RESEARCH ON HEAT TRANSFER CHARACTERISTICS OF LONG-DISTANCE PIPELINE UNDER SHUTDOWN AND MAINTENANCE CONDITIONS

Ying Xu [1] Kaijing Zhang [1*] Yuanyuan Zhu [2] Shu Chen [3]
Shaodong Zhao [2] Xiaoyan Liu [1] Chuan Ma[1]
1 Northeast Petroleum University, Daqing city, China, 163318
2 Jiangsu Zhengdao Ocean Technology Co., Ltd. Nantong, 226001, China
3 Petrochina Tarim Oilfield Company，Korla, xinjiang ,841000 , China
*Kaijing Zhang; E-mail:kaijingfighting@126.com

Abstract：When a long-distance pipeline is shut down for maintenance due to corrosion and damage, the process of cooling down and waxing of crude oil in the pipeline is accompanied by complex phase change heat transfer, and it is important to obtain its temperature drop law to reasonably control the shutdown time and formulate restart plan. In this paper, the heat transfer problem of long-distance pipelines under operation and maintenance conditions was studied and refined. Considering the influence of flow and wax precipitation characteristics of crude oil on heat transfer, a multi-field coupled action model was established and analyzed by numerical simulation in combination with the wide-phase interface partitioning method of crude oil. The evolution of the original flow and temperature fields in the pipeline at typical locations of the maintenance pipeline was revealed, and the reasonable maintenance time was proposed based on the change of liquid phase rate. The research in this thesis refined the heat transfer mechanism of the solidified phase change of crude oil for long-distance pipeline shutdown.

Key words： Wide phase interface; Three-dimensional buried pipelines; Solidification evolution; Phase change heat transfer; Excavation repair

1. Introduction

Most of the crude oil produced in China has a high wax content and a high freezing point. To improve its fluidity, crude oil containing wax is often heated during the transportation process. When a pipeline is shut down for maintenance due to corrosion or damage, the crude oil in the pipeline undergoes gelation and phase change heat transfer under the effect of the temperature difference between inside and outside, and its fluidity is changed significantly. When the temperature drops below the anomaly point not only do they exhibit complex rheological properties, but the structural strength of the crude oil increases further. When it is greater than the pump can provide the start-up pressure will occur condensate pipe accident, a serious impact on the safe delivery of pipeline and economic operations .Therefore, it is important to grasp the temperature drop rule of crude oil in buried hot oil pipelines under stoppage and maintenance conditions.

The temperature drop along the pipeline in steady-state operation and the soil temperature field distribution are the initial conditions for the study of heat transfer during shutdown. A large number of studies had been conducted by domestic and foreign researchers on the process of heat transfer during shutdown of long-distance pipelines [1-8]. In the early studies, the heat transfer between crude oil and the inner wall of the pipeline was mostly ignored, and the temperature of crude oil was equated with the temperature of the inner wall of the pipeline and calculated based on Sukhov's formula [9-10]. Some scholars had also introduced along-range temperature distributions based on the specific heat expressions of wax-containing crude oils in three different temperature zones from the energy balance relationship [11-12]. Both of these methods simplified the heat transfer coefficient between the crude oil and the wall in the pipe. Heat transfer between the crude oil and the wall in the pipeline involves a number of factors such as flow rate, crude oil temperature and the condition of the wall in the pipeline, resulting in different heat transfer coefficients along the journey. Therefore, the simplified method of calculating heat transfer coefficients can lead to a deviation between the along-track temperature drop and the actual temperature drop. This deviation can affect the accuracy of the temperature drop prediction for subsequent shutdowns. Therefore, the steady state operation model should fully consider the coupling effect of flow and heat transfer between crude oil and pipelines in the pipeline.

Phase change heat transfer studies where pipelines are shut down for maintenance for any reason mostly ignored the effect of axial temperature difference of the pipeline and used a two-dimensional heat transfer model. The phase transition of crude oil involves multi-physical phenomena such as latent heat nonlinear release, natural convection effects, and coupled liquid-solid interfaces, and its heat transfer study is exceptionally complex [12-15]. The former crude oil phase change model can be summarized in two aspects- infinite thin phase interface [16-20], enthalpy-porous medium model [21-26]. Xiaoyan Liu [17] used fluent software to construct a temperature drop model for overhead thermal oil pipeline shutdown, established the control equations of liquid-phase and solid-phase zones according to the phase state of crude oil, and used the equivalent thermal conductivity coefficient to deal with the natural convection heat transfer problem in the liquid-phase zone. Xu [19] carried out an analysis of crude oil variable physical properties on the temperature field of stopping transmission using an N-S combined laminar flow model. From the results, it can be seen that the crude oil physical properties were regarded as constant values, resulting in a temperature field distribution that differs from the actual one, especially the density term was constant, which was equivalent to neglecting the effect of natural convective heat transfer. Xiaoyu Chen [20-21] used the condensation point of crude oil as the partition point of the phase interface to solve the phase change heat transfer problem of crude oil. Lu Tao [24] firstly used enthalpy - porous medium method to solve the problem of crude oil temperature field in the stopping pipeline. His model considered that the latent heat and liquid phase rate in the porous medium zone varied linearly with the temperature, which was obviously inconsistent with the actual wax precipitation process. Liu [25] used simulations to analyze the temperature field and liquid phase cloud diagrams of gelled crude oil with different oil-water temperature differences, different water flow rates and different sizes, and obtained the total melting time and temperature variation curves of spherical gelled crude oil under different initial conditions. Min Wang[26] numerically simulated the solidification and melting of a wax-containing crude oil in a storage tank using an enthalpic porous medium model, in which the amount of wax precipitated was solved based on a linear distribution with temperature. During the shutdown process of a hot oil pipeline, the phase state of crude oil undergoes a complex change from liquid to porous media system to solid state. When crude oil shows porous media characteristics, its heat transfer mode is different from that of liquid and solid state, so the two-phase zone model cannot accurately describe its heat transfer process. At the same time, the enthalpy-porous medium model requires accurate determination of the phase change precipitation wax interval, which becomes the key to obtain the temperature drop pattern of crude oil stoppage. Based on this, the group [28] used the microscopic properties of wax precipitation from waxy crude oil and considered the influence of the phase evolution of wax crystals on the heat transfer mode, so as to construct a new partitioned "wide phase interface partitioning" heat transfer model, which was found to be more accurate in predicting the pipeline stoppage temperature distribution after experimental comparison.

