STUDY ON THE MELTING CHARACTERISTICS OF BOW-SHAPED WALL-BOUND GELLED CRUDE OIL MIXED WITH HOT WATER IN GATHERING AND TRANSPORTATION SYSTEMS

by

Xiaoyan LIU, Jingjing HOU*, Chuan MA, and Ying XU

College of New Energy and Materials, Northeast Petroleum University,
Daqing, Heilongjiang, China

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Waxy crude oil at the wellhead typically has a temperature below its pour point, leading to the accumulation of gelled crude oil on pipeline walls, causing blockages. The melting behavior of gelled crude oil in hot water is critical for pipeline safety and efficiency. This paper presents a numerical simulation of the phase-change heat transfer process of bow-shaped gelled crude oil blocks with hot water injection along the inner pipe wall. The melting and flow characteristics of the gelled crude oil are analyzed, and the effects of water temperature, initial oil temperature and oil thickness on the melting process are discussed. The results indicate that the melting rate of gelled crude oil is relatively fast before the liquid phase fraction reaches 55%, while the melting rate slows down for the remaining 45%. Increasing the water temperature, the initial oil temperature, and reducing the oil thickness can accelerate the melting process of the oil block. However, their effects on shortening the melting time of the oil block exhibit a non-linear relationship. During the flow process, the melted crude oil undergoes deformation, becoming "flattened and elongated" and exiting the pipeline with water in a thin, strip-like form. The lower boundary of the crude oil develops an irregular, corrugated shape. Additionally, an increase in crude oil thickness leads to the formation of small droplets. These findings provide valuable insights for improving the safety and efficiency of crude oil gathering and transportation, as well as enhancing energy savings in practical engineering applications.

Keywords*: numerical simulation, phase change heat transfer and flow, gelled crude oils, bow-shaped*

Introduction

Chinese crude oil is typically characterized by a high freezing point, high viscosity, and high wax content. In deeper oil wells or wells with low liquid production, the wellhead temperature of gelled crude oil often drops below its condensation point. As a result, gathering and transportation processes commonly require mixing crude oil with hot water. However, because crude oil at the wellhead cannot be rapidly melted by hot water, pipeline blockages may occur, potentially leading to well shutdowns. Thus, understanding the melting and flow characteristics of gelled crude oil in hot water is essential for ensuring the safe and efficient

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[*] Corresponding author, e-mail: houjingjing2022@163.com

transportation of crude oil in pipelines. Furthermore, due to its lower density compared to water, some crude oil tends to adhere to the upper wall of the pipeline during the mixing process.

Li *et al.* [1] has investigated the melting and flow characteristics of gelled crude oil particles in water and numerically simulated the flow process of these particles after melting under natural and forced convection. The results indicate that the melting rate on the surface of the crude oil is different, the oil particles do not melt concentrically, and the monitoring points and rate of increase in temperature are not substantially affected by the phase change interval. Wang [2] numerically simulated the melting process of spherical gelled crude oil particles under pipeline transport conditions. The results indicated that the time required for complete melting of the oil particles, when the melted liquid phase does not flow out with the heated water, is approximately 20 times longer than the time for complete melting when the liquid phase forms small droplets and is carried out by heated water. Liu *et al.* [3] conducted transient numerical simulations of the melting process of waxy crude oil slugs on the inner wall of elevated pipelines under varying water temperature and flow conditions. The results showed that the initial temperature distribution is *U*-shaped along the monitoring line, with temperature decreasing gradually from the free surface of the oil to its interface with the pipe wall. The flow pattern has a significant influence on the melting time in its transition from laminar to turbulent but has little effect after the transition. Cui [4] has integrated experimental and numerical methods to study the melting behavior of bow-shaped gelled crude oil in hot water under no-slip conditions. This research analyzed the melting of the oil block under varying operational conditions, including the effects of different influencing factors on the melting time, the temperature changes at the center point, and the transformation of the oil block's shape.

So far, scholars have investigated the melting and flow characteristics of spherical crude oil particles suspended in water within pipelines. However, in practical engineering scenarios, due to the lower density of crude oil compared to water, some crude oil adheres to the upper wall of the pipeline during the mixing process with hot water. Regarding the transport conditions of cemented crude oil adhering to the wall, existing studies have primarily focused on the melting characteristics at planar interfaces. However, the flow behavior of gelled crude oil after melting, specifically near the wall during the crude oil gathering and transportation process, has not been reported in the literature. Consequently, this paper examines the coupled melting and flow characteristics of bonded gelled crude oil during its gathering and transportation when mixed with hot water.

The flow structure of crude oil is determined by the state of waxes, and the core issue in the melting of gelled crude oil lies in the melting of waxes within the oil, a non-stationary heat transfer problem involving phase change [5, 6]. Research on paraffin and other PCM is currently well-developed [7-13]. Bai [14] has investigated the factors influencing the melting rate of cylindrical ice columns and the evolution of their shape during the melting process. The results showed that the melting rate of the cylindrical ice column increases significantly with the rise in the Peclet number or Stefan number. Ice columns with different initial shapes exhibit the same self-similar behavior before the melting process reaches its conclusion. Guo *et al.* [15] has investigated the upward movement and melting characteristics of ice particles under different water superheating and ice particle subcooling conditions. They analyzed the morphological changes of the ice particles and the influence of local heat transfer coefficients on the melting process. Chen *et al.* [16] developed a heat storage model for paraffin melting in a square cavity to evaluate its heat storage performance. They studied the effects of heating direction and constraint form on paraffin's performance and validated the computational model through experimental tests. Debasree and Chandan [17] used numerical simulations to explore how variations in thermophysical properties of cavity materials and boundary conditions affect the melting process of paraffin wax in a spherical cavity. They found that an increase in the Stefan number or the thermal diffusion coefficient of the cavity material accelerates the melting rate of paraffin wax. Zhang *et al*. [18] employed FLUENT software to analyze the melting characteristics of PCM under different operating conditions. Results indicated that the inlet temperature of the thermal fluid had the greatest impact, followed by the thickness of the PCM and its initial temperature. Yang *et al*. [19] combined experiments and numerical simulations to study how cavities with different aspect ratios influence the melting characteristics of PCM. Their findings revealed that smaller aspect ratios lead to faster temperature changes within the cavity during melting. Jiang *et al*. [20] enthalpy-porosity and volume of fluid (VoF) methods were adopted to simulate the melting process of wax in the crude oil gathering pipeline. The results show that the wax melts quickly before the liquid fraction reaches 80%, while the remaining 20% melts very slowly.

