HEAT TRANSFER CHARACTERISTICS OF OIL-WATER TWO-PHASE IN PIPELINE TRANSPORTATION DURING SHUTDOWN

by

Ying XU[a], Zhenjia LI[a], Qiang ZHANG[b], Xiaoyan LIU[a*], and Chuan MA[a]

[a]School of Mechanical Science and Engineering, Northeast Petroleum University, Daqing, China
[b]The No.2 Oil Mine of No. 3 Oil Production Company of Daqing Oilfield Co. Ltd, Daqing, China

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Gathering and transportation pipelines often appear shutdown condition due to damage, leakage, and other reasons. The reasonable maintenance time should be controlled by closely combined with the change law of the oil-water temperature in the pipeline. This paper established a multi-field coupling 3-D heat transfer mathematical model of the oil-water pipeline environment based on the two-phase shutdown pipeline as the research object. According to the changing law of the oil-water temperature field and flow field under a typical pipe diameter, the evolution behavior of the gelation layer in the pipe and the transformation process of heat transfer mode were analyzed, and the heat transfer characteristics between oil-water phase and its interface in the pipe were defined. With the liquid phase ratio of the oil phase changing the rule, reasonable maintenance time suggestions were given for gathering and transporting pipelines with different water content.

Key words*: gathering and transportation pipelines, oil-water two-phase, heat transfer characteristic, oil-water interface, maintenance time*

Introduction

Because of power failure, leakage, and other reasons, the oil and water gathering and transportation pipeline often appears the phenomenon of shutdown. Once the shutdown time is too long, the crude oil in the pipeline will solidify, and the restart failure will inevitably impact the environment and economy. The smooth progress of restarting after maintenance is closely related to the temperature drop of the medium in the pipeline. The heat transfer of oil pipeline shutdown involves many physical phenomena, such as oil phase transformation and heat transfer at the oil-water interface. Due to the difference in physical properties of oil and water, there is a complex coupled heat transfer process between oil, water, and pipe wall in the whole pipeline. Clarifying the temperature variation law of the oil-water two-phase during the shutdown process and exploring the heat transfer mechanism of the oil-water two-phase have important guiding significance for reasonable control of shutdown time and formulation of a restart plan.

At present, the heat transfer of fluid in pipeline transmission is mainly concentrated on the heat transfer characteristics of pure crude oil under the shutdown condition, and the research on the heat transfer of oil and water in the pipeline needs to be further studied. Liu and

[*]Corresponding author, e-mail: liu_xydq@163.com

Zhang [1] believed that the study on the temperature drop of waxy crude oil in a shutdown pipeline mainly adopted numerical simulation methods for heat transfer boundary movement of wax phase transition, natural convection of crude oil, and simplification of soil outside the buried pipeline. Rossi di Schio *et al.* [2] believed that natural convection particularly influenced the heat transfer of buried pipelines under the condition of high Reynolds number. Yu *et al.* [3] divided crude oil phase transition into four stages, used the enthalpy porosity model to describe the heat transfer process, and proposed a phase transition heat transfer model for waxy crude oil during an outage, which included the influence of non-Newtonian behavior, phase transition evolution, and turbulence. Girma *et al.* [4] discussed the change of pore volume in the gel of waxy crude oil with time when there is a temperature gradient between waxy crude oil and ambient temperature. Xu *et al.* [5] used polarized light microscopy to conduct microscopic experiments on the wax deposition process of wax-containing crude oil. They believed that the wax deposition process mainly included nucleation, growth, and bonding of wax crystals, which led to the formation of wax crystal networks. Alcazar-Vara *et al.* [6] believed that the rheological behavior of crude oil occurred when the temperature of crude oil in the pipe dropped to the point of paraffin evolution. Zhao *et al.* [7] believed that the gelation process of waxy crude oil near the wall surface was mainly affected by the wall temperature and convective heat transfer coefficient near the wall surface. Mohsen *et al.* [8] calculated the maximum safe shutdown time of hot oil pipelines based on the freezing point of crude oil by combining experiment and simulation. Liu *et al.* [9] determined the final complete solidification position and time of crude oil in the tube by tracking the plane's maximum temperature point change trajectory.

