SENSITIVITY ANALYSIS OF CRUDE OIL'S PHYSICAL PROPERTIES TO TOTAL FREEZING TIME

by

Yang LIU[a], Ying XU[a*], Xiaoyan LIU[a*], Qinglin CHENG[a], Xin NIE[a], and Zhonghua DAI[b]

[a] Northeast Petroleum University, Daqing, China
[b] Daqing Oilfield Company NO.3 Oil Production Plant, Daqing, China

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The physical parameters of crude oil are one of the main factors affecting the heat transfer of phase change. A mathematical model for a hot oil overhead pipeline was established, taking latent heat impact, the non-Newtonian properties of crude oil, and nature convection heat transfer into account. Compared with the experimental data, the model and the solution method were correct. A criterion was made to estimate the crude oil total freezing in a pipeline by tracking the change trajectory of the maximum temperature point. The effects of the crude oil with average properties on the total freezing time in a pipeline were analyzed, and the sensitivity of the different influencing factors was investigated by orthogonal test.

Key words: *influence factor, total freezing time, sensitivity analysis, crude oil's physical properties*

Introduction

During the shutdown of a hot oil pipeline in a cold region, the temperature of the crude oil will decrease and the oil will be condensed because of the temperature difference between the inside and outside of the pipe. The solidification heat transfer process of crude oil in a pipeline is a typical problem of Stefan with moving boundary [1-4]. The studies in this area have mainly focused on the treatment of latent heat, natural convection heat transfer, non-Newtonian fluid handling, and tracking the phase change interface position [3-5]. However, the wax contents, thermal conductivity, viscosity, density, and heat capacity of crude oil are closely related to the handling of these key issues [6-8]. Among these, the wax contents determine the release process for latent heat and the amount of waxes [9-11]. Changes in viscosity and density are related to natural convection heat transfer and fluid properties, and changes in the thermal conductivity and specific heat capacity impact the thermal diffusivity.

In recent years, enthalpy-porous medium methods have been widely used to simulate the temperature drop of crude oil in a pipe, which avoided the determination of the position of liquid-solid interface. These models have included a linear release in a narrow temperature zone near the freezing point for the wax-appearance latent heat of the crude oil, but the selection basis for this temperature zone were not clearly explained [5, 12-16].

One of the main characteristics of waxy crude oil phase transition is that when the temperature is lower than the wax precipitation point, the waxy crystals precipitate out and the

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* Corresponding author, e-mail: xuying1019@126.com; liu_xydq@163.com

latent heat is released [4, 5, 10, 11]. Wang *et al.* [16] considered the influences of the variable physical properties of the crude oil, but there was no the latent heat treatment in the model, and the final temperature field was symmetric about the center, which did not comply with the actual situation. Li [17] established a heat transfer model, which believed that the latent heat was completely released at the liquid-solid interface at one time, but according [10, 18, 19], we knew that the latent heat and temperature of crude oil solidification release were non-linear. So considering the heat latent all releasing in a phase interface was inaccurate.

With the development of DSC curve to determine the specific heat capacity variation in the phase change process, the application of additional specific heat capacity to describe the phase change problem was an effective way to solve the phase change heat transfer [10, 20-23]. Zhang [20] regarded the latent heat as an additional specific heat capacity to establish a model, and the solidified cloud maps at different shutdown times were determined. Liu *et al.*[21, 22] analyzed the temperature distribution of the typical position in a pipeline with an additional latent heat method. Cheng *et al*. [23] established the temperature drop model for shutdown by apparent heat capacity method, and simulated the distribution of temperature field in pipeline and soil. However, in their models, the non-Newtonian fluid description for crude oil was missing.

The moving phase interface makes the treatment of natural convection heat transfer difficult [4, 6]. The temperature drop models of a submarine pipeline were established in [24, 25], they all ignored the influence of the natural convection heat transfer. Firmansyah, *et al.* [5] used CFD to simulate the temperature drop of crude oil in shutdown, however, in the model, there was no treatment of natural convection heat transfer in the governing equation. Wang and Yu [26] regarded the heat transfer as a pure thermal conduction process. Patience and Mehrotra [27] and Nagano *et al.* [28] took the crude oil properties as constant, which meant there was no natural convection in the models.