The aforementioned literature focuses on the influence factors of PCM such as ice and paraffin in the melting process, and the flow and heat transfer characteristics of ice slurry and paraffin in the melting process. The previous references provide a reference for the study of flow and heat transfer characteristics of crude oil in pipeline. In this paper, the phase change heat transfer and flow coupling characteristics when hot water melts the cemented crude oil in a gathering and transportation pipeline under different working conditions are numerically simulated. The effects of inlet water temperature, flow rate, crude oil thickness and initial temperature on the melting and flow characteristics of gelled crude oil were discussed, which provided theoretical basis and reference for the mixed transport process of gelled crude oil with hot water.

Modeling and validation

Physical model

The physical model of wall-adherent gelled crude oil is shown in fig. 1. The pipeline material is steel, length $L = 1000$ mm, inner diameter $\Phi = 53$ mm, wall thickness $\delta = 2$ mm, the oil block is located at 600 mm from the pipe inlet, the axial length of the crude oil is 50 mm, the upper surface is close to the inner wall of the pipeline, and the lower surface is 10 mm from the top of the inner wall of the pipeline.

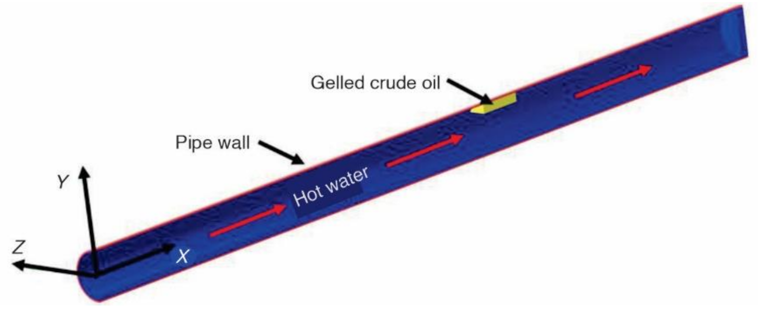

Figure 1. Physical model

The model assumes that the crude oil block adheres to the pipeline wall, with melted crude oil flowing out of the pipeline along with the water. The oil temperature should exceed the freezing point by at least 3 °C to ensure safe operations. In this study, the condensation point of the simulated crude oil is 38 °C, so safe gathering and transportation require the overall crude oil temperature to be maintained above 41 °C. The model accounts for three types of heat transfer processes: forced convection heat transfer between hot water, crude oil, and the pipeline wall, heat conduction between crude oil and the pipeline wall, and phase change heat transfer within the crude oil. Melted crude oil exits the pipeline along with the hot water.

Mathematical model

To simplify the simulation analysis, the following four assumptions are made:

- The thermophysical properties of crude oil remain constant with temperature, and the crude oil is considered incompressible and isotropic.
- The phase change temperature range of crude oil is defined as 38-41℃, with a fixed latent heat value assigned within this range.
- The flow within the pipeline is assumed to occur in a fully developed region.
- No heat exchange occurs between the system and its external environment.

Based on the previous assumptions, the mathematical model is formulated as:

- Control equations

For water:

Continuity

$$\nabla \vec{u} = 0 \tag{1}$$

Momentum

$$\rho_{\mathrm{w}} \left[\frac{\partial \vec{u}}{\partial \tau} + \left(\nabla \vec{u} \right) \vec{u} \right] = F - \nabla \vec{p} + \eta_{\mathrm{w}} \nabla^2 \vec{u} \tag{2}$$

Energy

$$\frac{\partial T}{\partial \tau} + (\nabla \vec{u}) T = \frac{\lambda_{\mathrm{w}}}{\rho_{\mathrm{w}} c_{p,\mathrm{w}}} \nabla^2 T \tag{3}$$

For oil:

Energy

$$\frac{\partial H}{\partial \tau} = \frac{\lambda_o}{\rho_o} \nabla^2 T \tag{4}$$

$$H = h + \Delta H \tag{5}$$

$$h = h_{\mathrm{ref}} + \int_{T_{\mathrm{ref}}}^{T} c_p \mathrm{d}T \tag{6}$$

$$\Delta H = \gamma L \tag{7}$$

where c_p is the specific heat capacity at constant pressure, L – the latent heat of phase transition, T_{ref} – the reference temperature, γ – the liquid fraction, and h_{ref} – the enthalpy of the phase transition material at the reference temperature.