The research on the heat transfer between oil and water in pipes at home and abroad mainly focuses on the flow state. Izwan *et al.* [10] carried out the flow experiment of oil-water two-phase flow. The flow pattern and wax precipitation temperature were observed by measuring the pressure drop and liquid rate changes of waxy crude oil and water at different flow rates. This was the first attempt to use waxy crude oil and water two-phase flow. Shang and Sarica [11] derived analytical solutions for the temperature distribution of stratified oil-water flows during pipeline transport through energy balance based on the controlled volume method. Somer *et al.* [12] experimentally studied the heat transfer of oil-water dispersions in horizontal pipes. They concluded that the heat transfer rate depends on the volume fraction of the liquid. By analyzing the heat transfer and flow resistance data of five typical crude oils in horizontal pipes, Tuo *et al*. [13] found the influence law of crude oil viscosity and water content on the oil-water mixture's heat transfer and resistance. Karimi and Boostani [14] measured the heat transfer coefficient of oil-water two-phase flow under different flow patterns in a horizontal pipeline. They believed that the influence of water velocity on the heat transfer coefficient was more significant than oil velocities. Li *et al.* [15] developed a mathematical model for heat transfer characteristics in non-Newtonian liquid-liquid layered wavy tube flows. This model simulated the pressure variation, velocity characteristics, and temperature of oil-water flow in a horizontal pipeline and was verified by experiments in the literature. Li [16] studied the characteristics of oil flow pattern under the characteristic temperature of pressure drop, defined the two characteristic temperatures corresponding to flow pattern conversion and pressure drop transition as the characteristic temperature of gelling of high water cut crude oil, and established a simple and accurate calculation model for the characteristic temperature of gelling sedimentation. Syed *et al*. [17] experimentally studied the oil-water heat transfer characteristics of high-viscosity oil and low-viscosity oil under different fluid flow rates and components and found that the heat transfer phenomenon in liquid-liquid flow was affected by fluid volume fraction.

In conclusion, the complex heat transfer characteristics of the oil-water two-phase under the shutdown condition must be further studied for the oilfield gathering and transportation system. This paper established the 3-D two-phase thermodynamic model of oil and water in an overhead pipeline for the first time, and the numerical simulation and analysis were carried out. The change law of the temperature field and flow field in the oil-water zone was analyzed, the heat transfer characteristics between the oil phase, water phase, and oil-water interface were explored, and the mechanism of oil-water two-phase heat transfer in the shutdown pipeline was revealed. The research results were of great value in oil and gas storage and transportation.

Physical model

In the shutdown process, the oil and water dissipate heat to the outside world simultaneously, the oil-water interface heat exchange between the oil and water phase due to the different heat dissipation rates of the oil and water. In order to simplify the heat transfer process, the following three assumptions are made:

- To simplify the calculation, the solid medium is regarded as isotropic, with close contact between each layer and no heating resistance.
- In the early stage of the shutdown, under gravity, the fluid in the pipe has been in a stable state of stratification on oil and water, and the fluid temperature distribution is uniform.
- During the phase transition of crude oil, the crude oil in the liquid phase is regarded as an incompressible fluid, the wax crystals in the solid-liquid mixing zone are evenly distributed, and the volume change of crude oil is ignored.

Based on the aforementioned assumptions, the 3-D physical model of oil-water two-phase flow in overhead pipeline transport under the shutdown condition is shown in fig. 1. The distances from the center of the pipeline to the inner wall of the pipeline, the inner wall of the insulation layer and the outer wall of the insulating layer are r^1, r^2, and r^3, respectively.

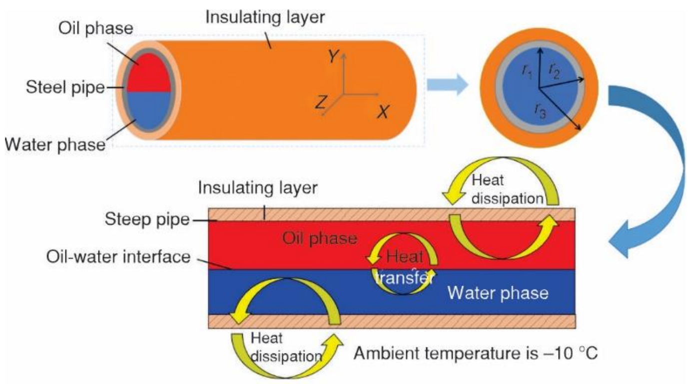

Figure 1. The 3-D physical model of oil-water two-phase in the overhead pipeline

Mathematical model

Correlated physical parameters

In the simulation process, the steel pipe with ∅ 168 × 7 mm was taken as an example, the insulating layer was 30 mm, and the pipe length was 1 m. The initial shutdown temperature of the pipeline was 60 °C, the ambient temperature was –10 °C, the convective heat transfer coefficient of the outer surface was 25 W/m^{2}K, the surface emittance was 0.9, the initial fluid temperature in the pipeline was 333 K, the wax precipitation temperature of crude oil was 315 K, the aggregation temperature of crude oil was 311 K, and the condensation temperature of crude oil was 305 K. The corresponding relation of main physical properties was as:

– The relation between the density of crude oil and temperature

$$\rho_o = 0.902 - 8.177\times10^{-4}(T_o - 273.15) + 1.54\times10^{-6}(T_o - 273.15)^2 \tag{1}$$

where ρ_o is the density of crude oil, [kgm^{-3}]. T_o is the temperature of water, K.

– The latent heat was converted into instantaneous equivalent specific heat capacity

$$\frac{\mathrm{d}H(t)}{\mathrm{d}T} = \dot{m}c_{p,o}(T)\frac{\mathrm{d}T}{\mathrm{d}t} \tag{2}$$

$$c_{p,o} = \begin{cases} 18.33T - 2327.75 & T \le T_1 \\ -35.8T + 13667.5 & T_1 < T \le T_2 \\ 2140 & T > T_2 \end{cases} \tag{3}$$

where $c_{p,o}$ [Jkg^{-1}k^{-1}] is the specific heat capacity of crude oil, T_1 is 303 K, and T_2 is 322 K.