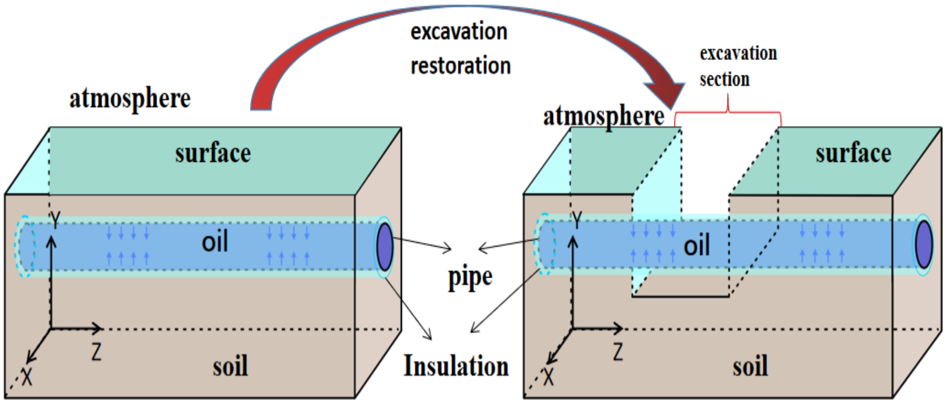
In this paper, the coupled heat transfer between crude oil flow and wall surface in pipeline during steady state operation was fully considered. Additionally, a three-dimensional steady-state thermal model of a long-distance pipeline was established for the first time by combining it with the k-ε model. This model aimed to obtain a more accurate temperature distribution along the pipeline and soil temperature field. On this basis, combining with the wax crystal phase state change rule, using the "wide phase interface partition" model, the establishment of three-dimensional stopping pipeline heat transfer mathematical model. Through numerical simulation of pipeline stopping non-steady state process, in-depth analysis of the change rule of temperature drop of crude oil in stopping and repairing pipeline, to further improve the long-distance pipeline stopping phase change heat transfer mechanism.

2. Physical model

The following assumptions and simplifications were made for buried oil pipelines: (1) All solid media were assumed to have isotropic physical properties. (2) External environmental conditions were assumed to be constant during the cooling of the crude oil. (3) It was assumed that the flow rate and temperature at the inlet of the pipeline were uniformly distributed in the inlet section and that the flow at the outlet was free flowing. The physical model of the buried pipeline was shown in Fig.1, with the horizontal direction boundary being the thermally influenced area of the pipeline, the longitudinal burial depth direction boundary being the thermostatic layer of the earth, and the rest of the thermally influenced area of the pipeline being set as the adiabatic wall surface. Convective heat transfer mainly occurred between the crude oil and the pipe wall inside the pipe, and heat conduction was mainly dominated between the pipe walls. And the composite heat transfer of convective heat transfer + radiative heat transfer occurred between the soil surface layer and the ambient air. Due to plan maintenance or the occurrence of unavoidable factors and stopping the transmission of excavation and repair, in the pipeline from the outgoing station 9km at the excavation of 2km, the excavation exposed the pipeline section boundary conditions into the convection radiation heat transfer between the pipeline and the atmosphere.

Fig. 1. Physical model of buried pipeline excavation

3 .Mathematical models



3.1 Equations of steady state operation

Conservation of mass equation:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (1)$$

k-ε model equation:

$$\frac{\partial}{\partial t}(\rho k)+\nabla\cdot(\rho K u)=\nabla\cdot(\mu\_t\nabla K)+G-\rho\varepsilon \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\nabla(\rho\varepsilon u)=\nabla\cdot(\mu\_t\nabla\varepsilon)+C\_1\varepsilon K-C\_2\rho\frac{\varepsilon^2}{k} \qquad (3)$$

Momentum conservation equation:

$$(\rho\vec{u}\cdot\nabla)\vec{u}=-(\nabla P)+(\nabla\cdot\tau)+F \qquad (4)$$

Differential equation of conservation of energy:

$$\rho u\cdot\nabla(h+(u^2)/2)=-\nabla(K\triangledown T)+\tau\cdot\nabla u+q \qquad (5)$$

3.2 Shutdown maintenance thermal modelling

(1) Crude oil liquid phase area:

The energy equation:

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}+\frac{\partial(\rho wT)}{\partial z}=\frac{\partial}{\partial x}\left(\frac{\lambda_s}{c_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\lambda_s}{c_p}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\lambda_s}{c_p}\frac{\partial T}{\partial z}\right) \qquad (6)$$

When T > Tx,

$$\lambda_t=\lambda_X \qquad (7)$$

When $T_j < T \leq T_x$,

$$\lambda_t=\lambda_l\frac{2+\lambda_s/\lambda_l+2\phi\left(\frac{\lambda_s}{\lambda_l}-1\right)}{2+\lambda_s/\lambda_l-\phi\left(\frac{\lambda_s}{\lambda_l}-1\right)} \qquad (8)$$

$$\phi = \frac{T_X - T}{T_X - T_J} \quad (9)$$

(2) Solid-phase zone in the pipeline:

When the temperature of the crude oil in the pipeline is below the freezing point, the heat transfer equation is as follows:

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho uT)}{\partial x} + \frac{\partial(\rho vT)}{\partial y} + \frac{\partial(\rho wT)}{\partial z} = \frac{\partial}{\partial x}\left(\frac{\lambda_s}{c_P}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_s}{c_P}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\lambda_s}{c_P}\frac{\partial T}{\partial z}\right) \quad (10)$$

(3) Liquid-solid mixed porous media fuzzy zone in the pipeline:

Continuity equation:

Liquid-solid mixed porous media fuzzy zone of the continuity equation is the same as the liquid phase zone.

