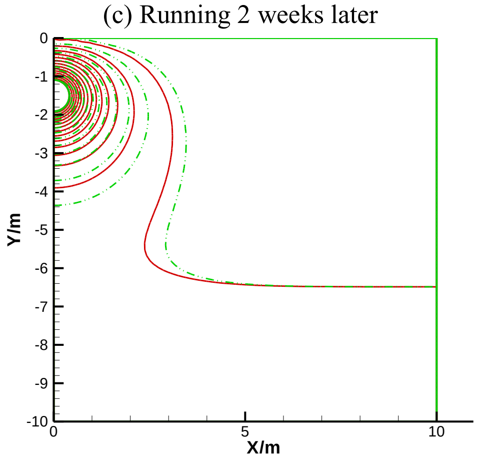
(a) Running 50 hours later



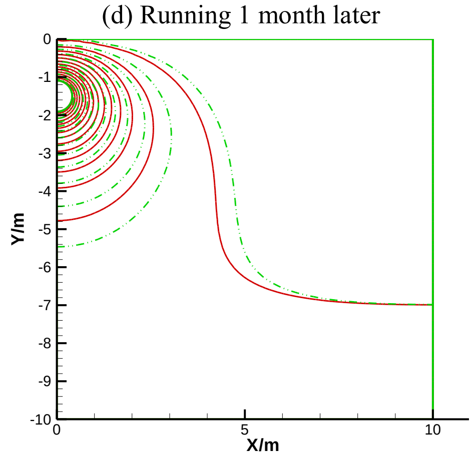
(b) Running 150 hours later



(c) Running 2 weeks later



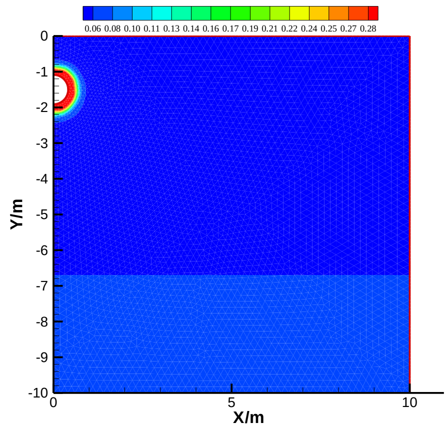
(d) Running 1 month later



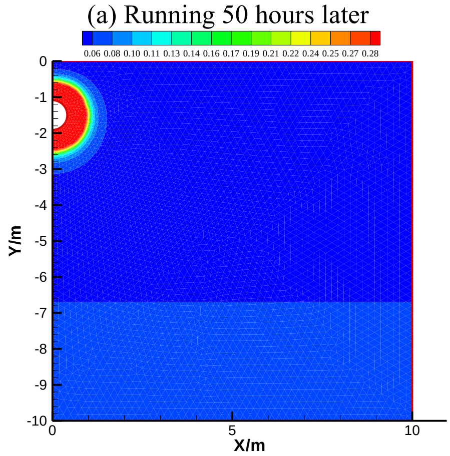
(e) Running 2 months later

Fig. 4 Comparison of soil temperature field

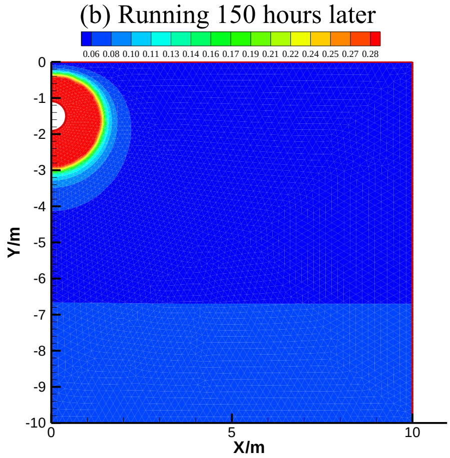
Figure 5 shows the water content field of frozen soil in different pipeline operation periods obtained by the water-heat coupling model. The red area represents the soil with large water content, namely melted soil; the blue area contains more solid ice and less liquid water, namely frozen soil; and there is an area between the melted soil and frozen soil, where ice coexists with certain amount of water, namely freezing soil. As the pipeline running, the ice in the frozen soil around the pipeline absorbs the heat from the pipeline and melts into water. Correspondingly, the water content of soil surrounding pipeline increases and this is clearly illustrated as the red area expands out over time. Because the soil above the pipeline also exchanges heat with the cold atmosphere, thus the thawing circle expands more slowly in the soil above the pipeline than in the soil beneath the pipeline. Consequently, the thermal affected area in frozen soil presents an asymmetrical distribution which is shifted down. And after the pipeline is running 150 hours, though the melted soil still expands beneath the pipeline, the thawing area above the pipeline remains stable at the location of -0.5m.