– The relation of thermal conductivity of crude oil with temperature

$$\lambda_o = \begin{cases} 0.15 & T_o \ge 322.15 \\ \dfrac{1.1265 - 0.011766(T_o - 273.15)}{1.7449 - 0.03922(T_o - 273.15)} & 313.15 < T_o \le 322.15 \\ 0.437932 - 0.005876(T_o - 273.15 & 305.15 < T_o \le 313.15 \\ 0.25 & T_o < 305.15 \end{cases} \tag{4}$$

where λ_o [Wm^{-1}K^{-1}] is the thermal conductivity of crude oil.

– The relation of viscosity of crude oil with temperature

$$\mu_o = 10^{5.06039 - 0.01951T_o} \tag{5}$$

where μ_o [Pa·s] is the dynamic viscosity of crude oil.

– The relation between the density of water and temperature

$$\rho_w = 1000.50 - 5.65\times10^{-3}\times(T_w - 261)^{1.89} \tag{6}$$

where ρ_w [kgm^{-3}] is the density of water and T_w [K] is the temperature of water.

The material parameters were shown in tab. 1.

Table 1. Physical parameters of simulated materials

Name/Unit	Steel	Insulating layer	Crude oil	Water
Density [kgm^{-3}]	7850	60	Eq. (1)	Eq. (6)
Specific heat capacity [Jkg^{-1}K^{-1}]	500	700	Eq. (3)	4182
Coefficient of thermal conductivity [Wm^{-1}K^{-1}]	48	0.04	Eq. (4)	0.6
Dynamic viscosity [Pa·s]			Eq. (5)	0.001

Governing equations

The research group [18] divided the waxy crude oil in the pipeline into a liquid phase region, a liquid-solid mixed porous media fuzzy region, and a solid phase region by constructing a regional heat transfer model of crude oil based on the aggregation point and freezing point. Then it established the governing equations for each region.

– Equation of continuity

The continuity equation was the same for the water and oil phases

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{7}$$

where u, v, and w [ms^{-1}] are the velocity components of the water and oil phases in the x-, y-, and z-directions.

– Momentum equation

(1) The momentum equation of the water phase was the same as that of liquid and solid oil

$$\rho_{\mathrm{o/w}}\left(\frac{\partial u}{\partial \tau}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=F_{\mathrm{ox/wx}}-\frac{\partial p_{\mathrm{o/w}}}{\partial x}+\eta_{\mathrm{o/w}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{8}$$

$$\rho_{\mathrm{o/w}}\left(\frac{\partial v}{\partial \tau}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=F_{\mathrm{oy/wy}}-\frac{\partial p_{\mathrm{o/w}}}{\partial y}+\eta_{\mathrm{o/w}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{9}$$

$$\rho_{\mathrm{o/w}}\left(\frac{\partial w}{\partial \tau}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=F_{\mathrm{oz/wz}}-\frac{\partial p_{\mathrm{o/w}}}{\partial z}+\eta_{\mathrm{o/w}}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{10}$$

where ρ [kgm^{-3}] is the density, τ [s] – the time, F_x, F_z, and F_z [N] are the component of the volume force in the x-, y-, and z-directions, P [Pa] – the static pressure, and η [kgm^{-1}s^{-1}] – the dynamic viscosity. The subscript w is for water, and o is for oil.

(2) When the temperature of the crude oil was between the coalescence point and the condensation point, the crude oil in the pipe was in the porous medium zone. The momentum equation of the fuzzy region in the liquid-solid mixed porous medium of crude oil in the pipeline was as:

$$\frac{\partial\left(\rho_{\mathrm{o}}\overrightarrow{u_{\mathrm{o}}}\right)}{\partial \tau}+\left(\rho_{\mathrm{o}}\overrightarrow{u_{\mathrm{o}}}\nabla\right)\frac{\overrightarrow{u_{\mathrm{o}}}}{\varepsilon}=-\nabla(\varepsilon\rho_{\mathrm{o}})+\mu_{\mathrm{oe}}\nabla^2\overrightarrow{u_{\mathrm{o}}}+F \tag{11}$$

$$F=-\frac{\varepsilon\mu_{\mathrm{oe}}}{K}\overrightarrow{u_{\mathrm{o}}}\rho_{\mathrm{o}}-\frac{\varepsilon F_{\varepsilon}}{\sqrt{K}}\overrightarrow{u_{\mathrm{o}}}\left|\overrightarrow{u_{\mathrm{o}}}\right|+\varepsilon\rho_{\mathrm{o}}g\beta(T_{\mathrm{o}}-T_{\mathrm{ref}}) \tag{12}$$

$$\varepsilon=1-\frac{H_{\mathrm{o}}(T_j)-H_{\mathrm{o}}(T_{\mathrm{o}})}{H_{\mathrm{o}}(T_j)-H_{\mathrm{o}}(T_N)} \tag{13}$$

$$F_{\varepsilon}=\frac{1.75}{\sqrt{150\varepsilon^3}} \tag{14}$$

$$K=\frac{\varepsilon^3}{C(1-\varepsilon)^2} \tag{15}$$

where ε is the liquid phase fraction in the liquid-solid mixing zone, namely the voidage during the phase transition, T_{ref} [K] – the reference temperature of porous media, T_J [K] – the aggregation temperature of crude oil, T_N [K] – the condensation temperature of crude oil, F_ε – the shape factor, K – the permeability, β [K^{-1}] – the coefficient of expansion, and C (=10^4~10^7) – the porous media coefficient.