Momentum equation:

$$\frac{\partial(\rho \vec{u})}{\partial \mathrm{t}} + \left(\vec{u}\rho \cdot \nabla \frac{\vec{u}}{\varepsilon}\right) = -\nabla(\varepsilon \mathrm{P}) + \mu_e \nabla^2 \vec{u} + F \quad (11)$$

$$F = -\frac{\varepsilon \mu_e}{K}\vec{u}\rho - \frac{\varepsilon F_\varepsilon}{\sqrt{K}}\vec{u}|\vec{u}| + \varepsilon \rho g \beta (T - T_{ref}) \quad (12)$$

$$F_\varepsilon = \frac{1.75}{\sqrt{150\varepsilon^3}} \quad (13)$$

$$K = \frac{\varepsilon^3}{C(1-\varepsilon)^2} \quad (14)$$

The energy equation:

$$\frac{\partial(\rho H)}{\partial t} + \left(\rho c_{\mathrm{p}} \vec{u} \cdot \nabla T\right) = \lambda_t \nabla^2 T \quad (15)$$

In order to characterise the non-linear change of wax precipitation with temperature during the phase change process of crude oil, combined with the DSC curve test results, the enthalpy method was used to solve the change of liquid phase rate of crude oil, and its calculation formula was as follows::

$$\varepsilon = 1 - \frac{H(T_j) - H(T)}{H(T_j) - H(T_N)} \quad (16)$$

$$H(T) = c_{Pj}T + \int_{T_N}^{T} \left(c_P(T) - c_{Pj}\right) dT \quad (17)$$

$$\lambda_t = (1-\varepsilon)\lambda_s + \varepsilon \lambda_l \quad (18)$$

3.3 Calculation of boundary conditions

Calculated boundary conditions: $\lambda \frac{\partial T}{\partial y} = \alpha_k (T - T_W)$;

The thermostatic layer is 8m below ground level: $y = T_0$;

Pipe walls: $y = R1; \lambda \frac{\partial T}{\partial R1} = \alpha \hbar (T - T_w)$

For pipeline repair excavations, there is no heat transfer from the soil, and convective heat transfer boundary conditions from the outer wall of the pipeline to the atmosphere:

$$\lambda_N \frac{\partial T_N}{\partial r}\bigg|_{r=R_N} = h_a (T_N - T_w)$$

4 .Validation analysis

4.1 Grid-independent verification

An "O-shaped" grid structure was used to discretize the fluid in the pipe. A quadrilateral grid was used to discretize the computational domain of the pipe and insulation, with the grid progressively thinner from the inner wall of the pipe to the outer wall of the insulation. The soil was designed with a non-uniform grid system, where the closer the pipe, the denser the grid. The number of grids per kilometre was 8,997,605. see Fig. 2(a).Discretize the computational domain using structured meshes. Comparing the computational effectiveness of the meshes used and determined the optimal mesh design method. The grid number was 6730910, 8997605 and 10712586, respectively, and it can be seen from Fig.2(b) that the three curves had the same trend, and there was a deviation in the curve with the grid number of 6730910, while the remaining two curves were almost overlapped, so the grid number of 8997605 was selected. 1s, 5s and 10s were used in the time step, respectively, and it can be seen from Fig. 2(c) that the overall trend was the same, and there was a slight deviation in the time step of 1s, so the time step of 5s was selected.

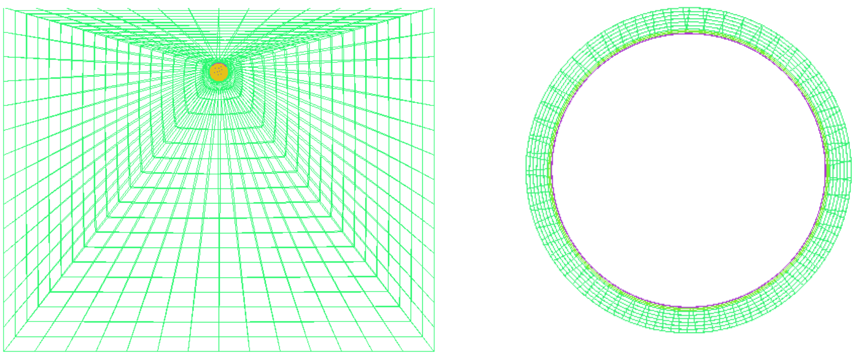
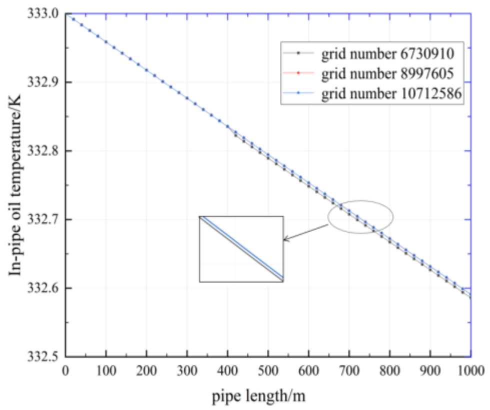