Most of the existing studies on the phase change heat transfer of crude oil were to determine the temperature fields or condensate situations at different shutdown times [12-20, 23-28]. In fact, the temperature fields and total freezing time of crude oil in pipeline are two important parameters of oil field operation management, who are closely related to the allowance shutdown time and the pressure required to restart [5, 29, 30]. However, so far, there has not been any research on the judgment basis and correlation analysis of total freezing time. Li [31] simulated temperature drop of the crude oil in shutdown by equivalent thermal conductivity method, and analyzed the influence of external pipeline factors on the temperature field. Xu *et al.* [6] analyzed the influences of the variable property parameters of crude oil on the temperature field, and the effects of variable properties and constant properties on heat transfer were compared. However, there has previously been no relevant report on which of the above main properties has the maximum impact on the total freezing time for the oil in a pipe.

To sum up, none of the existing models can deal with the all the key problems of natural convection heat transfer, latent heat release and non-Newtonian properties of crude oil. In this study, a novel model for crude oil heat transfer in shutdown was developed by the partition method, and its momentum equations were established for the liquid phase crude oil considering the Newtonian and non-Newtonian properties of crude oil, respectively. An additional specific heat capacity method was adopted to treat the problem of latent heat. The judgment basis for the total freezing of crude oil in a pipeline was determined, and then the influences of crude oil's physical properties on the freezing time of a hot oil pipeline were investigated, at last, the sensitivity of above properties were analyzed by orthogonal experiment.

Physical model

A physical model of an overhead oil pipeline is shown in fig.1. Assuming that the pipeline is full of crude oil with a uniform distribution, and ignoring the axial heat transfer of the pipeline, the heat transfer between the pipe and crude oil is reduced to a 2-D heat transfer problem in polar co-ordinates. The center of the pipe is regarded as the origin of the co-ordinate system, with outside layers consisting of the crude oil, pipe and insulation in turn. The heat transfer process includes the following: natural convection heat transfer between the oil inside the pipe and the inner wall or solidification layer, pure conduction between the condensate reservoir and the pipe or external insulation layer, and combined heat transfer between the outer layer of the pipe wall and the surrounding environment.

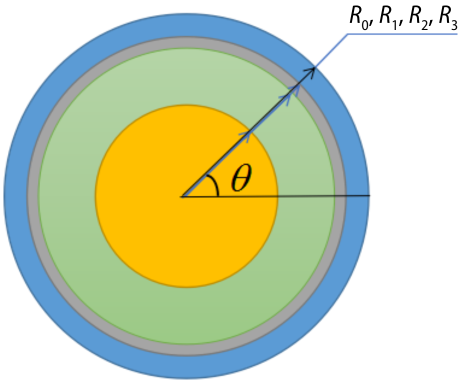

Figure 1. Physical model of overhead pipeline

Mathematical model

Fluid in pipe was satisfied with the continuity equation and momentum conservation equation [32]. A model for crude oil heat transfer in shutdown was developed by the partition method, and the oil in the pipe was divided into two zones: a liquid zone and a solid zone, with an infinitely thin phase interface. The latent heat is described by additional specific heat capacity method, that is, the latent heat is treated as the additional specific heat capacity by the oil DSC curve. The momentum equations were established for the liquid phase crude oil considering the Newtonian and non-Newtonian properties of crude oil, respectively. The partition governing equations were as follows.

Liquid zone

Momentum equations

For a Newtonian fluid:

$$\frac{\partial(\rho u_\theta)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial\theta}(\rho u_\theta u_\theta)+\frac{1}{r}\frac{\partial}{\partial r}(\rho r u_r u_\theta)=\frac{1}{r}\frac{\partial}{\partial\theta}\left(\frac{\mu}{r}\frac{\partial u_\theta}{\partial\theta}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\mu r\frac{\partial u_\theta}{\partial r}\right)+S_\theta \tag{1-a}$$

$$\frac{\partial(\rho u_r)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial\theta}(\rho u_\theta u_r)+\frac{1}{r}\frac{\partial}{\partial r}(\rho r u_r u_r)=\frac{1}{r}\frac{\partial}{\partial\theta}\left(\frac{\mu}{r}\frac{\partial u_r}{\partial\theta}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\mu r\frac{\partial u_r}{\partial r}\right)+S_r \tag{1-b}$$

$$S_\theta=-\frac{1}{r}\frac{\partial p}{\partial\theta}+\left(-\frac{\rho u_r u_\theta}{r}+\frac{2\mu}{r^2}\frac{\partial u_r}{\partial\theta}-\frac{\mu u_\theta}{r^2}\right)-g\rho\beta\Delta T\sin\theta \tag{1-c}$$

$$S_r=-\frac{\partial p}{\partial r}+\left(\frac{\rho u_\theta^{\,2}}{r}-\frac{2\mu}{r^2}\frac{\partial u_\theta}{\partial\theta}-\frac{\mu u_r}{r^2}\right)+g\rho\beta\Delta T\cos\theta \tag{1-d}$$