– Energy equation

(1) The energy equation of the water phase was the same as that of liquid and solid oil.

$$\frac{\partial T_{\mathrm{w/o}}}{\partial \tau}+u\frac{\partial T_{\mathrm{w/o}}}{\partial x}+v\frac{\partial T_{\mathrm{w/o}}}{\partial y}+w\frac{\partial T_{\mathrm{w/o}}}{\partial z}=\frac{\lambda_{\mathrm{w/o}}}{\rho_{\mathrm{w/o}}c_{p,\mathrm{w/po}}}\left(\frac{\partial^2 T_{\mathrm{w/o}}}{\partial x^2}+\frac{\partial^2 T_{\mathrm{w/o}}}{\partial y^2}+\frac{\partial^2 T_{\mathrm{w/o}}}{\partial z^2}\right) \tag{16}$$

$$T_{\mathrm{o}} > T_X, \qquad \lambda_{\mathrm{o}}=\lambda_{\mathrm{lo}} \tag{17}$$

$$T_J < T_{\mathrm{o}} \le T_X, \qquad \lambda_{\mathrm{o}}=\lambda_{\mathrm{lo}}\frac{2+\dfrac{\lambda_{\mathrm{so}}}{\lambda_{\mathrm{lo}}}+2\varPhi\left(\dfrac{\lambda_{\mathrm{so}}}{\lambda_{\mathrm{lo}}}-1\right)}{2+\dfrac{\lambda_{\mathrm{so}}}{\lambda_{\mathrm{lo}}}-\varPhi\left(\dfrac{\lambda_{\mathrm{so}}}{\lambda_{\mathrm{lo}}}-1\right)} \tag{18}$$

$$\varPhi=\frac{T_X-T_{\mathrm{o}}}{T_X-T_J} \tag{19}$$

$$T_{\mathrm{o}} < T_N, \qquad \lambda_{\mathrm{o}}=\lambda_{\mathrm{so}} \tag{20}$$

where T [K] is the temperature, λ [Wm^{-1}K^{-1}] – the thermal conductivity, cp [Jkg^{-1}K^{-1}] – the equivalent specific heat capacity, T_X [K] – the wax precipitation point temperature of crude oil, and $\varPhi$ – the solid phase fraction. The subscript *l* represents the liquid crude oil, and *s* represents the solid crude oil.

(2) The energy equation in the fuzzy region of solid-liquid mixed porous medium for crude oil in the pipeline.

$$\frac{\partial(\rho_{\mathrm{o}}H_{\mathrm{o}})}{\partial \tau}+\nabla\left(\rho_{\mathrm{o}}c_{p,\mathrm{o}}\vec{u}\nabla T_{\mathrm{o}}\right)=\lambda_{\mathrm{o}}\nabla^2 T_{\mathrm{o}} \tag{21}$$

The Enthalpy method was used to solve the change in the liquid phase ratio of crude oil, and its calculation formula was as:

$$H_{\mathrm{o}}(T)=\int_{T_N}^{T} C_{p,\mathrm{o}}(T_{\mathrm{o}})\mathrm{d}T_{\mathrm{o}}+C_{p,j}T_N \tag{22}$$

$$\lambda_{\mathrm{to}}=(1-\varepsilon)\lambda_{\mathrm{so}}+\varepsilon\lambda_{\mathrm{lo}} \tag{23}$$

where H_{o} [Jkg^{-1}] is the enthalpy of crude oil and $c_{p,j}$ [Jkg^{-1}K^{-1}] – the baseline specific heat capacity.

– Heat transfer equation for piping and insulating

$$\rho_{\mathrm{g/b}}c_{p,\mathrm{g/pb}}\frac{\partial T_{\mathrm{g/b}}}{\partial \tau}=\lambda_{\mathrm{g/b}}\left(\frac{\partial^2 T_{\mathrm{g/b}}}{\partial x^2}+\frac{\partial^2 T_{\mathrm{g/b}}}{\partial y^2}+\frac{\partial^2 T_{\mathrm{g/b}}}{\partial z^2}\right) \tag{24}$$

where the subscript *g* stands for pipe and *b* for insulating.