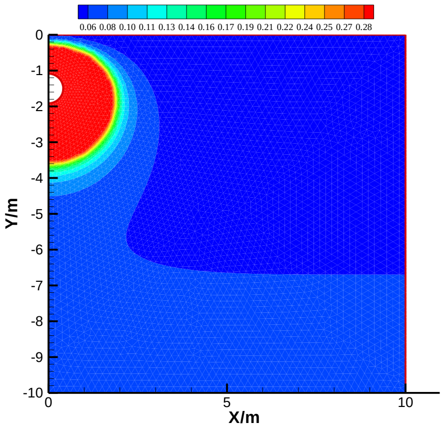
(a) Running 50 hours later



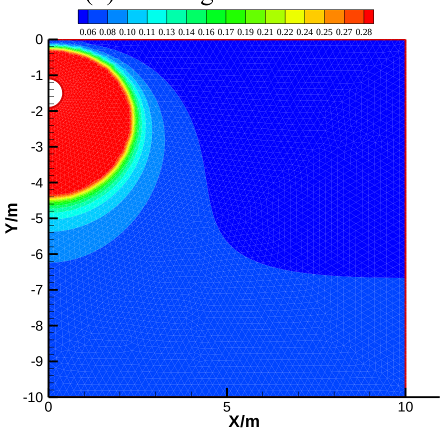
(b) Running 150 hours later



(c) Running 2 weeks later



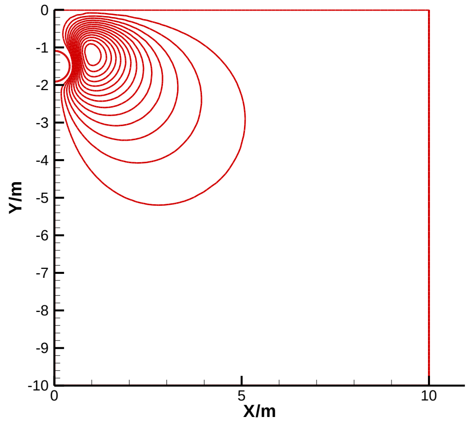
(d) Running 1 month later



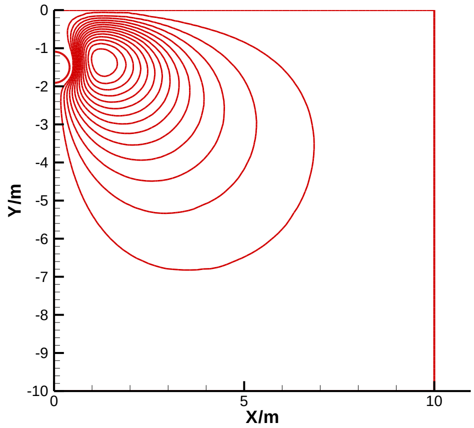
(e) Running 2 months later

Fig. 5 Water content field

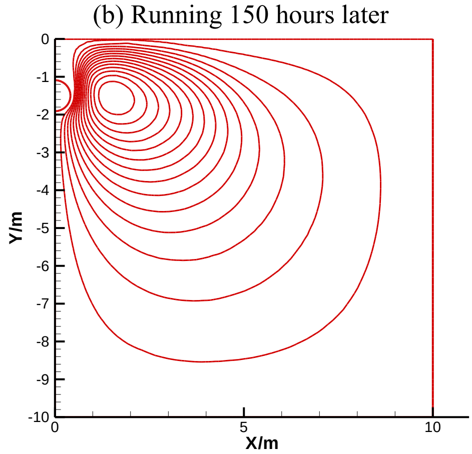
Figure 6 illustrates the streamlines of water migration diagram in different pipeline operation periods. The calculation results demonstrate that the amount of moisture migration is biggest in the early operation period of pipeline. To be specific, when the pipeline is running 50 hours, the maximum velocity of water migration reaches 4.21×10^{-7}m/s but the migration only occurs in a limited area due to the fact that most of the soil is still in the frozen state. As time goes by, the migrating velocity of unfrozen water in the soil decreases along with the drop of the temperature gradients between the hot oil pipeline and surrounding frozen soil. Meanwhile, the range of water migration expands to a larger area for the water content of more soil area is adequate to sustain the water migration. It is also worth pointing out that the magnitude of migrating velocity of unfrozen water in soil is only 10^{-7}-10^{-10}m/s which indicates the heat transfer caused by natural convection, the essence of water migration, has little effect on the whole temperature field of frozen soil. Through deep research and analysis, Taylor G.S. and Luthin J.N. [23] confirmed that the thermal migration because of water flow in frozen soil only occupies 1/100~1/1000 of thermal migration caused by heat conduction. In addition, it can be clearly seen that because of the largest temperature gradient near the pipeline, the closer location to the hot oil pipeline, the denser streamlines of water field deploy. Given the changing trend of streamlines, the unfrozen water mainly distributes around the soil area with positive temperature and has the tendency toward frozen soil area. And due to the different water content under different temperature distribution, in various pipeline operation periods the shape and intensity of heat convection vortex show significant difference which is in good accord with the experiment and simulation results in the literature [24].