Fig.2(a). Grid structure of the system



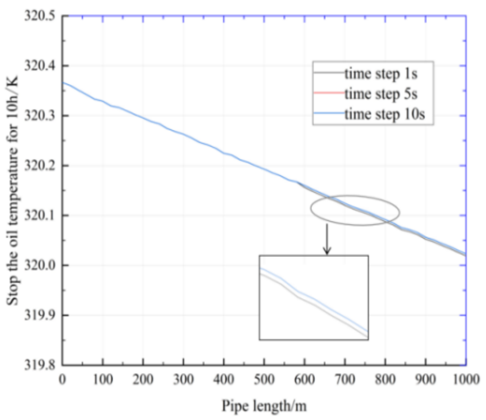
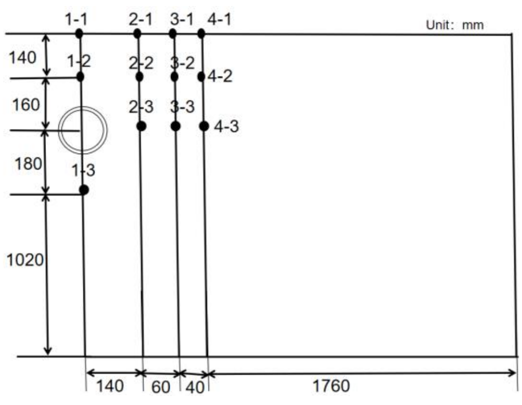


Fig. 2(b) .Grid-independent verification   Fig. 2(c). Time-step-independent verification

Fig.2 Grid structure and independence verification

4.2 Model validation

Wu [28] used steady state heat transfer experiments on an uninsulated oil pipeline of Φ89×3.5mm. The oil content was 100%, the crude oil temperature was 33°C, the air temperature at the sand surface was -17.5°C, the temperature of the thermostatic water bath under the sand box was 12.5°C, and the density was uniformly 1500 kg/m^3, and the temperature field of the soil around the pipeline was measured, as shown in Fig. 3(a). Comparing the simulation results with the experimental results as shown in Tab. 1, the maximum absolute error between the calculated and experimental temperature values was 2.63℃. In addition, the control of the surrounding environment of the pipe was 16 °C in the suspension heat transfer experiment of Xu [27], using the natural flow heat exchange experiment correlation of large space, after considering the air flow speed, it can be determined that the coefficient of the outer flow thermal exchange was 15W/(m·K); the surface emission rate was 0.7 outer pipe. The simulated results of monitoring the crude oil temperature at the centre point of the pipeline were compared with the experimental results as shown in Fig. 3(b), and the error between the two was less than 2%. The comparative verification analysis showed that the prediction results of the currently built three-dimensional buried pipeline heat transfer model were reliable, and further research on its heat transfer characteristics can be carried out.



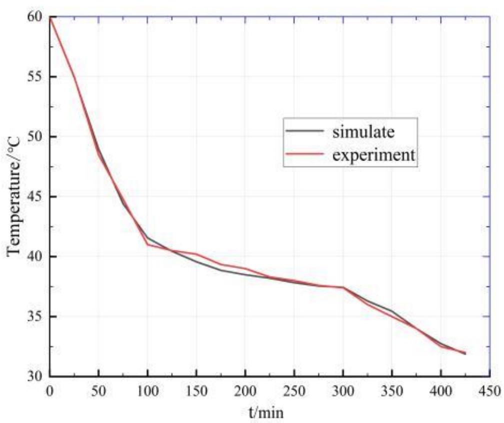


Fig. 3 (a) Soil temperature measurement location Fig. 3 (b) Comparison of simulated values and experimental values

Fig.3 Model verification

Tab. 1 . Comparison of experimentally measured and simulated temperature values unit：℃

Measuring point	1-1	1-2	1-3

Experimental	-12.54	1.63	15.02
Calculated	-12.4	0.33	13
error	0.1	1.3	2.02
Measuring point	2-1	2-2	2-3
Experimental	-12.6	0.63	11.34
Calculated	-12.82	-0.95	10.42
error	0.22	1.58	0.92
Measuring point	3-1	3-2	3-3
Experimental	-13.06	0.13	5.62
Calculated	-14	-2.5	4.73
error	0.94	2.63	0.89
Measuring point	4-1	4-2	4-3
Experimental	-12.38	-2.42	0.88
Calculated	-12.91	-2	2.95
error	0.53	0.42	2.07

5 .Analysis of results and discussion

5.1 Temperature drop along the steady-state operation

Crude oil leaves the station as it flows and dissipates heat between it and the envir along the journey. Taking Φ 219×6 mm pipel e atmospheric ambient temperature was -20°C oil temperature of stopping the trans erature drop along the course was shown in Fig. 4

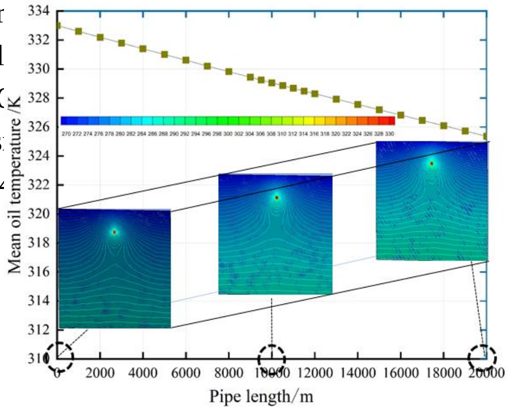
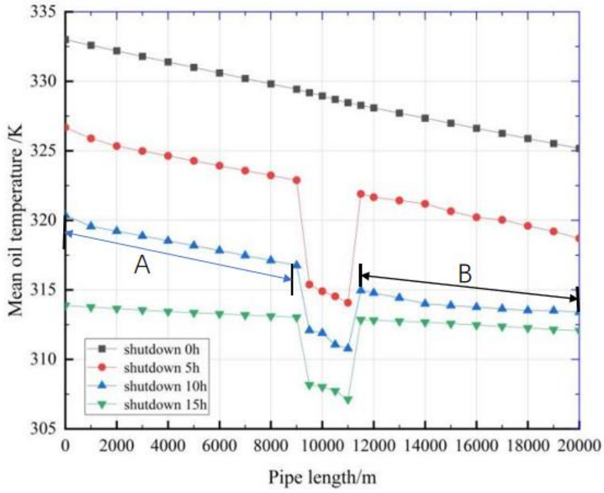