- The VoF volume fraction equation:

$$\frac{\partial \alpha_{\mathrm{i}}}{\partial \tau} + \vec{\mu} \nabla \alpha_i = 0 \tag{8}$$

and

$$\alpha_1 + \alpha_2 = 1 \tag{9}$$

$$\rho=\alpha_1\rho_1+\alpha_2\rho_2 \tag{10}$$

$$\mu=\alpha_1\eta_1+\alpha_2\eta_2 \tag{11}$$

where α_i is the concentration of phase i and subscripts 1, 2 represent two different phases.

- The SST k-ω:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-Y_k+S_k \tag{12}$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_i}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]+G_\omega-Y_\omega+D_\omega+S_\omega \tag{13}$$

where k is the turbulent kinetic energy, ω – the specific dissipation of turbulent kinetic energy, and S_k and S_ω – the specified source terms:

$$G_k=\mu_t f_c S^2-\frac{2}{3}\rho k\nabla v-\frac{2}{3}\mu_t(\nabla v)^2 \tag{14}$$

$$G_\omega=\rho\gamma\left[\left(S^2-\frac{2}{3}(\nabla v)^2\right)-\frac{2}{3}\omega\nabla v\right] \tag{15}$$

where ∇v is the velocity dispersion, S – the modes of the average strain tensor, and σ_ω, γ are the mixing coefficients of the model.

Initialization conditions: A constant value is set for the pipeline, the inlet water temperature, and the initial temperature of the oil block.

$$T=T_{\text{ini}},\quad \tau=0 \tag{16}$$

Boundary conditions: During the melting process, the inlet boundary of the pipeline was set as velocity-inlet, and the outlet was set as outflow. The crude oil is coupled to both the hot water and the pipeline wall, with an adiabatic outer boundary condition and a coupled inner wall surface.

Verification

The SIMPLE method in the commercial software FLUENT was used to solve the governing equations. Before the melting begins, the initial temperatures of the gelled crude oil, hot water, and the pipeline are set to constant values. Throughout the melting process, the pipeline inlet is defined as a velocity inlet, and the pipe walls are assumed to be adiabatic. The second-order windward scheme discretizes the momentum and energy equations, and the convergence criterion is maintained at its default setting. The pressure relaxation factors for pressure, density, volumetric force, momentum, liquid fraction update, and energy are set to the following values: 0.3, 1, 1, 0.7, 0.9, and 1.

Independence verification of grid and time step

The meshing software was used to generate four sets of hexahedral meshes with grid counts of 204109, 469820, 674411, and 971027. At a water temperature of 60 °C, with an initial oil block temperature of 10 °C, an oil block thickness of 10 mm, and a time step of 0.01 seconds, the variation in the liquid fraction of gelled crude oil over time for different mesh resolutions is shown in fig. 2. The results indicate that the influence of mesh resolution on the liquid fraction of gelled crude oil during the melting process is negligible. Consequently, to ensure computational accuracy while optimizing computational efficiency, a mesh size of 204109 was selected for the numerical study.

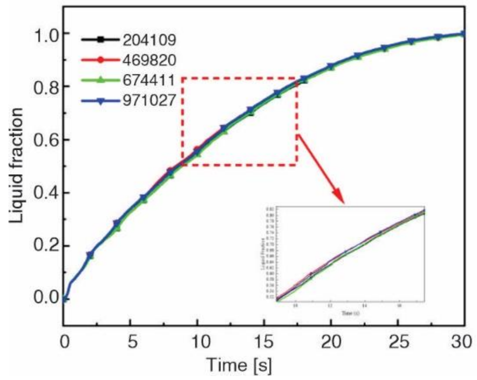

Figure 2. Variation of crude oil liquid fraction at different grid numbers

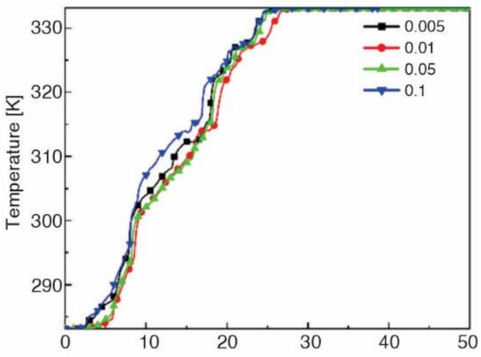

Figure 3. Variation of oil center point temperature at different moments

As shown in fig. 3, the change in the crude oil center, located in point (625, 0, 21.5), temperature over time exhibits slight differences under the four time steps analyzed. However, when the time step is reduced to 0.005 seconds, the temperature variation trend closely aligns with that observed at a time step of 0.01 seconds. Considering both the accuracy of the simulation results and the need to minimize computational effort, a time step of 0.01 seconds was selected for subsequent simulations.

Melting model validation

To verify the feasibility of using the finite volume method for modeling the solid-liquid two-phase melting problem, a comparison was made between the results of this study and those from Wang [2], who analyzed the three-dimensional forced convection melting of gelled crude oil in a pipeline. The verification results are presented in tab. 1. The physical model is displayed in fig. 4. The crude oil particles remain stationary at this position, and the melted liquid-phase gelled crude oil does not flow out of the pipeline with the water. Throughout the melting process, heat was transferred from the water to the oil via convective heat exchange. By validating the accuracy of the phase change heat transfer calculations, it was confirmed that the finite volume method, incorporating turbulence and fluid heat transfer, is capable of solving the phase change problem associated with the melting of gelled crude oil.