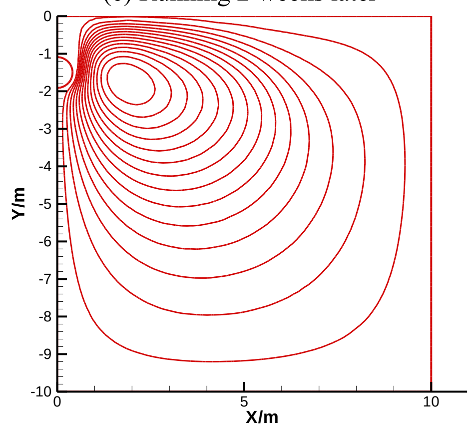
(a) Running 50 hours later



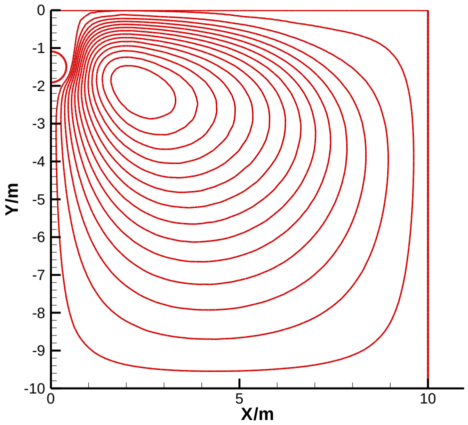
(b) Running 150 hours later



(c) Running 2 weeks later



(d) Running 1 month later



(e) Running 2 months later

Fig. 6 Water migration diagram

3.2 Heat flux density and oil temperature along the pipeline

In order to further illustrate the influence of interactions between soil temperature field and water field, the heat flux density and oil temperature along the pipeline are calculated by pure heat conduction model and water-heat coupling model respectively.

Take one month as the operation period and define the average heat flux density as q. By comparing the data in Table 2 and Fig. 7, the heat flux density at the inlet of the pumping station is smaller than that at the outlet of the next pumping station. This because in the process of crude oil transportation, due to the continuous heat release, oil temperature and the temperature gradient between crude oil in pipeline and frozen soil around decrease at the same time. With water-heat coupling model, the influence of water content change on the heat transfer performance of soil is taken into consideration. The declined proportion of ice to water in soil worsens the whole heat transfer property of frozen soil, thus the heat flux density obtained by water-heat coupling model is smaller than that by pure heat conduction model. Moreover, for the water content of soil at the outlet is higher than those in other locations along the pipeline, the difference between heat flux densities calculated by two models all decrease in the direction of oil flow.

Given the data in Table 3 and Fig. 8, oil temperature along the pipeline presents the opposite tendency compared with that of heat flux density. When employing the water-heat coupling model, the heat flux density is smaller so the corresponding oil temperature turns out to be higher than the result obtained by pure heat conduction model, and the maximum difference could reach 2.0℃. And this phenomenon is in accord with the comparison result of heat flux density stated above.