Fig. 4 .Temperature drop and soil temperature field at typical positions(0km、10km、20km)

Based on Fig. 4.it was evident that due to the existence of radial temperature differences, the heat carried by the oil flow continuously dissipated to the outside of the pipe, resulting in a gradual decrease in temperature along the pipeline. Under a certain flow rate, the temperature decreased along the 20 km pipeline segment was 8℃. Combining with the cloud diagram of the soil temperature field around the pipe, it can be seen that the isotherms of the soil temperature field were distributed in an eccentric ring, and the surrounding soil temperature gradually decreased from the centre of the pipe to the outside, and the soil isotherms were dense at the top and sparse at the bottom. This was because the pipeline dissipated heat to the atmosphere through the soil surface, with the pipe being closer to the surface, resulting in a smaller radial thermal resistance and a larger temperature difference, leading to higher heat flux density. Low density of heat flow underneath the pipe.

5.2 Variation of average oil temperature along the pipeline under stoppage and maintenance conditions



The excavation of 2000m at 9km from the outgoing station was carried out for stopping transmission maintenance, and the average temperature distribution of crude oil in the pipeline along the pipeline axis direction at different stopping moments was shown in Fig. 5.

Fig.5. Plot of average temperature variation of crude oil in excavation and stopping transmission

According to Fig.5,when the excavation and maintenance section was exposed to the atmosphere, the thermal resistance between the pipeline and the environment decreased abruptly, leading to a significant temperature drop. At both ends of the excavation section, they were more influenced by the temperature drop along the buried section, resulting in higher temperatures compared to the middle section of the excavation. Based on the change in the slope of the temperature drop curve along the pipeline, it can be observed that after 10 hours of shutdown, the temperature drop rate was faster in the pre-excavation section (Section A) compared to the post-excavation section (Section B). This was due to the fact that the average temperature of the crude oil in the pipeline section B has dropped to the wax precipitation point, and the wax crystals precipitate to release latent heat. At the same time, after the crude oil cooling gelation, the formation of radial wax crystal grid structure of the pipeline, inhibiting the natural convection heat transfer of crude oil, both of the above aspects lead to the slowdown of the crude oil temperature drop rate in this section of the pipeline. When stopping the transmission of 15h, the entire section of crude oil were below the wax precipitation point, A, B section of the overall temperature drop rate was basically equal.

From the interval between the two curves of 10 and 15h, it can be seen that the temperature drop in section A was obviously higher than that in section B for the same pipeline cross section. This was because the crude oil in the section A at 10h was above the waxing point, the heat exchange method was mainly the natural co-current heat exchanges, the raw oil in B section was already below the Waxing Point, showing the characteristics of the porous medium, the method of heat transmission changed. The temperature drop in section B was significantly slower than that in section A at 15h.

5.3 Changes in crude oil temperature and flow fields at typical locations under maintenance conditions

The flow and temperature fields in the pipeline at the typical locations of the inlet section, excavation section and inlet section at different times of stoppage were shown in Fig.6.

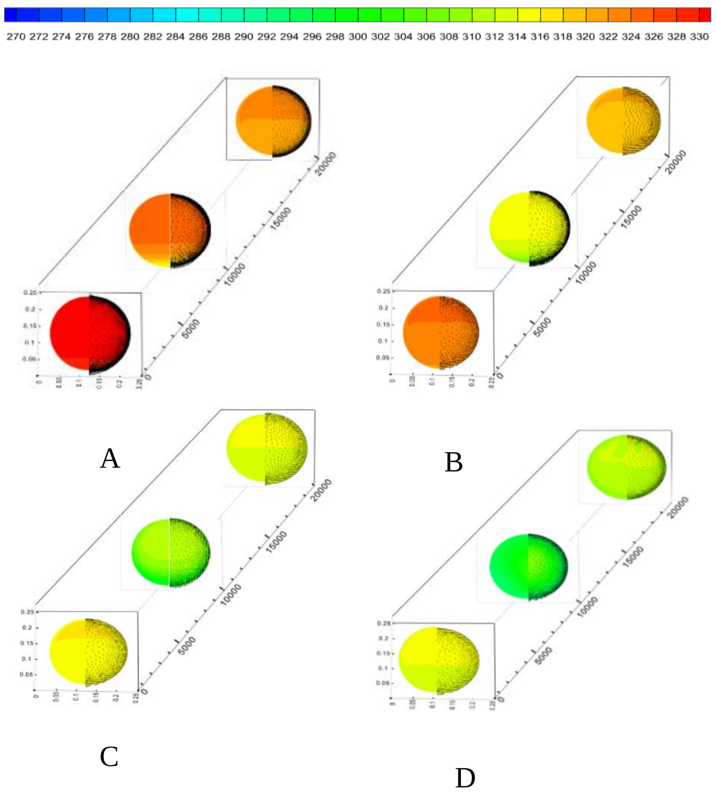


Fig. 6. Cloud images of flow field and temperature field in radial section at different locations

As shown in Fig. (A), after the crude oil pipeline was shut down, the oil temperature was high and evenly distributed in the middle and upper part of the excavated section of the pipeline, but there was a local low temperature zone in the lower part of the pipeline, and it was stratified. Large vortices were formed throughout the pipeline. As the shutdown time increased, the oil temperature near the pipe wall decreased more significantly. Due to the increase in density of the cold oil, it will accumulate at the bottom of the pipeline under the effect of natural convection, and the hot oil with higher temperature will move to the upper part of the pipeline, and the flow field in the whole pipeline was significant. From the clouds of the excavated pipe section clouds in Fig. (B)-(C), it can be seen that the isotherm at the bottom area of the pipeline had gradually changed from an almost parallel line to an elliptical shape similar to the geometry of the pipeline. When the pipeline was stopped for 17h, as shown in Fig. (D), the crude oil isotherm gradually changed from an elliptical shape to a concentric circle shape, and the flow almost completely disappeared, at which time the heat transfer mode of the crude oil in the pipeline was mainly conduction.