For a non-Newtonian fluid:

$$\frac{\partial(\rho u_\theta)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial\theta}(\rho u_\theta u_\theta)+\frac{1}{r}\frac{\partial}{\partial r}(\rho r u_r u_\theta)=-\frac{\partial p}{r\partial\theta}+\left[\frac{1}{r^2}\frac{(r^2\tau_{r\theta})}{\partial r}+\frac{1}{r}\frac{\partial\tau_{\theta\theta}}{\partial\theta}\right]-g\rho\beta\Delta T\sin\theta \tag{2-a}$$

$$\frac{\partial\left(\rho u_r\right)}{\partial t}+u_r\frac{\partial\left(\rho u_r\right)}{\partial r}+\frac{u_\theta}{r}\frac{\partial\left(\rho u_r\right)}{\partial\theta}-\frac{\rho u_\theta^2}{r}=-\frac{\partial p}{\partial r}+\left[\frac{1}{r}\frac{\left(r\tau_{rr}\right)}{\partial r}+\frac{1}{r}\frac{\partial\tau_{r\theta}}{\partial\theta}-\frac{\tau_{\theta\theta}}{r}\right]-\mathrm{g}\rho\beta\Delta T\cos\theta \tag{2-b}$$

$$\tau_{\theta\theta}=2\mu\frac{1}{r}\left(\frac{\partial v_\theta}{\partial\theta}+v_r\right)-\frac{2}{3}\mu\nabla\vec{V}=\frac{2}{3}\mu\left(2\frac{\partial v_\theta}{r\partial\theta}-\frac{\partial r v_r}{r\partial r}-\frac{\partial u}{\partial x}\right)+\mu\frac{2v_r}{r} \tag{2-c}$$

$$\tau_{r\theta}=\tau_{\theta r}=\mu\left(\frac{\partial v_\theta}{\partial r}+\frac{\partial v_r}{r\partial\theta}-\frac{v_\theta}{r}\right)=\mu\left(\frac{\partial r v_\theta}{r\partial r}+\frac{\partial v_r}{r\partial\theta}\right)-2\mu\frac{v_\theta}{r} \tag{2-d}$$

$$\tau_{rr}=2\mu\frac{\partial v_r}{\partial r}-\mu\frac{2}{3}\nabla\vec{V}=\frac{2}{3}\mu\left(2\frac{\partial r v_r}{r\partial r}-\frac{\partial v_\theta}{r\partial\theta}-\frac{\partial u}{\partial x}\right)-2\mu\frac{v_r}{r} \tag{2-e}$$

When the crude oil cools to form a similar porous medium, its momentum equations were:

$$\frac{\partial(\rho u)}{\partial t}+(\rho u\nabla)\frac{u}{\varepsilon}=-\nabla(\varepsilon P)-\mu_\mathrm{e}\nabla^2 u+F \tag{2-f}$$

$$F=-\frac{\varepsilon\mu_e}{K}u\rho-\frac{\varepsilon F_\varepsilon}{\sqrt{K}}u|u|+\varepsilon\rho\mathrm{g}\beta(T-T_\mathrm{ref}) \tag{2-g}$$

$$F_\varepsilon=\frac{1.75}{\sqrt{150\varepsilon^3}} \tag{2-h}$$

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

Continuity equation

$$\frac{\partial\rho}{\partial t}+\frac{1}{r}\frac{\partial\left(\rho r u_r\right)}{\partial r}+\frac{1}{r}\frac{\partial\left(\rho u_\theta\right)}{\partial\theta}=0 \tag{3}$$

Heat transfer equation

$$\frac{\partial\left(\rho T\right)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial\theta}\left(\rho u_\theta T\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\rho\ u_r T\right)=\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(\frac{\lambda}{c_p}\frac{\partial T}{\partial\theta}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\lambda}{c_p}r\frac{\partial T}{\partial r}\right) \tag{4}$$

In the process of solidification, crude oil releases latent heat, which can be demonstrated by the c_p variation.