Initial and boundary conditions

At the initial moment of shutdown, the fluid temperature distribution throughout the pipeline was uniform and fixed value:

$$T_o = T_w = T_{in} \tag{25}$$

The fluid in the pipe was in contact with the pipe's inner wall:

$$-\lambda_g \frac{dT_g}{dr}\bigg|_{r=r_1} = h_{o/w}(T_{o/w} - T_g) \tag{26}$$

The tube wall was in contact with the insulating layer:

$$\lambda_g \frac{dT_g}{dr}\bigg|_{r=r2} = -\lambda_b \frac{dT_b}{dr}\bigg|_{r=r_2} \tag{27}$$

The outer wall of the insulating layer of the overhead pipe came into direct contact with the atmosphere:

$$-\lambda_b \frac{dT_b}{dr}\bigg|_{r=r_3} = h_b(T_b - T_f) \tag{28}$$

where h_b [Wm^{-2}K^{-1}] is the comprehensive convective heat transfer coefficient and T_f [K] – the atmospheric ambient temperature.

Numerical solution methods and independence verification

In the process of model building, the finite volume method was used to discrete the governing equation, the enthalpy method was used to deal with the phase transformation heat problem, laminar flow and solidification/melting model were selected, the SIMPLE algorithm and the second-order upwind scheme were used to solve the problem, and the phase-to-phase coupling method was used to solve the coupling of crude oil and water. The compound heat transfer of convection and radiation occurred between the outer wall of the pipeline and the atmospheric environment. In order to simulate the shutdown process more accurately, the steady-state simulation of the pipeline was carried out first to obtain the temperature field distribution of the pipeline and insulating layer. On this basis, the unsteady state numerical simulation was carried out to obtain the temperature field distribution after shutdown.

The average oil phase temperature in the pipeline was taken to verify grid and time step independence, as shown in figs. 2 and 3. Since the selected model was a symmetrical geometric figure, O-shards in ICEM were used for grid drawing.

As shown in fig. 2, the number of grids in Grid 1, Grid 2, and Grid 3 were 80523, 149144, and 241250, respectively. Through comparative analysis, the curves of Grid 2 and Grid 2 almost coincided. Grid 2 had met the accuracy requirements, so Grid 2 was selected for the numerical simulation analysis of the ∅ 168 × 7 mm steel pipe.

For the verification of time step independence, as shown in fig. 3. The number of grids was 149144, and the time steps were selected as 10 seconds, 20 seconds, and 40 seconds, respectively. Through comparative analysis, the oil phase average temperature curves with time steps of 10 seconds and 20 seconds almost coincided. Considering the calculation rate, the 20 seconds was used as the time step in the subsequent transient numerical simulation.

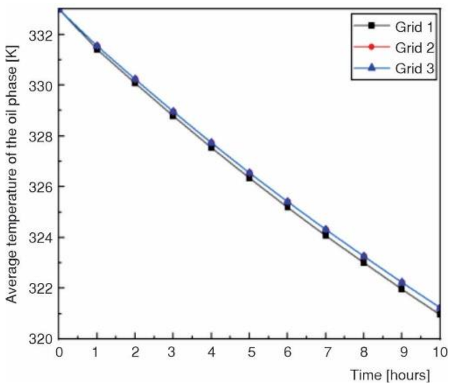

Figure 2. Average temperature of the oil phase under different grids

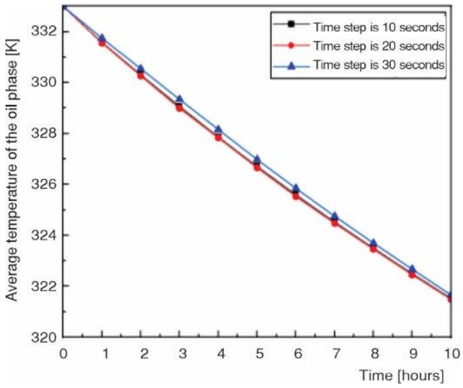

Figure 3. Average temperature of the oil phase under different time steps

Simulation results and analysis

Analysis of the temperature drop characteristics of the oil-water two-phase in the shutdown pipeline

Since the axial temperature gradient of the oil pipeline was much smaller than the radial temperature gradient, the section (center plane of the pipeline) at $Z = 0.5$ m was selected when the temperature field and flow field changed of the oil and water two phases in the shutdown pipeline are analyzed. In the shutdown process of the overhead pipeline, the oil-water interface was $Y = 0$ m, the conversion coefficient of the flow field was 1, and the length of the flow field vector was 1. The fig. 4 showed the temperature field and flow field at the ventral surface of a pipe with a 50% water content of $\varnothing$ 168 × 7 mm.

In the early stage of the outage, as shown in figs. 4(a) and 4(b). According to the flow field cloud diagram, in the oil phase and water phase region, the internal temperature difference led to the relative movement of cold and hot fluids, which made the oil and water two phases form two approximately symmetric eddies, respectively. The natural convection effect was violent at this time. According to the temperature cloud diagram, the lowest temperature area was on the upper wall. This is because, compared with water, oil's thermal conductivity and specific heat capacity were lower, and the oil phase carried less heat near the pipeline wall. Hence, the heat supplement to the upper wall of the pipeline was relatively slow. Meanwhile, the flow field vector direction generated by the oil and water phases at the oil-water interface was the opposite. Heat transfer occurred between the depositing cold oil and the floating high-temperature water, making the cold oil float after absorbing heat. As a result, the highest temperature area in the pipeline was in the crude oil area. The cold oil near the wall on the oil-water interface exchanged heat with the water phase and the pipe wall simultaneously, so the temperature drop here was faster than at the center of the oil-water interface.