Table 1. Melting model validation results

Flow rates	0.1 m/s	0.2 m/s	0.3 m/s
Simulation results by [2]	114.2 seconds	92.7 seconds	53.8 seconds
Validation results	109.6 seconds	90.1 seconds	52.3 seconds
Errors	4.0%	2.8%	2.8%

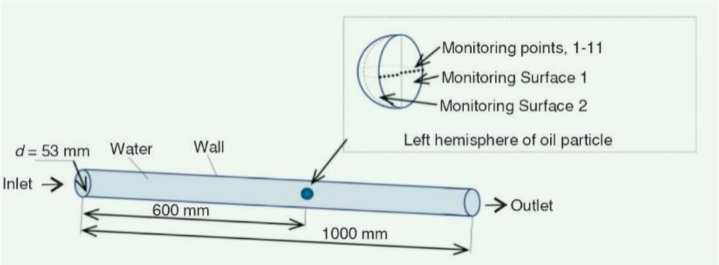

Figure 4. Verified physical model [2]

Flow model validation

To validate the finite volume method for solving flow and heat transfer problems in the solid-liquid two-phase system, a comparison was made with the work of Wang [2], who analyzed the melting and flow of 3-D spherical gelled crude oil in a pipeline. The validation results are presented in tab. 2. The physical model is depicted in fig. 4. Numerical simulations were performed to study the melting phase transition of crude oil under conditions of relative slip between the oil and water phases, as well as variations in particle shape. This comparison confirmed the accuracy of the mathematical models and solution methods of the finite volume method in addressing the flow and heat transfer of gelled crude oil.

Table 2. Flow model validation results

Flow rates	0.1 m/s	0.2 m/s	0.3 m/s
Simulation results by [2]	2.33 seconds	1.26 seconds	0.83 seconds
Validation results	2.52 seconds	1.37 seconds	0.91 seconds
Errors	8.2%	8.7%	9.6%

Simulation results and analysis

The physical parameters of the steel pipeline and gelled crude oil used in this study are presented in tabs. 3 and 4, respectively. Table 5 provides the latent heat values applied in the simulation, determined through differential scanning calorimetry testing combined with a calculation method for wax precipitation during crude oil wax formation. In the simulation, the crude oil temperature is set to a constant value below its freezing point, ensuring it remains in a subcooled state. The outer wall of the pipeline is modeled as an adiabatic boundary, and the initial pipeline temperature is assumed to be constant.

Table 3. Parameters of the pipeline

Parameter	Value
Density	8030 kg/m^3
Specific heat	502.48 J/kgK
Thermal conductivity	16.27 W/mK

Based on the diameter and flow velocity of the simulated oilfield gathering pipeline, the flow is classified as forced convection. A monitoring surface, referred to as Surface 1, is located 625 mm downstream from the pipeline inlet, as illustrated in fig. 5.

Table 4. Parameters of Daqing crude oil

Parameter	Value
Density	889.8 kg/m^3
Thermal conductivity	0.2 W/mK
Specific heat	2400 J/kgK
Solidification point	311.15 K
Melting point	314.15 K
Dynamic viscosity	0.05 Pa·s

Table 5. Latent heat of melting of gelled crude oil at different temperature intervals

Oil temperature [°C]	Hot water temperature [°C]	Latent heat [Jkg^{-1}]
10	50	29056.8
10	55	29995.9
10	60~70	30302.1
5	60	33266.1
15	60	26506.6
20	60	21834.3
25	60	16506.9
30	60	11141.4

Nine monitoring points are designated on Monitoring Surface 1, as shown in fig. 5. The coordinates of the points are as follows: Point-1 (625, 0, 16.5), Point-2 (625, 0, 19), Point-3 (625, 0, 21.5), Point-4 (625, 0, 24), Point-5 (625, 0, 26.5), Point-6 (625, -10, 16.5), Point-7 (625, -10, 19), Point-8 (625, -10, 21.5), and Point-9 (625, -10, 24).

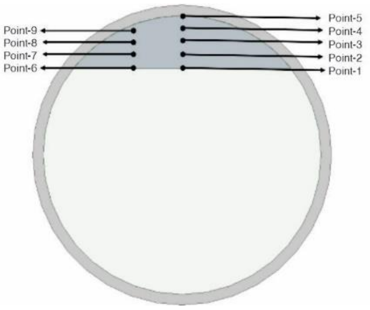

Figure 5. Monitoring points and surfaces

Melting process analysis

The inlet water flow rate was set to 0.3 m/s, with a water temperature of 60 °C and a gelled crude oil thickness of 10 mm. At an initial crude oil temperature of 10 °C, the distribution of oil and water phases on Monitoring Surface 1 at different time intervals is shown in fig. 6.

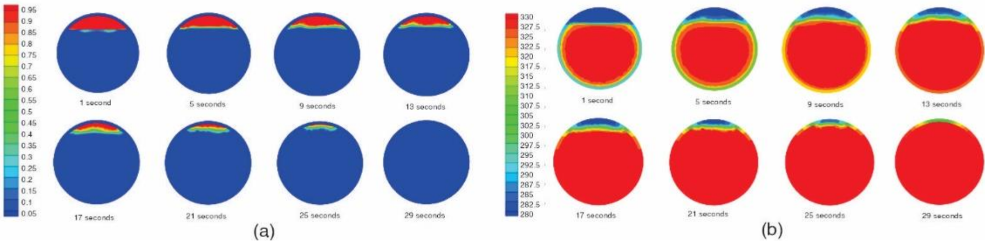

Figure 6. Monitoring surfaces at typical times contours; (a) oil-water two-phase distribution and (b) temperature distribution

The temperature distribution contours and oil-water two-phase distribution contours on the monitoring surface revealed that the lower boundary of the crude oil did not remain a smooth plane during the melting process. This irregularity arose because the lower surface of the oil block, being in direct contact with high temperature water, experienced continuous forced convection heat transfer, leading to a rapid temperature rise at the lower boundary. The liquid crude oil reaching the melting point melted first and flowed out of the pipeline in the direction of the water flow, causing the shape of the lower boundary to change irregularly. Additionally, during this flow, a velocity boundary layer formed on the crude oil surface in contact with the water, resulting in significant variations in fluid velocity. This velocity gradient caused different melting rates at various positions on the oil block's surface. Consequently, the lower boundary of the crude oil continuously deformed, exhibiting an irregular wavy pattern.