Solid zone

The pure heat conduction equation for the solid phase of crude oil is:

$$\frac{\partial\left(\rho T\right)}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(\frac{\lambda}{c_p}\frac{\partial T}{\partial\theta}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\lambda}{c_p}r\frac{\partial T}{\partial r}\right) \tag{5}$$

Other zones

The heat transfer equations for the pipe wall and insulating layer are given by:

$$\rho_p c_{1p} \frac{\partial T_1}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_1 r \frac{\partial T_1}{\partial t}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda_1 \frac{\partial T_1}{\partial \theta}\right) \tag{6}$$

$$\rho_\mathrm{i} c_\mathrm{i} \frac{\partial T_2}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_2 r \frac{\partial T_2}{\partial t}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda_2 \frac{\partial T_2}{\partial \theta}\right) \tag{7}$$

Boundary conditions

There were coupling heat transfer boundaries between liquid crude oil, solid crude oil, pipe walls, and thermal insulation layers. That is, the parameter values on these boundaries did not need to be set in advance, but were dynamically loaded and solved according to the exchange of energy during melting and heat transfer. The heat flow density and temperature were continuous.

Initial conditions

$$T_0 = \text{constant} \tag{8}$$

Simulation and verification

The experiment pipe size was 274 × 7 mm, and the 20 mm thickness insulation material were applied on its outside. Using to the specific conditions for the experimental pipeline, the Gambit 14.0 software was used to establish a pipeline geometry model, generating 27960 meshes using the ancient coin method, the computational mesh in full pipe cross-section model was shown in fig. 2. The outer wall temperature of the insulation layer was constant, which was 283 K. There was a coupling boundary between the inner surface of the pipeline and the crude oil. The experiment crude oil was from the oil field site in Da Qing, and its wax precipitation and freezing point are 315 K and 305 K, respectively. The main oil physical properties are given by eqs. (9)-(13). The relevant parameters of steel pipe and insulation material were listed in tab. 1. The SIMPLE algorithm and k-ε model were adopted for the simulation in FLUENT.

$$\rho = 0.902 - 8.177 \cdot 10^{-4}(T - 273.15) + 1.54 \times 10^{-6}(T - 273.15)^2 \tag{9}$$

$$\lambda = \begin{cases} 0.15, \quad T \geq T_1 \\ \lambda_l \varepsilon + \lambda_s (1-\varepsilon), \quad 0.7 > \varepsilon > 0 \\ \lambda_l \dfrac{2 + \dfrac{\lambda_s}{\lambda_l} + 2(1-\varepsilon)\left(\dfrac{\lambda_s}{\lambda_l}\right)}{2 + \dfrac{\lambda_s}{\lambda_l} - (1-\varepsilon)\left(\dfrac{\lambda_s}{\lambda_l} - 1\right)}, \quad 1 > \varepsilon \geq 0.7 \\ 0.25, \quad T < T_2 \end{cases} \qquad T_1 = 325.15\text{K}, \quad T_2 = 305.15\text{K} \tag{10}$$

For Newtonian fluid:

$$\mu = 10^{5.06039 - 0.01951T}, \quad T \geq T_1 \tag{11}$$

For non Newtonian fluid:

$$\mu=\begin{cases}10^{37.30785-0.12235T}, & T_2\le T<T_1\\ 10^{-14.44979+0.0511T}, & T_3\le T<T_2\\ 10^{20.81207-0.06799T}, & T_4\le T<T_3\end{cases} \tag{12}$$

$$T_1=313.15,\text{ K}\quad T_2=298.15\text{ K},\quad T_3=296.15\text{ K},\quad T_4=292.15\text{ K}$$

$$c=\begin{cases}809.717+3.607T, & T\ge T_1\\ -76349.22+568.75T-1.01T^2, & T_1>T\ge T_2\\ -11987.72+82.15T-0.10979T^2, & T<T_2\end{cases}\quad T_1=325.15\text{K},\quad T_2=305.15\text{ K} \tag{13}$$