In the middle shutdown period, the pipe temperature was lower for the oil phase than the wax precipitation temperature of crude oil, as shown in fig. 4(c). The flow field gradually weakened, and wax crystals precipitated in the oil phase area. The wax crystals released latent heat outward, and the oil phase isotherm presented a wave-like annular distribution. As shown in fig. 4(d), the temperature in the pipe was all lower than the aggregation temperature of crude oil. At this time, the eddies current of the oil phase flow field disappeared. The wax crystals precipitated gradually formed a porous grid structure, which made the liquid crude oil appear static in the pores, and the oil phase isotherm was evenly distributed in a ring. As shown in fig. 4(e), the temperature in the pipe was lower than the condensation temperature of crude oil. The oil phase flow field disappeared. For the water phase, the eddies current intensity gradually weakened with the temperature decrease. It can be seen from the temperature cloud diagram that the lowest temperature in the pipe at this stage appears on the lowest wall. This was due to the latent heat release effect of wax crystals in the oil phase region, and the heat loss between the crude oil and the wall could be quickly replaced so that the heat dissipation rate between the oil phase and the upper wall was lower than that between the water phase and the lower wall.

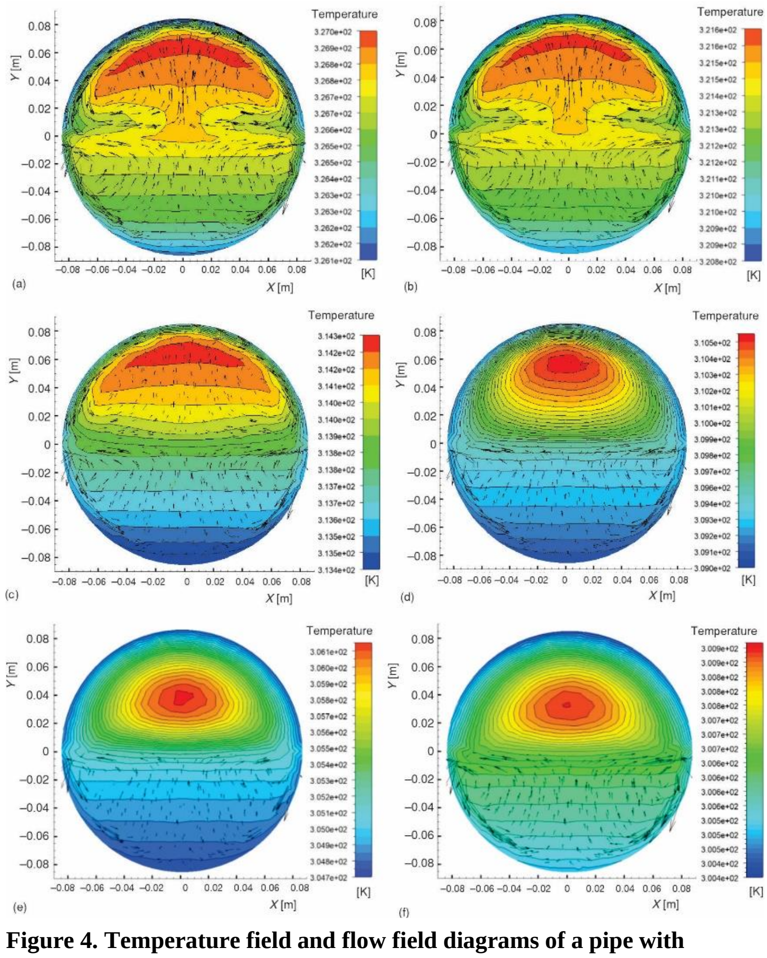

Figure 4. Temperature field and flow field diagrams of a pipe with a water content of 50% at typical times; (a) 5 hours, (b) 10 hours, (c) 20 hours, (d) 30 hours, (e) 43 hours, and (f) 50 hours

In the late outage period, as shown in fig. 4(f). The lowest wall temperature appeared on the upper wall, and the highest was found in the center of the oil phase. In the oil phase region, the latent heat release of the wax crystal ended, and the crude oil was all solidified, resulting in the heat transfer mode being mainly heat conduction. Due to the radial thermal resistance, the heat transfer of crude oil to the wall had slowed down. The flow field diagram showed that the heat of water could quickly replenish to the lower wall surface. During this period, convective heat transfer between the oil phase and the water phase interface was formed.

Analysis of gelation characteristics of oil-water two-phase flow in shutdown pipeline

During the shutdown process of the ∅ 168 × 7 mm overhead pipeline with 50% water content, the gelling cloud diagram of the oil-water two-phase flow on the central surface of the pipeline at a typical time was shown in fig. 5. The section of the pipeline (ventral surface of the pipeline) at $Z = 0.5$ m was taken, and the oil-water interface was $Y = 0$ m.