The difference in heat transfer characteristics between the excavated and unexcavated sections was more obvious when comparing the calculated results of the temperature clouds of the excavated and unexcavated sections. The buried pipeline was slower to dissipate heat from the crude oil due to the heat storage in the soil and the long natural convection effect. Comparison of the velocity vectors showed that the high flow rate of the crude oil was concentrated near the inner wall of the pipeline, especially the lower wall of the pipeline, while the relative velocity of crude oil at other locations was smaller and showed upward movement. The slow temperature drop of crude oil containing wax in buried pipelines and the high specific heat of the soil around the pipeline were the main reasons for this phenomenon.

5.4 Solidification pattern of crude oil in the pipe at typical locations

The solidification pattern of crude oil in the pipe at typical locations under maintenance conditions.

It can be seen from Fig. 7, the solidification process is similar for different radial sections of the crude oil pipeline. For the excavated section at -20℃ ambient temperature when stopping the transmission for 5h, the bottom of the crude oil pipeline had appeared obvious gelling layer. At the beginning of the shutdown, as the heat dissipation of the crude oil in the pipeline gradually increased, the crude oil near the pipe wall was the first to dissipate and cool, and was the first to solidify when its temperature drops to the solidification point. Due to natural convection, the hot oil is always in the upper part of the pipeline, so the condensate layer appeared first on the lower wall of the pipeline, and the solidification phenomenon appeared on the lower wall of the excavated section of the pipeline after 5h, and the condensate appears on the upper wall of the pipeline after 15h. In the middle and late stage of stopping transmission, due to the release of latent heat of solidification, the "crescent-shaped" condensate layer gradually became bigger, thicker and starts to transform to the circular shape, which was characterized by the thinning on top and the thickness underneath. With the increase of stopping time, the natural convection effect was weakened, the heat conduction effect was gradually enhanced, the thickness difference between the upper and lower condensate layer was gradually reduced, and the radial thermal resistance of the pipeline in the whole excavation section was approximately equal. During the solidification phase transition, the liquid phase rate in the liquid-phase region gradually decreased, and the liquid-phase region continued to shrink until it solidifies.

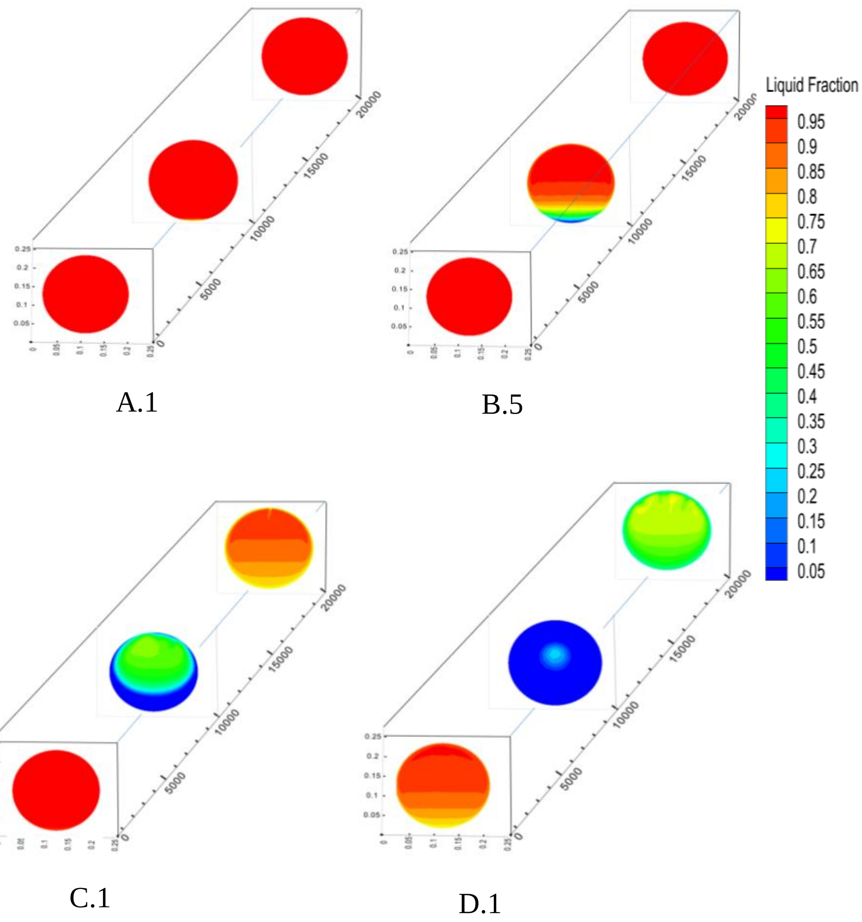
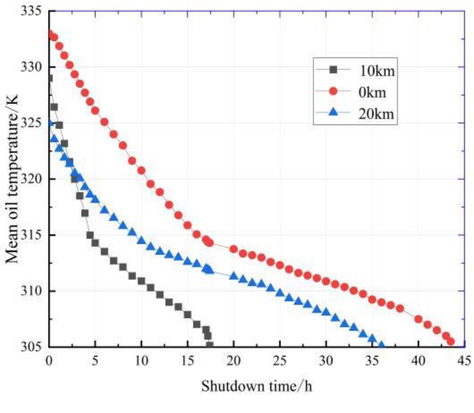


Fig. 7. Frozen cloud image



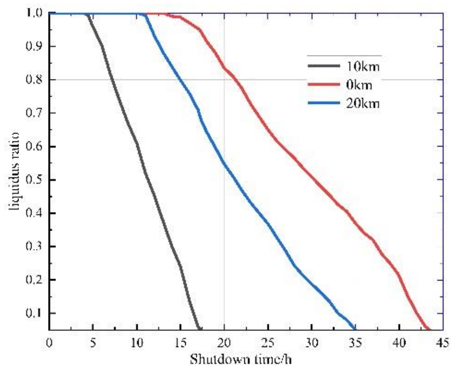


Fig. 8. Comparison of average temperature in the tube

Fig.9. Comparison of liquid phase rates

Because of the soil heat accumulation effect, the crude oil in the non-excavation section of the pipeline was all liquid oil, the natural co-flowing effect is weak, so the entire gel layer separation interface showed the level characteristics.