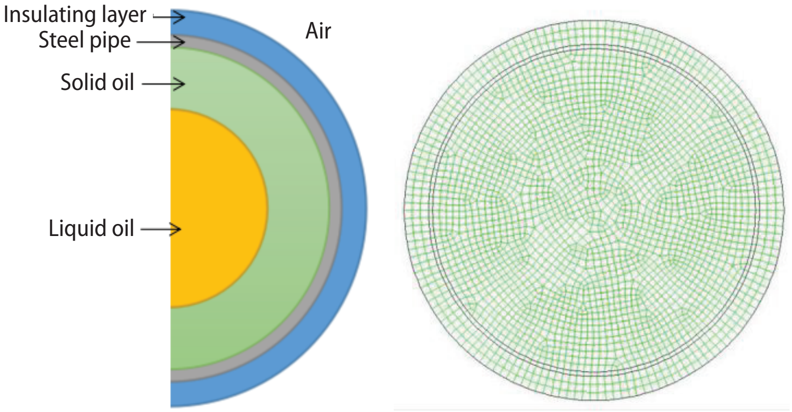

Figure 2. Computational mesh in full pipe

Table 1. Physical properties of material

Material	Density [kgm^{-3}]	Conductivity [Wm^{-1}K^{-1}]	Specific heat capacity [Jkg^{-1}K^{-1}]
Steel pipe	7850	48	500
Insulation layer	60	0.04	700

The test-bed included the heated water bath, the refrigeration systems, crude oil heating system the experimental pipeline, the power pumps, the temperature sensor and data transfer system. The experimental device has been granted a national invention patent (No. 201510573481.X). The specific experimental steps were: used crude oil heating system to heat crude oil to 333 K and pumped it into experimental pipeline. Produced the water of 283 K from the refrigeration systems and pumped it into the water bath, simultaneously. Both ends of the experimental section were sealed with insulation material, and the axial heat transfer can be neglected, so the temperature distribution was approximately the same along the axial sections. Thirty temperature monitoring points were set up along the axis in the pipe center, and the experimental data took the mean results of the thirty sets.

The results of experiment and simulation were shown in fig. 3, there was good agreement with a maximum relative error of 4.09%, which meant the model was correct, and the method was reasonable. Thus, the model can be used to discuss the influence of oil properties on total freezing time for hot oil pipeline.

Determination of total freezing time of all crude oil in pipe

Considering that the hot oil is always moving upwards, in this study, we set up some monitoring points on the *Y*-axis of a pipeline to study the change in the maximum temperature point position at different moments for shutdown. Along the *Y*-axis, 19 monitoring points were set up from the center to the inner wall of the pipe, with the first observation point at the physical center of the pipe. The change trajectory of the highest temperature point in the pipeline was shown in fig. 4.

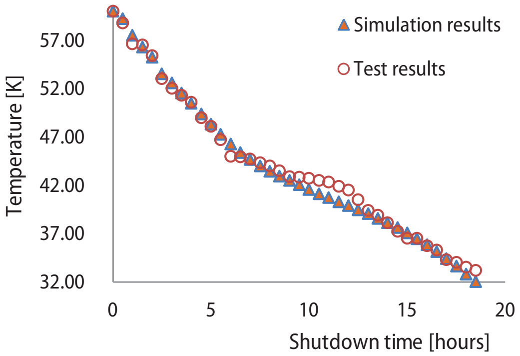

Figure 3. Comparison of simulation results and experimental

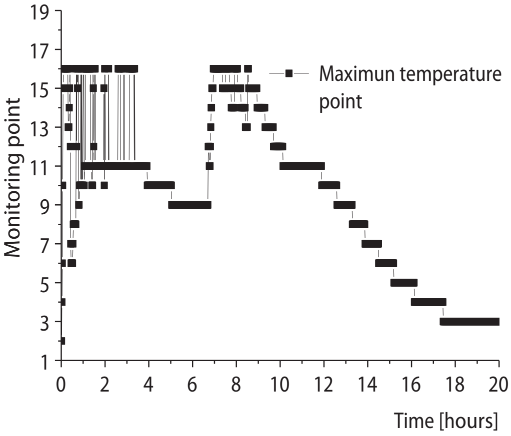

Figure 4. Change trajectory of highest temperature position

After shutdown, the temperature of the crude oil around the inner wall of the pipeline quickly decreased. Therefore, the maximum temperature crude oil in the center moved upward, producing natural convection heat transfer [4, 6, 22, 31]. At the beginning of the shutdown, the maximum temperature point fluctuated as a result of the intense heat transfer of natural convection. With an increase in the shutdown time, the effect of this natural convection heat transfer decreased, the maximum temperature point in the pipeline moved closer to the center, and the final freezing point was approximately 7 mm above the center of the pipe. Therefore, to determine the total freezing time of crude oil in the pipeline, the final location of the condensing point needs to be determined first. Then, when the crude oil temperature reaches freezing point, the corresponding shutdown time is the total freezing time for all the crude oil in the pipe. In the following study, all the temperature drop curves were the temperature curves at the final freezing point.