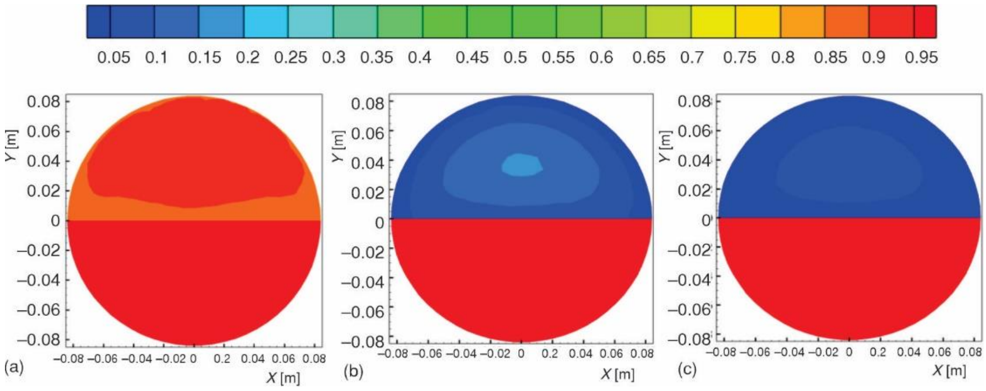

Figure 5. Gelling cloud diagrams of a pipe with a water content of 50% at typical times; (a) 20 hours, (b) 43 hours, and (c) 45 hours

According to fig. 5, with the increase of the stopping time, the crude oil in the inner wall of the pipeline was the first to dissipate heat under the effect of natural convection inside the oil phase and convective heat transfer between the water phase and the oil phase. The crude oil near the wall of the oil-water interface transferred heat with the pipe wall and water phase simultaneously, so the crude oil dissipated heat fastest there. Due to the existence of the water phase and the low thermal conductivity of the insulating layer, the temperature distribution gradient of the fluid in the whole tube was insignificant, and the oil phase waxy crystal state lasted for a long time. The gelation layer appeared on the inner wall of the oil phase pipe at 43 hours, and the thickness of the wall gelation layer near the oil-water interface was more significant than that on the upper wall. The highest temperature of the oil phase was located in the center of the oil phase. At 45 hours, the oil-water interface was covered by a gelation layer, and the thickness was the thinnest at the center of the oil-water interface. As the gelation layer thickened gradually, the natural convection in the oil phase was weakened, and the thermal conductivity was strengthened. The gelation layer interface gradually shrunk, approached the center of the oil phase, and finally wholly solidified.

Influence of different moisture content on the liquid phase ratio of the oil phase

With the increase in shutdown time, the fluid temperature in the tube drops below the crude oil wax evolution point, and the crude oil wax crystal precipitates, weakening its fluidity and the gradual decline of the liquid phase ratio of crude oil. Therefore, the safe shutdown time (the reasonable maintenance time) set in this paper should be controlled within the period of liquid phase ratio of 1.

According to figs. 6 and 7, the safe shutdown time of pipelines with 30% water content was 4.8 hours less than that of pipelines with 70% water content. Within 55 hours of the shutdown time, the lower the water content, the shorter the time of oil phase wax crystal precipitation, the slower the decline rate of oil phase liquid ratio, the shorter the safe shutdown time of the pipeline, and the longer the complete solidification time of crude oil. In the early stage of the shutdown, because of the large contact area between the oil phase area and the pipe wall of the pipeline in the low water content pipe, the liquid crude oil near the wall lost heat faster, and the crude oil wax crystal there was the first to occur. With the increase in shutdown time, because the oil phase in the pipeline with low water content had more heat storage and the potential heat release of crude oil was more significant, the temperature drop of crude oil was slower, the liquid phase rate was slower, and the complete solidification time was longer.

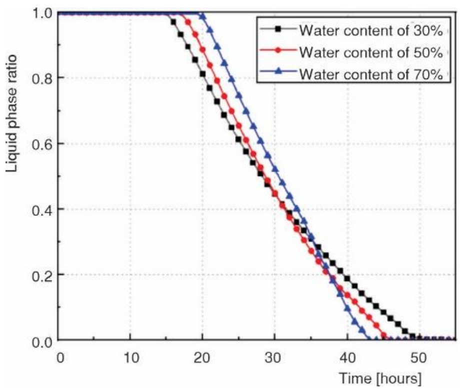

Figure 6. Liquid phase ratio of the oil phase with different water content

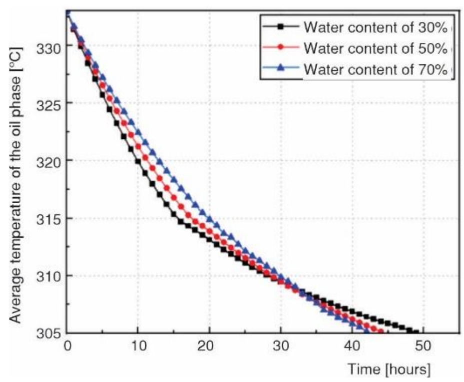

Figure 7. Average temperature of the oil phase with different water content

Conclusions

This paper established a 3-D oil-water heat transfer model in the overhead shutdown pipeline, and numerical simulation and heat transfer process analysis were carried out, focusing on the change law of the oil-water two-phase flow field and temperature field in the pipeline. The main conclusions were drawn as follows.