Table 2 Heat flux density

Model	L (km)						
	0	16	32	48	64	80	100
Pure heat conduction	75.8	69.2	63.0	57.6	52.5	47.8	43.7
Water-heat Coupling	69.2	63.8	58.9	54.2	50.2	46.3	42.6

Table 3 Oil temperature

Model	L (km)						
	0	16	32	48	64	80	100
Pure heat conduction	55.0	48.1	43.6	39.6	35.9	32.7	29.3
Water-heat Coupling	55.0	50.0	45.4	41.2	37.3	33.7	29.8

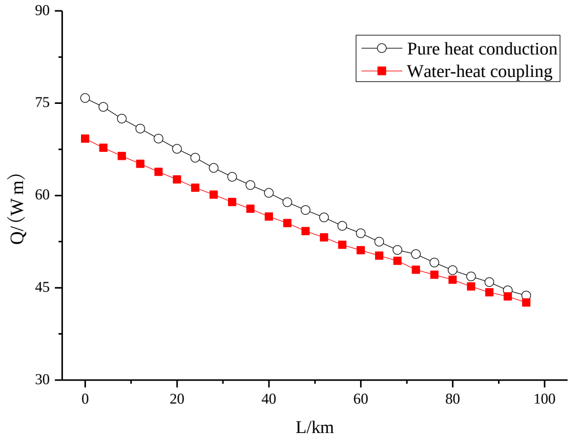


Fig. 7 Heat flux density along the pipeline

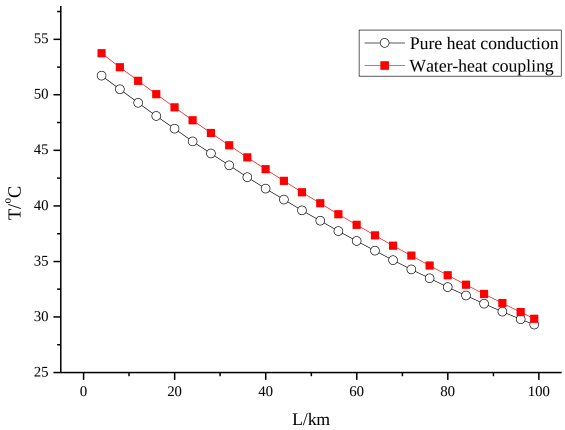


Fig. 8 Oil temperature along the pipeline

4 Conclusions

The present paper studies the temperature and water fields of saturated frozen soil surrounding the hot crude oil pipeline by establishing the water-heat coupling model for porous soil media and comparing the different results obtained by pure heat conduction model and water-heat coupling model respectively. Based on the above results and analysis, general conclusions can be drawn as follows:

(1) The temperature fields of saturated frozen soil obtained by pure heat conduction model and water-heat coupling model present different distributions. In details, the thermal affected area of hot oil pipeline expands more slowly due to the change of water content in frozen soil. Because the whole heat conductivity of frozen soil is determined by three phases, the soil skeleton particles, solid ice and liquid water in the porosity. When the ice in surrounding soil absorbs the heat from the pipeline and melts into liquid water which has lower heat conductivity, the heat conductivity of soil decreases with the declined proportion of ice to water. Meanwhile, when the ice

converts into water, the latent heat of phase change also slow down the heat transfer process in the soil.

(2) Under the temperature gradients of frozen soil, the unfrozen water would migrate in the porosity of soil and the streamlines of migration diagram distribute denser near the pipeline where there is the largest temperature gradient. It is also worth noting that the magnitude of water migrating velocity is about 10^{-7}-10^{-10}m/s so the natural convection of unfrozen water in soil has little effect on the ultimate soil temperature field.

(3) Taking the influence of water field in saturated frozen soil into account, the whole heat conductivity of soil decreases along with the declined proportion of ice to water in the porosity. The average heat flux density along the pipeline is smaller with the consideration of water field effect and as a result of this, the oil temperature obtained by water-heat coupling model presents higher than that obtained by pure heat conduction model. Under the operation period of one month, the biggest difference could reach 2.0℃ while at the inlet of next pumping station, the temperature difference is 0.5℃.

Acknowledgments

The study is supported by the National Science Foundation of China (No. 51134006, No. 51176204 and No. 51276198), and the Science Foundation of China University of Petroleum, Beijing (No. 2462011LLYJ33, No. 2462011LLYJ55 and No. 2462012KYJJ0404).

References

[1] Xu X.Z., Wang J.C., Zhang L.X., Frozen soil physics[M], Beijing: Science Press, 2001. (in Chinese)

[2] Li J.F., Lv H.Q., Li Z.X., Experience and Revelation Learned from Foreign Pipeline Construction Projects in Permafrost Regions[J], Petroleum Engineering Construction, 2006, 32(6): 1-4. (in Chinese)

[3] Xu G.F., Qi J.L., Jin H.J., Model test study on influence of freezing and thawing on the crude oil pipeline in cold regions[J], Cold Regions Science and Technology, 2010, 64: 262-270.