Effects of oil properties on total freezing time

In order to analyze the sensitivity of the physical parameters to the influence of total freezing time, the average values were adopted in the simulation. The thermal conductivity coefficient of crude oil is 0.15 W/mK, the viscosity is 0.03 Pa·s, the average density is 900 kg/m^3, the average specific heat capacity is 2000 J/K. In the following simulation, all the temperature drop curves were for the positions of the final freezing point.

Effects of different mean densities on total freezing time

In the process of heat transfer, medium density is an important factor affecting thermal diffusion rate, $a = \lambda/(\rho c)$, which determines the heat required for temperature rise [32]. Because the thermal diffusion was inversely proportional to the density, a higher crude oil density resulted in a lower temperature conductivity, slower temperature change, and longer freezing time. Therefore, when the density of the crude oil was greater, it had less ability to conduct heat, greater heat storage capacity, and slower heat dissipation. Figure 5 shows the temperature drop curves for crude oil with average densities of ρ = 810 kg/m^3, 900 kg/m^3, and 990 kg/m^3. With these three different densities, the total freezing times of all the crude oil in the pipe were 30.0 hours, 33.4 hours, and 36.6 hours, respectively. When the density increased by 10%, the freezing time increased by approximately 10%.

Influence of different mean thermal conductivity on total freezing time

Figure 6 shows the temperature drop curves for crude oil with average thermal conductivities of λ = 0.15 W/mK, 0.165 W/mK, and 0.18 W/mK. For the three different thermal conductivities, the total freezing times of all the crude oil in the pipe were 33.4 hours, 32.1 hours, and 30.9 hours, respectively. When the thermal conductivity increased by 10%, the total freezing time decreased by approximately 4%. For the oil with a larger thermal conductivity, the heat transfer ability was greater, thermal resistance was small, and heat transfer was fast. Thus, the freezing time was relatively short compared to the oil with a small thermal conductivity.

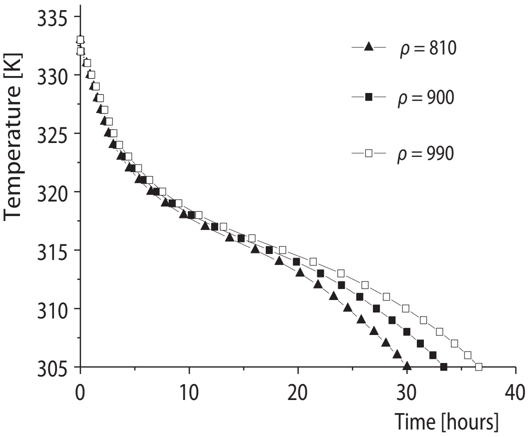

Figure 5. Temperature drop curves for different oil densities

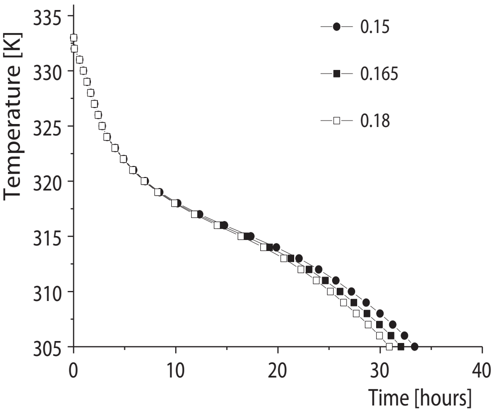

Figure 6. Temperature drop curves for different oil conductivities

As can be seen from fig. 6, in the first half of the shutdown, the difference of thermal conductivity has little effect on temperature drop curve. This was because, at the initial moment of shutdown (combined with fig. 4), the maximum temperature point fluctuated greatly, and there was intense hot and cold flow mixing. This indicated that at this stage, the main heat exchange mode was natural convection [4, 31]. In the second half of the shutdown, the heat transfer was dominated by heat conduction, so the effect of thermal conductivity difference on temperature drop was obvious.