Analysis of temperature changes at monitoring sites

Figure 7 presents the temperature-time curves for an oil block with an initial temperature of 10 °C, a thickness of 10 mm, subjected to an inlet water temperature of 60 °C and a flow velocity of 0.3 m/s.

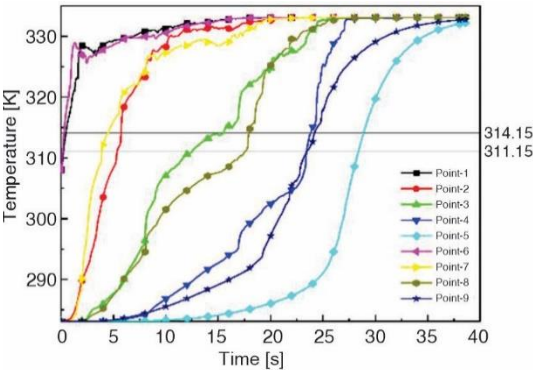

Figure 7. Temperature changes at points on the monitoring surface

As shown in fig. 7, during the initial stage of melting, heat from the water was not immediately or fully transferred to the interior of the oil block, causing the crude oil's temperature to remain constant. Due to the absence of a temperature gradient within the oil block, no heat transfer occurred, and its temperature remained at the initial level for a short period. As convective heat transfer progressed, the temperature-time curve exhibited an increasing slope, indicating a gradual transfer of heat from the hot water into the crude oil. The lower edge of the oil block underwent convective heat transfer with water. Once the first melted oil reached its melting point, the underlying crude oil had already absorbed heat and undergone phase transition. Since its temperature exceeded the melting point, the internal temperature gradient accelerated heat transfer. In the later stages of melting, the slope of the curve decreased as the crude oil fully absorbed heat from the hot water, leading to a temperature increase. Consequently, the temperature difference between the oil and water diminished, and the overall crude oil temperature approached that of the hot water, eventually stabilizing.

At the initial moment, monitoring Points 1 and 6 were located at the oil-water interface, where forced convection heat transfer occurred. Due to the high heat transfer rate at this stage, the initial temperatures at these points were significantly higher than the overall initial temperature of the crude oil. Additionally, the warming rate at monitoring Points 1-9 did not exhibit a notable change during the phase transition interval. This can be attributed to the continuous contact between the melting crude oil and high temperature hot water, causing the interface to advance inward as melting progressed. The intense heat transfer between oil and water was sustained throughout the process. When the crude oil temperature at any monitoring point reached the melting point, a significant temperature difference remained between that point and the surrounding crude oil, ensuring rapid heat transfer from the high temperature region to the low-temperature region. This temperature-gradient-driven convective heat transfer mechanism allowed the phase change to occur without a noticeable reduction in the heat transfer rate during the melting interval.

Analysis of the effect of water flow temperature on the melting process

The variation of the time required for complete melting of the gelled crude oil when the water temperature is 50-70 °C and other conditions are constant is shown in fig. 8.

Figure 8 illustrates that as the temperature of the water stream increases, the time required for the complete melting of the gelled crude oil decreases. According to the fundamental principle of heat transfer, heat flows from high temperature regions to low temperature regions. When higher temperature water is introduced into the pipeline, the temperature difference between the water and the crude oil increases, thereby accelerating the rate of heat transfer. Consequently, the high temperature water transfers heat to the crude oil more efficiently, enhancing molecular motion and expediting the melting process. Additionally, since the melting of crude oil is an endothermic process, a higher water temperature improves the heat transfer efficiency per unit time. As the crude oil absorbs heat, its solid phase gradually transitions into a liquid state, further accelerating the melting process.

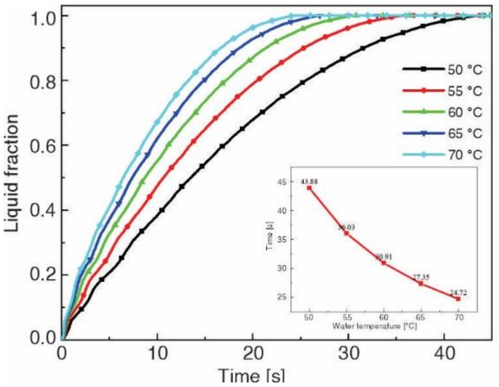

Figure 8. Liquid fraction *vs.* time at different water temperature

When the hot water temperature increased from 50-60 °C, the melting time decreased by 29.6%. A further increase to 70 °C resulted in a 20.2% reduction in melting time. This indicates the presence of a temperature threshold in the crude oil melting process. Once the hot water temperature reaches this threshold, further increases have a diminishing effect on reducing melting time. Additionally, excessively high heating temperatures lead to unnecessary energy loss and decreased energy utilization efficiency. In practical applications, optimizing the gathering process and minimizing energy consumption require identifying an optimal hot water temperature. This ensures a shorter melting time while maintaining efficient energy use, thereby reducing overall energy consumption.