- At the initial stage, the overall oil phase temperature dropped rapidly due to the difference physical properties between the crude oil and the water. Since then, with the release of latent heat of phase transition and the appearance of porous medium structure in the crude oil region, the natural convection effect was weakened, and the average temperature of the water phase in the pipeline was lower than that of the oil phase, at the same time, the heat of oil phase was transferred to water phase through the oil-water interface.
- Due to the heat transfer between the oil-water interface, the thickest gelation layer in the pipeline was located at the pipe wall near the oil-water interface at the beginning of the formation of the gelation layer.
- For the shutdown pipelines with different water content, the wax crystal occurred first in the pipelines with the lowest water content (the liquid phase ratio started to be less than 1). However, due to the larger oil phase capacity of the pipeline with lower water content, the whole oil solidification time was longer. Considering the safe restart, it was suggested to reasonably adjust the pipeline's maintenance time based on its liquid phase ratio curve of the oil phase.

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References

[1] Liu, G., Zhang, Y. Y., Research Progress on the Shutdown and Cooling Process of Hot Oil Pipelines, *Journal of Beijing Institute of Petro-chemical Technology, 18* (2010), 3, pp. 11-17
[2] Rossi di Schio, E., *et al.,* Natural Convection Effects in the Heat Transfer from a Buried Pipeline, *Applied Thermal Engineering, 102* (2016), June, pp. 227-233
[3] Yu, G., *et al.,* A New General Model for Phase-Change Heat Transfer of Waxy Crude Oil During the Ambient-Induced Cooling Process, *Numerical Heat Transfer, Part A: Applications, 71* (2017), 5, pp. 511-527
[4] Girma, T., *et al.,* Temporal Variation of Voids in Waxy Crude Oil Gel in the Presence of Temperature Gradient, *Chemical Engineering Communications, 207* (2020), 10, pp. 1403-1414
[5] Xu, Y., *et al.,* Study on Micro-Structure Wax Evolution Behavior of Waxy Crude-Oil During Cooling, *Thermal Science, 26* (2022), 6A, pp. 4633-4643
[6] Alcazar-Vara, L. A., *et al.,* Effect of Asphaltenes on Equilibrium and Rheological Properties of Waxy Model Systems, *Fuel, 93* (2012), Mar., pp. 200-212
[7] Zhao, J., Li, Y. P, Numerical Simulation on the Thermal Process of Waxy Crude Oil During Its Storage Nuder Different Wall Temperatures, *Thermal Science, 26* (2022), 6B, pp. 4881-4895
[8] Mohsen, D., *et al.,* Experimental and Numerical Simulation on Buried Hot Fuel Oil Pipelines in Three Modes Flow Regime Considering Temperature Loss During a Shutdown, *Thermal science, 25* (2021), 1B, pp. 747-766
[9] Liu, Y., *et al.,* Sensitivity Analysis of Crude Oil’s Physical Properties to Total Freezing Time, *Thermal science, 24* (2020), 6A, pp. 3735-3747
[10] Izwan, I. A. S., *et al.,* Experimental Investigation of Oil–Water Two-Phase Flow in Horizontal Pipes: Pressure Losses, Liquid Holdup and Flow Patterns, *Journal of Petroleum Science and Engineering, 127* (2015), Mar., pp. 409-420
[11] Shang, W., Sarica, C., A Model for Temperature Prediction for Two Phase Oil/Water Stratified Flow, *Journal of Energy Resources Technology, 135* (2013), 3, pp. 1-7
[12] Somer, T. G., *et al.,* Heat Transfer to an Immiscible Liquid Mixture and Between Liquids in Direct Contact, *Desalination, 13* (1973), 3, pp. 231-249
[13] Tuo, L., *et al.,* Numerical Simulation Analysis of Oil-Water Mixed Transport in Horizontal Pipe, *China Petroleum and Chemical Standards and Quality, 33* (2012), 15, pp. 273-274
[14] Karimi, H., Boostani, M., Heat Transfer Measurements for Oil–Water Flow of Different Flow Patterns in a Horizontal Pipe, *Experimental Thermal and Fluid Science, 75* (2016), July, pp. 35-42
[15] Li, Y., *et al.,* Numerical Simulation of Oil-Water Non-Newtonian Two-Phase Stratified Wavy Pipe Flow Coupled with Heat Transfer, *Applied Thermal Engineering, 140* (2018), July, pp. 266-286
[16] Li, J., Study on Flow Characteristics and Technological Application of Oil-Water Two-Phase Flow in Unheated Oil Collection, Ph. D. thesis, China University of Petroleum, Qingdao, China, 2020
[17] Syed, A. A., *et al.,* Predictive Correlations for Heat Transfer Characteristics of Oil-Water Horizontal Pipe Flow-An Experimental Study, *Journal of Petroleum Science and Engineering, 75* (2021), Sept., pp. 35-42
[18] Xu, Y., Heat Transfer Mechanism of Waxy Crude Oil Based on Wide Phase Interface Partition Method, Ph. D. thesis, Northeast Petroleum University, Qaqing, China, 2020

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