Influence of different mean viscosity on total freezing time

Figure 7 shows the temperature drop curves for crude oil with average viscosities of 0.03 Pa·s, 0.033 Pa·s, and 0.036 Pa·s. For the three different viscosities, the total freezing times of all the crude oil in the pipe were 33.38 hours, 33.39 hours, and 33.40 hours, respectively. In other words, the viscosity increased only 0.03% for each 10% increase in viscosity, which showed that the change in viscosity had the weakest effect on the freezing time [6, 31].

Combined with the change in the position of the maximum temperature point in the first 2 hours (as shown in fig. 8), at the initial moment of the shutdown process, the crude oil in the center of the pipe moved closer to the top wall of the pipe over a period of approximately 10 minute. This meant that, in the radial direction, the velocity of the crude oil was extremely slow, and the influence of the viscosity difference on the heat transfer could be ignored. However, in the course of crude oil transportation, as the crude oil flows through the pipeline, viscosity changes affect the movement resistance and heat transfer along the axis [5, 7, 8]. Therefore, these oil viscosity effects need to be studied separately.

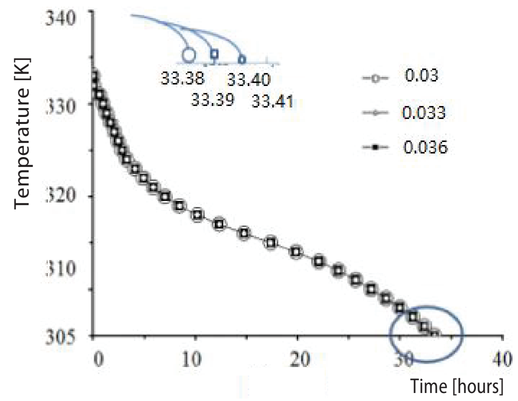

Figure 7. Temperature drop curves for different oil viscosities

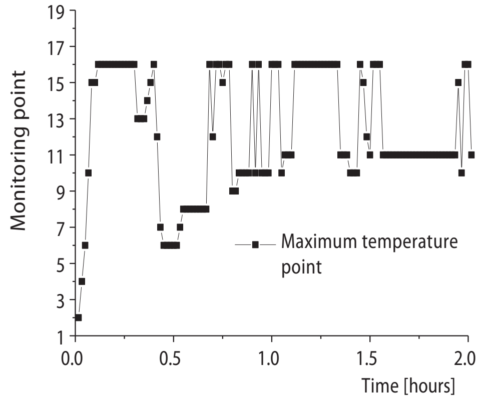

Figure 8. Maximum temperature position of at initial moment

Influence of different mean specific heat capacity on total freezing time

Figure 9 shows the temperature drop curves when the total latent heat capacity of the wax was 40000 J, and the average heat capacities were 2000 J/K, 2200 J/K, and 2400 J/K. For the three different average specific heat capacity values, the total freezing times of all the crude oil in the pipe were 33.4 hours, 35.3 hours, and 37.2 hours. Thus, when the average specific heat capacity increased by 10%, the freezing time increased by approximately 5.5%. This was because the magnitude of the specific heat capacity determined the heat transfer capacity, with a larger specific heat capacity leading to a smaller thermal diffusion rate [33].

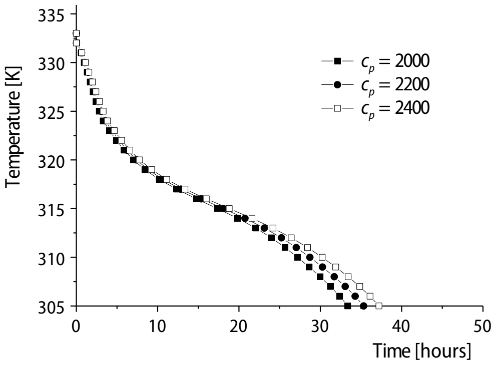

Figure 9. Temperature drop curves for different specific heat values

In addition, as shown in fig. 9, according to the slope of the temperature curve changes, the freezing process of crude oil can be mainly divided into three parts. The first stage was the convection of the liquid phase of the crude oil, and the thermal conductivity and convection heat transfer coexisted in this stag [4]. At the initial moment of shutdown, the temperature difference between the oil and environment was large. Thus, the temperature drop rate was fast. In the next stage, when the oil temperature dropped to the wax precipitation point, because of the release of the oil's latent heat, the temperature decrease was inhibited. With the release of latent heat and the increase in the thickness of the condensate reservoir, the thermal conductivity was dominant, and the temperature falling rate increased in the last stage.