Analysis of the effect of initial oil temperature on the melting process

The initial temperature of the oil block was 5-30 °C, other conditions remain unchanged. The crude oil liquid phase rate curves at different flow rates are shown in fig. 9.

When the initial crude oil temperature increased from 10-20 °C, the melting time decreased by 12.8%. A further increase from 20-30 °C resulted in a 13.8% reduction. These results indicate that when the initial crude oil temperature is relatively close to its melting point, increasing the initial temperature significantly accelerates the melting process. However, when the initial temperature is much higher than the melting point, the effect of further increasing the initial temperature on accelerating melting diminishes. This is because a higher initial temperature reduces the temperature difference between the oil and water, thereby lowering the heat transfer rate. Nonetheless, since higher temperature crude oil requires less additional heat to reach the melting point, it still melts more quickly despite the reduced heat transfer rate. Furthermore, high temperature crude oil typically has lower viscosity and improved flow properties, allowing for better mixing and heat distribution within the pipeline. This enhanced heat transfer efficiency further accelerates the melting process.

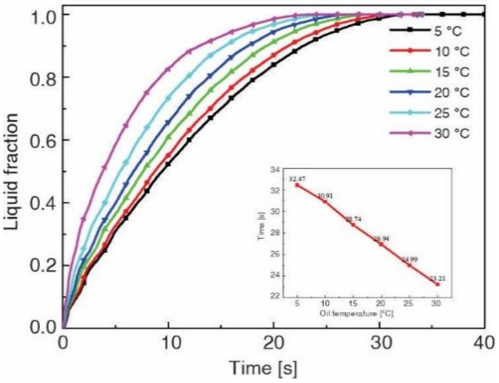

Figure 9. Liquid fraction *vs.* time at different initial oil temperature

Figure 10(a) presents the temperature distribution contours at different time points on monitoring surface 1 when the initial crude oil temperature was 5 °C. In the early stage of melting, the crude oil temperature was lower than the pipeline wall temperature. Consequently, in addition to convective heat transfer between the crude oil and water, thermal conduction occurred between the hotter pipeline wall and the colder crude oil, accelerating the melting process to some extent. Conversely, when the initial crude oil temperature exceeded the pipeline wall temperature by 10 °C, heat transfer occurred in the opposite direction, with the crude oil transferring heat to the pipeline wall via thermal conduction. This reversed heat transfer process slowed the melting of the crude oil. Figure 10(b) illustrates the temperature distribution cloud diagrams at different moments when the initial crude oil temperature was 20 °C.

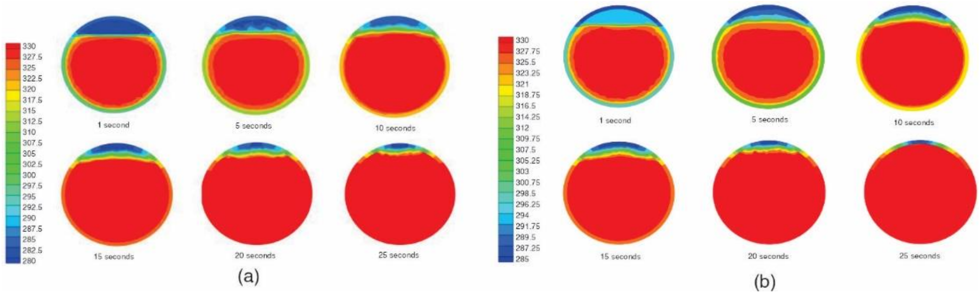

Figure 10. Temperature distribution contours; (a) T_{oil} = 5 °C and (b) T_{oil} = 20 °C

Flow process analysis

Effect of crude oil thickness on flow patterns

The interaction between the flowing fluid and the deformable solid-phase boundary of the gelled crude oil significantly influences the evolution of the solid boundary shape. Figures 11 and 12 present the cloud diagrams of the oil-water two-phase distribution for an initial oil block temperature of 10 °C, a water temperature of 60 °C, a flow rate of 0.3 m/s, and crude oil thicknesses of 10 mm and 30 mm.

As illustrated in fig. 11, the gelled crude oil gradually melted and deformed as hot water flowed over it. Due to the fluid's kinetic characteristics, a velocity boundary-layer formed at the interface between the hot water and the crude oil. The crude oil's velocity toward the hot water flow was higher at the leading edge than at the backflow region. In the direction of gravity, the un-melted oil block remained stationary, with only the velocity at its lower surface increasing. The heat transfer rate at the lower surface was higher than in the middle, leading to the formation of an irregular arc at the backflow surface during the initial stage of melting. As

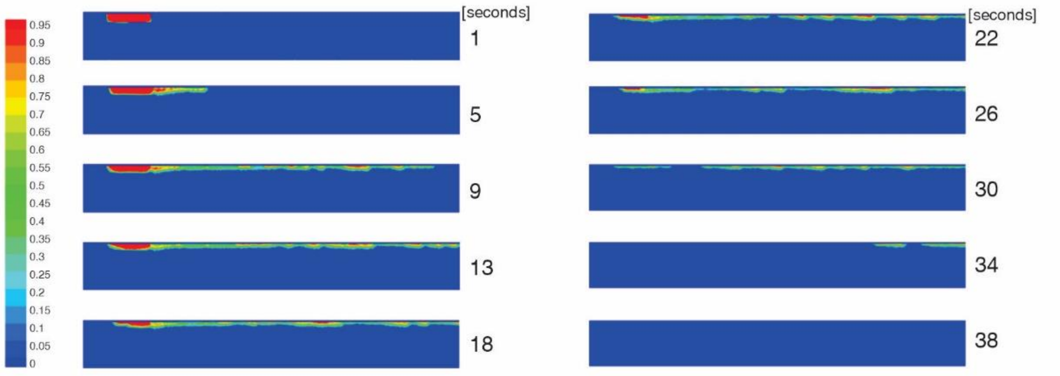

Figure 11. Oil-water two-phase distribution at different moments (δ_{oil} = 10mm)

melting progressed, the combined effects of shear force and buoyancy caused the oil block to gradually thin, taking on a *squashed elongated* shape resembling a thin strip. Within the velocity boundary layer, the liquid-phase crude oil, influenced by these forces, formed irregular corrugations that moved toward the pipeline outlet. Meanwhile, buoyant forces acted on the upper pipeline wall, gradually pushing the crude oil outward.