[4] Yang S.Z., Jin H.J., Yu S.P., Chen Y.C., Hao J.Q., Zhai Z.Y., Environmental hazards and contingency plans along the proposed China-Russia Oil Pipeline route, Northeastern China[J], Cold Regions Science and Technology, 2010, 64: 271-278.

[5] Zheng P., Numerical Simulation for Couplings of Water, Temperature and Stress Fields of Underground Oil Pipeline in Cold Region[D], Shandong: Oil & Gas Storage and Transportation Department in China University of Petroleum, 2011. (in Chinese)

[6] Penner E., Pressure developed during the unidirectional freezing of water saturated porous materials[C], Proceedings of International Conference on Low Temperature Science, 1966, 1: 1401-1412.

[7] Miller R.D., Freezing and heaving of saturated and unsaturated soils[J], Highway Research Record, 1972, 393: 1-11.

[8] Williams P.J., Properties and behavior of freezing soil[J], Norwegian geotechnical Institute, 1967, 72: 1-119.

[9] Harlan R.L., Analysis of coupled heat-fluid transport in partially frozen soil[J], Water Resources Research, 1973, 19(5): 1314-1323.

[10] Ling F., Zeng Z., Zhang L.X., Impact of construction seasons on maximum thawing depth of roadbed[C], Proceedings of 9th International Symposium on Ground Freezing, 2000: 47-50.

[11] Lai Y.M., Wu Z.W., Zhu Y.L. et al., Nonlinear analysis for the coupled problem of temperature, seepage field in cold region tunnels[J], Cold Region Science and Technology, 1999, 29(1): 89-96.

[12] Flerchinger G.N., Pierson F.B., Modeling plant canopy effect on variability of soil temperature and water[J], Agriculture and Forest Meteorology, 1991, 56: 227-246.

[13] Li R.P., Shi H.B., Takeo A. et al., Study on water-heat-salt transfer in soil freezing-thawing based on Simultaneous Heat and Water model[J], Journal of Hydraulic Engineering, 2009, 40(4): 403-413. (in Chinese)

[14] Fremond M., Lassoued R., Raln falling on a frozen ground[C], Proceedings of 9th International Symposium on Ground Freezing, 2000: 25-30.

[15] Osokin N.I., Samoilov R.S., Sosnovskiy A.V. et al., On evaluation of Influence of variability of snow cover properties on a freezing of grounds[J], Cryosphere of the Earth, 1999, 3(1): 3-10.

[16] Goering D.J., Instanes A., Kundsen S., Convective heat transfer in railway embankment ballast[C], Proceedings of 9th International Symposium on Ground Freezing, 2000: 3l-36.

[17] He P., Cheng G.D., Zhu Y.L., The Progress of Study on Heat and Mass Transfer in Freezing Soils[J], Journal of Glaciolgy and Geocryology, 2001, 23(1): 92-98. (in Chinese)

[18] Mao X.S., Hu C.S., Dou M.J. et al., Dynamic Observation and Analysis of Moisture and Temperature Field Coupling Process in Freezing Soil[J], Journal of Glaciolgy and Geocryology, 2003, 25(1): 55-59. (in Chinese)

[19] Liang C.J., Li H.S., Numerical Analysis for Coupled of Moisture Heat and Stress Fields during Soil Freezing around the Buried Chilled Pipeline[J], Journal of Shanghai Maritime University, 2000, 21(4): 85-91. (in Chinese)

[20] Zhang J.M., Qu G.Z., Jin H.J., Estimates on thermal effects of the China– Russia crude oil pipeline in permafrost regions[J], Cold Regions Science and Technology, 2010, 64: 243-247.

[21] Lu T., Wang K.S., Numerical analysis of the heat transfer associated with freezing/solidifying phase changes for a pipeline filled with crude oil in soil saturated with water during pipeline shutdown in winter[J], Journal of Petroleum Science and Engineering, 2008, 62: 52-58.

[22] Yang X.H., Design and Management of Oil Pipelines, 1st Edition, Beijing, China University of Petroleum Press, 2006, 98.

[23] Luthin J.N., Taylor G.S., A model for coupled heat and moisture transfer during soil freezing[J], Canadian Geotechnology Journal, 1978, 15: 548-555.

[24] Zhang F.C., Zhang Y.P., Zhang J.C., Temperature Effect on Soil Water Retention[J], ACTA PEDOLOGICA SINICA, 1997, 34(2): l60-169. (in Chinese)