Sensitivity analysis of physical properties by orthogonal test

Based on the aforementioned four main properties of crude oil, this paper used four factors and three dimensions orthogonal test to analyze the sensitivity of oil physical properties on total freezing time. The horizontal orthogonal table was shown in tab. 2, the orthogonal experimental results were shown in tab. 3, and the range analysis of each parameter was shown in tab. 4.

The results of range analysis indicated that, the order of multi-factor sensitivity from large to small with total freezing time as the indicator was: density > specific heat capacity >

Table 2. Experimental factors

	Level 1	Level 2	Level 3
Density, ρ	810	900	990
Thermal conductivity, λ	0.15	0.165	0.18
Dynamic viscosity, μ	0.03	0.033	0.036
Specific heat capacity, c_p	2000	2200	2400

Table 3. Experimental results

Test\factor	Density	Thermal conductivity	Dynamic viscosity	Specific heat capacity	Total freezing time [hours]
1	1	1	1	1	30.95
2	1	2	2	2	31.45
3	1	3	3	3	32.07
4	2	1	2	3	38.13
5	2	2	3	1	32.97
6	2	3	1	2	33.7
7	3	1	3	2	39.58
8	3	2	1	3	40.05
9	3	3	2	1	34.93

Table 4. Range analysis of each parameter

Parameter	Density	Thermal conductivity	Dynamic viscosity	Specific heat capacity
K1/3	31.47	36.22	34.9	32.95
K2/3	34.93	34.82	34.84	34.91
K3/3	38.19	33.55	34.86	36.73
Range	6.72	2.67	0.06	3.78
Degree of influence order	1	3	4	2
Percent [%]	50.76	20.19	0.46	28.59

> thermal conductivity > viscosity. The ratios of the degree of influence are 50.76%, 28.59%, 20.19% and 0.46%, respectively.

Conclusions

A partition method mathematical model was established in this study, taking latent heat impact, the non-Newtonian properties of crude oil, and nature convection heat transfer into account. The simulations and calculations were done by CFD, and the results were compared with experiment data, with a maximum relative error of 4.09%. Then the effects of different properties on total freezing time were analyzed, the following conclusions were concluded.

- The judgment basis of total freezing time of crude oil in pipeline was presented. The final freezing position of all the crude oil in the pipe was determined by tracking the change in the maximum temperature point of the crude oil in the pipeline, and the time that the temperature of the crude oil at this position dropped to the freezing point was called the total freezing time.
- Based on the influence of the different thermal conductivities of crude oil on the temperature drop, combined with the change trajectory of the maximum temperature point, it was found that from the initial stage of the shutdown to all the crude oil freezing, the second half of the process was dominated by heat conduction.
- The influences on the total freezing time and change in the temperature at a typical position were analyzed using equal proportional increases in the main physical parameters of crude oil, and a 4 factors and 3 dimensions orthogonal test was finished to verify the sensitivity of the influencing factors, the conclusion was: density > specific heat capacity > thermal conductivity > viscosity. For shutdown hot pipeline, the influence of viscosity is very weak.

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Nomenclature

C – coefficient, (= 10^5)
c_p, c_{1p}, c_i – specific heat capacity of crude oil, pipe and insulating layer, respectively, [Jkg^{-1}°C^{-1}]
F_ε – shape factor
g – acceleration of gravity, [ms^{-2}]
K – permeability
T_0 – initial temperature of the crude oil, [K]
T, T_1, T_2 – temperature of oil, pipe and insulating layer, respectively, [K]
T_{ref} – reference temperature [K]
u_θ, u_r – velocity components of u in polar co-ordinates, [ms^{-1}]
v_θ, v_r – velocity components of v in polar co-ordinates, [ms^{-1}]

Greek symbols

ε – liquid fraction
λ, λ_1, λ_2 – thermal conductivity of crude oil, pipe and insulating layer, respectively, [Wm^{-1}K^{-1}]
μ – dynamic viscosity of crude oil, [Pas]
ρ, ρ_p, ρ_I – density of crude oil, pipe and insulating layer, respectively, [kgm^{-3}]

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