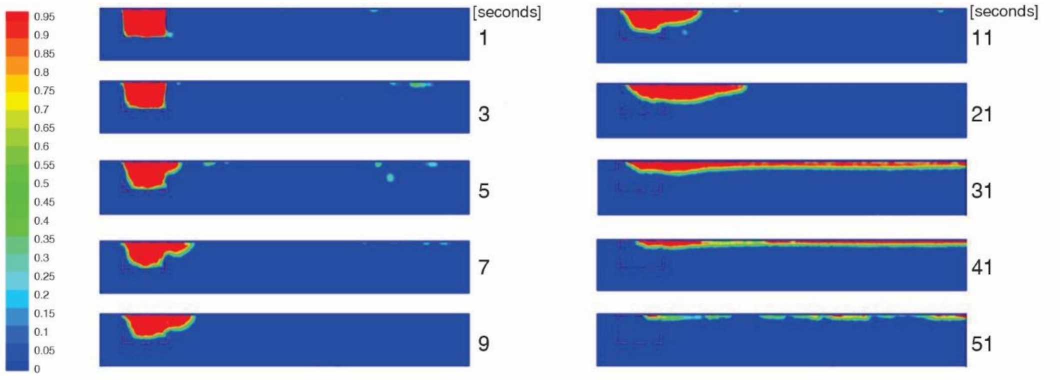

Figure 12. Oil-water two-phase distribution at different moments (δ_{oil} = 30mm)

Figure 12 illustrates that the thickness of the crude oil significantly influences the overall flow pattern. During the initial stage of melting, as hot water flowed through the gelatinized crude oil, a small amount of melted liquid-phase crude oil gradually detached from the main oil block and exited the pipe with the water in the form of oil droplets. As melting progressed, the proportion of liquid-phase crude oil steadily increased. The presence of gelatin and asphaltene in the crude oil enhanced intermolecular interactions, increasing the viscosity of the melted liquid-phase crude oil. This higher viscosity led to the formation of a cohesive mixture that was resistant to dispersion, resulting in the development of crude oil sheets. Under the influence of buoyant forces and the density difference relative to the pipeline wall, this mixture flowed outward along with the water.

Figure 12 also illustrates that liquid oil droplets first melted on the lower surface of the oil block, then flowed to the backflow surface area, where they remained for some time before detaching from the upper side of the pipeline. In conjunction with the velocity field on the xoz plane for a crude oil thickness of 30 mm, as shown in fig. 13, it can be observed that at 7 seconds into the melting process, a larger oil block results in the formation of distinct eddy

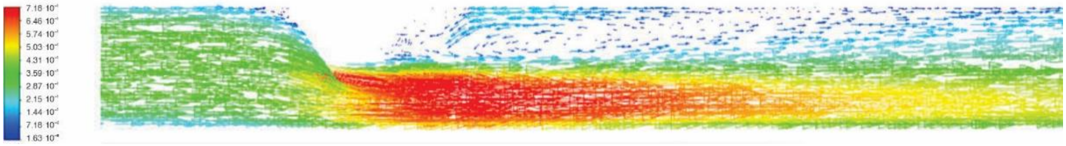

Figure 13. Velocity field on the xoz plane at t =7 seconds (δ_{oil} = 30mm)

currents on its backflow surface. These eddy currents alter the flow direction of the liquid-phase crude oil, causing oil droplets to remain in the backflow region. Figure 14 presents the variation in the complete melting time of the oil block at different crude oil thicknesses, demonstrating that the relationship between the complete melting time of the gelled crude oil and its thickness is non-linear.

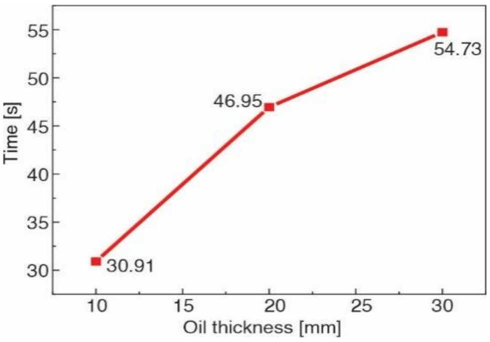

Figure 14. Melting time of oil blocks with different crude oil thicknesses

Figure 15 presents the velocity contours in the x-direction and the stream trace patterns of fluid flow on monitoring Surface 1 under conditions where the crude oil thickness was 10 mm, the water temperature was 60°C, and the oil temperature was 10°C. During the initial stage of melting, the velocity distribution in the x-direction across the pipe cross-section was non-uniform, with the highest velocity at the pipe center gradually decreasing toward the pipe wall. This variation resulted from viscosity effects near the pipe wall, where fluid velocity was lower, forming a viscous sublayer. As the distance from the wall increased, the velocity gradually increased, forming a buffer layer and an overlap layer.