5.5 Changes in the average temperature and liquid phase rate of crude oil in the pipeline

The changes in the average temperature and liquid phase rate of crude oil in the pipeline during the shutdown process were shown in Fig. 8,and Fig.9.

As can be seen from Fig.8, the trend of oil temperature reduction after pipeline shutdown at different locations was the same and divided into three stages. Stage 1: The slope of temperature drop of crude oil was the largest. In the initial stage of stoppage, due to the large temperature difference between the crude oil inside the pipe and the soil outside the pipe, the crude oil inside the pipe lost heat to the soil area outside the pipe and the temperature decreased rapidly. Stage 2: The temperature of crude oil reached the waxing point, the temperature drop rate of crude oil slowed down and the natural convection in the porous medium weakened; at the same time, the wax crystal grid started to form in the lower temperature area on the inner side of the pipe wall, the wax crystal will release the latent heat of waxing in the process of precipitation, which slowed down the temperature drop rate of crude oil. Stage 3: The temperature drop rate increased slightly compared to the second stage, due to the fact that the heat was mainly dissipated to the outside world in the form of condensate heat transfer, the thermal conductivity of the condensate was large and the overall thermal resistance was relatively small. However, compared with the first stage, the temperature drop rate was relatively slow. This was due to the fact that there was no natural convection heat transfer in this stage, and the heat transfer can be regarded as pure conduction heat, and the thermal resistance was larger in this stage, and the temperature difference between the crude oil inside the pipe and the soil outside the pipe was smaller, which lead to a significantly smaller temperature drop rate than the first stage.

As can be seen from Fig.9 the liquid phase rate of the crude oil in the first stage was basically unchanged because the cold oil at low temperature sinks and the hot oil floats, and the temperature did not reach the wax precipitation point of the transition state. Since then, due to the influence of internal and external temperature differences, the crude oil in the pipeline was rapidly transformed into a transitional state and a gel, the curve approximately resembling the palliative line below the opening. With the extension of the stoppage time, the rate of liquid phase rate of crude oil decreased gradually, the crude oil was in the fuzzy area of porous medium, and the temperature drop of crude oil slowed down significantly. As the crude oil temperature gradually approached the freezing point, the effect of the porous media fuzzy zone on the liquid phase rate change become more obvious. The pipeline wall surface crude oil all solidified as the pipeline stopping thermal conditions, 17 h pipeline wall surface crude oil completely solidified, so for this condition should be controlled within 17 h of the maintenance time to complete.

6 .Conclusion

This paper established a three-dimensional mathematical model of heat transfer under the multi-field coupling of atmosphere-soil-pipeline-crude oil for steady-state operation and shutdown maintenance conditions, carried out relevant numerical simulations, analyzed the thermal change characteristics of the shutdown pipeline, and obtained the following main conclusions:

1. The three-dimensional heat transfer temperature drop model established in this paper obtained simulation prediction results that were closer to the measured results than the two-dimensional model (the error was 2.63℃ and less than 2%, respectively).

2. At the two ends of the excavated section, the temperature drop along the buried section was more affected, and its temperature was higher than that of the middle section of the excavation. The rate of along-range temperature drop was faster before the overall excavated section than after the excavated section. When the whole pipe section crude oil were below the wax precipitation point, the overall temperature drop rate was basically equal.

3. The temperature field, flow field, and solidification evolution in the excavation section had experienced a significant change. The buried section of the pipeline exhibited a horizontal interface throughout the entire oil condensation layer due to the thermal storage effect of the soil.

4. For this simulated pipeline, according to the liquid phase rate change, the optimal repair excavation time should be controlled within 17h.

Acknowledgment

This certificate verifies that its holder has been awarded a fellowship from the China Postdoctoral Science Foundation(Certificate Number:2023MD734177).

Nomenclature

C	Constant
	Permeability factor， C = 104~107
cρ	Instantaneous equivalent specific heat capacity of crude oil， J/（kg·K）
cpj	Baseline specific heat capacity， J/(kg·K)
Fε	Form factor
Gk	Turbulent kinetic energy from laminar velocity gradients
Gb	Turbulent kinetic energy from laminar velocity gradients
H	Crude oil enthalpy， J/kg
h_a	Surface heat transfer coefficient of convective heat transfer from the outer wall of the pipe to the atmosphere， W/(m^2·K)
K	Permeability
P	Apparent pressure， Pa
Sk,	Customisation
S, ε	Crude oil temperature， K
T	Crude Oil Waxing Point Temperature， 315.15K.
TX	Polycondensation point temperature， 311.15K
TJ	Freezing point， 305.15K

TN	Atmospheric temperature，K
TK	Reference temperature，K
Tre	Initial temperature of pipeline medium，K
Tw	Thermostat temperature，K
T0	Fluctuations from excessive diffusion in compressible turbulence
Ym	Exothermic coefficient of the soil surface to the atmosphere, W/m²·K
αk	Heat transfer coefficient between the oil in the tube and the tube wall, W/m²·K
αh	Coefficient of expansion，1/K
β	Porosity during phase transitions zone
ε	Crude oil equivalent thermal conductivity，W/（m·K）
λ_t	Solid fraction
Φ	Thermal conductivity of liquid phase crude oil，W/（m·K）
λ_l	Thermal conductivity of solid phase crude oil，W/（m·K）
λ_s	Effective thermal conductivity，W/(m·K)
λt	Effective kinematic viscosity of crude oil，m2 /s
μe	Liquid phase crude oil kinematic viscosity，m2/s
μ0	Turbulent Prandtl number for the K-equation (factorless number)
σ k	Turbulent Prandtl number (uncaused number) for the σ ε equation
σ ε	Viscous stress
τ	

References

[1] Ying Xu, Xin Nie, et al, Phase-change heat transfer analysis of shutdown overhead pipeline, Case Stud. Therm. Eng. 13 (2019), 3.