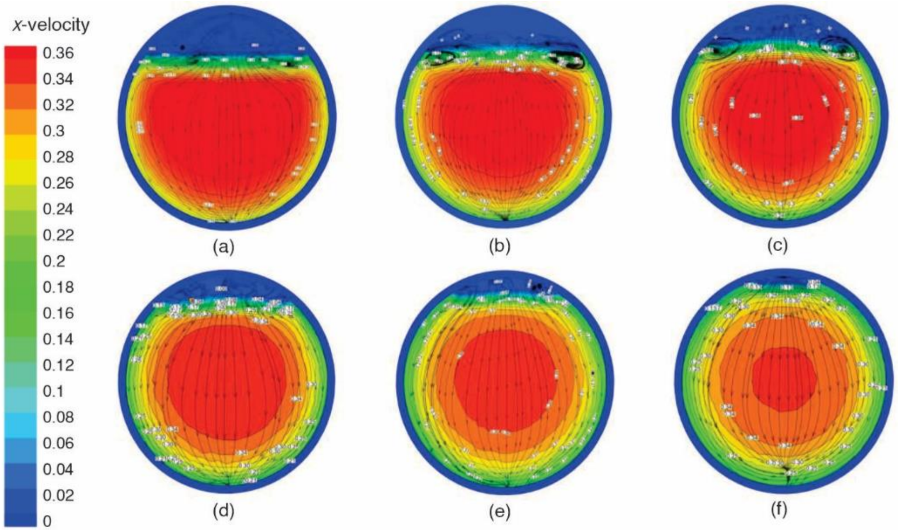

Figure 15. X Velocity distribution and stream traces at typical times; (a) 1 seconds, (b) 5 seconds, (c) 10 seconds, (d) 15 seconds, (e) 20 seconds, and (f) 25 seconds

Additionally, the stream trace patterns indicate that at the initial stage of melting, vortices formed at both ends of the oil blocks due to the scouring action of water. These vortices gradually diminished and eventually disappeared as melting progressed. This vortex formation was influenced by two primary factors. First, due to viscous effects, the fluid in direct contact with the oil block's edges slowed down, while the interior fluid, driven by inertia, maintained a higher velocity. This velocity difference induced rotational motion at the edges, leading to vortex generation. Second, as hot water contacted the crude oil, the oil's density changed with temperature, driving buoyancy-induced flow and further contributing to vortex formation. As melting continued, the oil blocks gradually shrank, the boundary layer between oil and water became thinner, and the contact area between the fluid and the oil blocks decreased, ultimately reducing or eliminating the vortices.

Conclusions

This paper presents a numerical simulation of the melting process of walled gelled crude oil mixed with hot water along the inner wall of a pipeline under various working conditions using FLUENT software. The study examines the effects of key factors, including inlet water flow rate, temperature, crude oil thickness, and initial oil temperature, on the melting characteristics of gelled crude oil. The main findings are summarized as follows.

- In comparison to previous studies [2, 3], significant differences were observed in the flow behavior of bow-shaped and spherical gelled crude oil after melting. These differences can be attributed to factors such as the shape, volume, and position of the oil masses. However, the melting trends under various operating conditions were similar to those observed for the spherical form.
- During the melting process, a velocity boundary-layer formed on the surface of the crude oil in contact with water, causing continuous deformation of the lower boundary, which exhibited an irregular wavy pattern. Furthermore, due to the temperature difference between oil and water, the melting rate of the crude oil was initially fast but gradually slowed over time.
- During the melting process, the oil block gradually thinned, and its overall shape became *compressed and elongated* into a slender strip. Additionally, the thickness of the gelled crude oil influenced the evolution of the solid boundary shape: as the oil block's thickness increased, crude oil droplets formed and flowed out of the pipe with the water.
- The time required for crude oil to melt exhibited a nonlinear decreasing trend with increasing inlet water temperature and initial oil temperature. However, once these temperatures reached a threshold, further increases had a diminishing effect on the melting rate. The melting rate of gelled crude oil is relatively fast before the liquid phase fraction reaches 55%, while the melting rate slows down for the remaining 45%. In practical engineering applications, it is essential to determine the optimal heating water temperature to ensure a short melting time while minimizing energy consumption.

Nomenclature

C – empirical model constant, [–]
Cp – specific heat capacity, [$\mathrm{Jkg^{-1}K^{-1}}$]
F – body force, [$\mathrm{kg\ m\ s^{-2}}$]
G – turbulent kinetic energy, production term [J]
H – enthalpy, [$\mathrm{Jkg^{-1}}$]
k – turbulent kinetic energy, [$\mathrm{Jkg^{-1}}$]
L – pipeline length, [mm]
S_k,S_ω – specified source terms, [–]
T – temperature, [K]
q – heat flux, [$\mathrm{Wm^{-2}}$]
$\vec{u}, \vec{p}$ – velocity and pressure component, [$\mathrm{ms^{-1}}$]

Greek symbol

α_1 – phase volume fraction of the primary phase, [–]
α_2 – phase volume fraction of the secondary phase, [–]

∇ – Hamiltonian operator, [–]
δ – w thickness, [mm]
λ – thermal conductivity, [$\mathrm{Wm^{-1}K^{-1}}$]
η – dynamic viscosity, [$\mathrm{kgm^{-1}s^{-1}}$]
τ – time, [s]
ρ – density, [$\mathrm{kgm^{-3}}$]
ω – specific dissipation rate, [$\mathrm{s^{-1}}$]
Φ – inner diameter, [mm]

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