[2] Liu Xiaoyan, Xu Ying. The analysis of influential factors on medium temperature distribution during the process of shutdown in overhead pipeline [J]. Journal of Engineering Thermophysics, 2012,33(5):847-850.

[3] Dai Zhonghua. Analysis on influencing factors of buried hot oil pipeline[J].Case Studies in Thermal Engineering,2019,16(C).

[4] Ying Xu. Sensitivity analysis of heat dissipation factors in a hot oil pipeline based on orthogonal experiments, Sci. Progr. 10 (2019) 1-19.

[5] Edvik, A.P. Leandro, et al. Effect of the flow shutdown temperature on the gelation of slurry flows in a waxy oil pipeline, Ind. Eng. Chem. Res. 54 (16) (2015) 4455–4459.

[6] Enbin Liu, et al, Simulation on the temperature drop rule of hot oil pipeline, Open Fuels Energy Sci. J. 6 (1) (2013) 55–60.

[7] Wei He,et al. Effects of different water-cooling heat sinks on the cooling system performance in a data center, Energy and Buildings, 2023, 113162.

[8] Bo Yu, Chao Li.Numerical simulation of a buried hot crude oil pipeline under normal operation, J. Eng. Thermophys. 30 (17) (2008) 2670–2679.

[9] Li Hao. Research on safe stopping time and restarting process of hot transmission waxed crude oil pipeline[D]. Xi'an Petroleum University, 2020. (MSc. Chinese)

[10] Meng Deli. Numerical simulation study of stopping and restarting of insulated crude oil pipeline [D]. Liaoning University of Petrochemical Technology,2019. (MSc. Chinese)

[11] Wang Kai. Calculation of axial temperature drop along hot waxy oil pipeline [J]. Pipeline Technique and Equipment,2005(02):8-9.

[12] Wang Haiqin. Calculation of temperature drop along the hot transport pipeline of wax-containing crude oil[J]. Oil and Gas Storage and Transportation, 2002(07):9-12+3.

[13] Lixin Wei, QM Lei, et al. Numerical simulation for the heat transfer behavior of oil pipeline during the shutdown and restart process[J]. Case Studies in Thermal Engineering, 2018, 12:470-483 .

[14] Weiqiang. Thermal characteristics of waxy crude oil during its static cooling in an overhead pipeline[J]. Case Studies in Thermal Engineering,2019,14(C).

[15] Li Chuanxian,Ji Bing. Numerical calculation of the temperature drop of the waxy crude oil pipeline [J]. Journal of Petrochemical Higher Education, 2019,32(03):95-102.

[16] Zhang Guozhong. Research on cooling process of buried thermal oil pipeline[J]. Oil and Gas Storage and Transportation,2004,23(12): 33-38.

[17] Qinglin Cheng, et al.The study on temperature fifield variation and phase transition law after shutdown of buried waxy crude oil pipelines[J]. Case Studies in Thermal Engineering, 2017, 10: 443-454.

[18] XiaoYan Liu, et al. Study on Heat Transfer Performance of Medium in Aerial Hot Oil Pipe for Shutdown[J]. Advances in Mechanical Engineering, 2015, 6:571676-571676.

[19] Xu Y, Cheng QL, et al. Effects of crude oil's variable physical properties on temperature distribution in a shutdown pipeline[J]. Advances in Mechanical Engineering, 2017, 9(4): 1-9

[20] Chen Xiaoyu. Numerical simulations of temperature field of an oil pipeline when transportation is stopped . [J]. Energy Storage Science and Technology, 2014, 3(2): 137-141.

[21] Wang Zicheng, Ma Guiyang. Crude oil property impacts on the rule of shutdown temperature drop for exposed pipeline [J]. Journal of Liaoning Shihua University, 2014, 34(5): 28-31.

[22] Guo CS , Nian XB, et al. Analysis of 2D flow and heat transfer modeling in fracture of porous media[J]. Journal of Thermal Science, 2017, 26(4): 331-338.

[23] Bhattacharya M, Basak T. A fixed-grid finite element based enthalpy formulation for generalized phase change problems: role of superficial mushy region[J]. International Journal of Heat and Mass Transfer, 2002, 45: 4881-4898.

[24] Lu Tao. Heat transfer model and numerical simulation of temperature decreasing and oil solidifying of buried crude pipeline during shutdown [J]. Journal of Thermal Science and Technology, 2005, 04: 298-303.

[25] Liu Xiaoyan, et al. Particle melting characteristics of spherical gelled crude oil In pipeline transportation [J]. Practice and Understanding of Mathematics, 2019, 15: 123-131.

[26] Wang Min. Numerical calculation research on complex heat transfer law in storage tanks of wax-containing crude oil [D]. Beijing: China University of Petroleum, 2017: 13-18.(MSc. Chinese)

[27] Gao DY, Chen ZQ. A thermal lattice Boltzmann model for natural convection in porous media under local thermal non-equilibrium conditions[J]. International Journal of Heat and Mass Transfer, 2014, 70: 979-989.

[28] Xu Ying. Study on the heat transfer mechanism of phase change of waxy crude oil based on wide phase interface partitioning[D]. Northeast Petroleum University, 2020.(PhD. Chinese)

[29] Wu Guozhong. Research on heat transfer in buried oil pipelines with stop-start [D]. Daqing Petroleum Institute, 2007. (PhD. Chinese)

Paper submitted: 14 October 2023
Paper revised: 19 December 2023
Paper accepted: 27 December 2023