Research on heat transfer characteristics of hot oil pipeline during the shutdown and restarting process

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Abstract. By setting up mathematical model of the restarting after stopping process of the hot oil pipeline, Using finite difference method and finite volume method to simulate the complex process of stop and restart numerically. The heat transfer characteristics of crude oil and the soil around the pipeline were investigated. During the shutdown process, the axial temperature drop of crude oil and soil showed an exponential law change. With the increase of stopping time, the starting rate of cooling rate was higher than that of end point and the temperature gradient gradually decreased. After 30 hours of continuous operation, the oil temperature and the soil temperature along the pipeline tend to be stable. During this process, the heating mechanism of the hot oil head in the front and rear is different, and the distance of the hot oil head from the starting point of the pipe is nonlinear with the increase of the restart time.

Key words. Vibration, trapezoidal plate, taper constants, thermal gradient, aspect ratio, non-homogeneity.

1. Preface

The crude oil produced by many oil fields in our country is high in waxy crude oil [1]. It is less liquid at normal temperature and mainly adopts the heating conveyor process to reduce the viscosity of crude oil. In recent years, hot oil pipeline gradually into the high incidence of accidents, the number of unexpected shutdown and planned shutdown significantly increased, In the case of long stopping time or bad operation

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condition, the coagulation accident can occur easily, which seriously threatens the safe operation of hot oil pipeline[2]. In order to ensure the safe and efficient operation of the hot oil pipeline, it is necessary to understand the temperature change of the pipeline under various conditions after the shutdown and restart of the pipeline. At present, there have been some studies on the question of stopping and restarting of the hot oil[3−9]. But in general, the existing research mainly focus on the question of the single aspect of oil or soil in the process of restarting the pipeline. and there are few reports on the heat transfer characteristics of crude oil and soil as a whole. Therefore, in this paper, the numerical simulation of the restart process of hot oil pipeline is carried out to study the heat transfer characteristics of oil flow and surrounding soil at different stop and restart times, and provide reference for production management and efficient operation of hot oil pipeline.

2. Mathematical model and calculation method

2.1. Mathematical model of normal operation

Because the real heat changes of the buried pipeline are complicated, it is assumed that the soil around the pipeline is an isotropic homogeneous medium when the numerical model of the normal operation of the pipeline is established, and the heat affected area of the pipe in the soil is taken as 5m in the X direction, Y direction 12.5m; The temperature of the crude oil in the pipeline is only related to the axial and time of the pipe and evenly distributed in the pipe section.
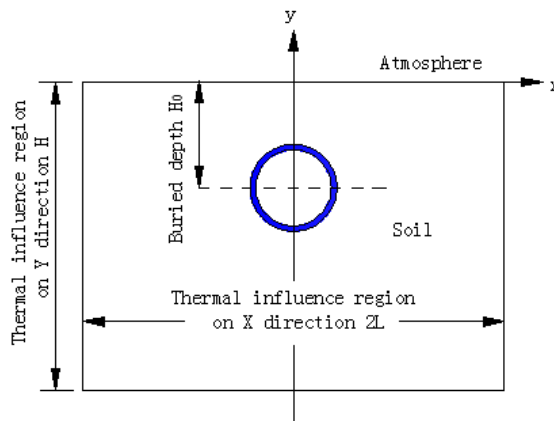

Fig. 1. Sketch map of buried hot oil pipeline

(1)Based on the above simplification and hypothesis, the mathematical model of the normal operation of hot oil pipeline is established.

Continuity equation

$$\frac{\partial}{\partial t}\left(\rho A\right) + \frac{\partial}{\partial z}\left(\rho V A\right) = 0 \quad 1$$

Momentum equation

$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial z} = -g \sin \alpha - \frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{f}{D} \frac{V^2}{2} 2$

Energy equation

$\frac{\partial}{\partial t} \left[(\rho A) \left(u + \frac{V^2}{2} + gs \right) \right] + \frac{\partial}{\partial z} \left[(\rho V A) \left(h + \frac{V^2}{2} + gs \right) \right] = -\pi D q \ 3$

According to the continuity equation, momentum equation and energy equation, we can deduce the numerical model of pipeline normal operation:

$c_p \frac{dT}{dt} - \frac{T}{\rho} \beta \frac{dp}{dt} - \frac{fV^3}{2D} = -\frac{4q}{\rho D} \ 4$

(2)The heat transfer equation of wax layer, pipeline wall and anti-corrosive layer:

$\rho_k c_k \frac{\partial T_k}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda_k r \frac{\partial T_k}{\partial t} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left(\lambda_k \frac{\partial T_k}{\partial \theta} \right) \ 5$

(3)Soil thermal equation:

$\rho_s C_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} \left(\lambda_s \frac{\partial T_S}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_s \frac{\partial T_S}{\partial y} \right) \ 6$

(4)The process of heat transfer between the pipeline crude oil, the wax layer, the pipe wall, the coating layer and the soil is interrelated to satisfy:

$$-\lambda_1 \frac{\partial T_k}{\partial r} \mid_{r=R_0} = \alpha_0 \left(T - T_0 \right)$$

$$\lambda_k \frac{\partial T_k}{\partial r} \mid_{r=R_k} = \lambda_{k+1} \frac{\partial T_{k+1}}{\partial r} \mid_{r=R_r} (k = 1, 2)$$

$$T_k \mid_{r=R_k} = T_{k+1} \mid_{r=R_k} (k = 1, 2)$$

$$\lambda_3 \frac{\partial T_3}{\partial r} \mid_{r=R_3} = \lambda_s \frac{\partial T_s}{\partial r} \mid_{r=R_3}$$

$$T_3 \mid_{r=R_3} = T_s \mid_{r=R_3}$$

(5)Due to the symmetry of the calculated area, we only study the right half of the pipeline, the boundary condition is:

$$\lambda_s \frac{\partial T_s}{\partial x} = 0 x = 0$$

$0 \le |y| \le H_0 - R_3 H_0 + R_3 \le |y| \le H$

$\frac{\partial T_s}{\partial y} = \frac{\alpha_a}{\lambda_s} \left(T_a - T_s \right) y = 0$

$\frac{\partial T_s}{\partial x} = 0 |x| = L T_s = T_n |y| = H \ 7$

2.2. Mathematical model of temperature drop process after a shutdown

During the process of the temperature drop after stopping the transmission, the thermal conductivity of the crude oil in the pipeline is:

$\rho c \frac{\partial T}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda r \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left(\frac{\lambda}{r} \frac{\partial T}{\partial \theta} \right) 8$

The thermal conductivity equation and the soil thermal conductivity equation of the wax layer, pipeline wall and anti-corrosive layer are the same as those of equations(5) and (6).

2.3. The mathematical model of the restart process

When the crude oil does not show thixotropy, the numerical model of the restart process is the same as the normal delivery. When the crude oil shows thixotropy, the numerical model of the restart process is:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial z} + g\sin\alpha + \frac{4\tau_w}{\rho D} = 09$$

In the formula, the value of τ_w the Houska thixotropic model[11].

2.4. The mathematical model of the restart process

In order to ensure the precision and accuracy of the calculation, the DELAUNAY triangulation method, the polar coordinate grid and the finite difference method are used to separate the soil, the wax layer, the steel pipe wall, the anti-corrosion layer and the pipeline respectively in the heat affected zone of the pipeline. The results are shown in Figures 2 and 3.

3. Analysis and discussion

3.1. Simulation of working conditions

The length of the pipe is 30km, using buried 1.5m way laying, select seamless steel pipe, the outer wall of the steel pipe is 30mm thick insulation layer, the material of the insulation layer is polyurethane rigid foam, the temperature involved is within the range of the actual oil temperature change under the condition of the pipeline oil transportation. With a constant flow mode to start, the design of the output is 82kg/s. The mean value of the temperature of the surrounding soil at the same distance from the center of the pipeline is taken as the average soil temperature.

3.2. The change of temperature inside and outside the pipeline after stopping

The numerical simulation of the temperature of the oil flow and the surrounding soil at different stop times during the shutdown process of the hot oil pipeline is shown in Figure 4.

After hot oil pipeline running for some time, the soil and the crude oil heat coupling, forming a stable temperature field. At this time, the temperature of the crude oil and the surrounding soil is not changed with time, and the pipeline runs steadily. The temperature of the whole pipeline oil and the surrounding soil at different positions around the pipeline gradually decrease with the increase of the conveying distance, and the change trend is the same, all follow the exponential law change.

The initial state of the stop is one of the main factors that affect the process of restarting the pipeline. The initial state of the different shutdowns corresponds to different heat transfer process. The simulation results show that the temperature drop of oil flow is significantly higher than that of the surrounding soil with the

prolonging of the stopping time. In Figure 4a, At the beginning of the pipeline, the oil flow temperature is 37.2, 32.9,30.0 and 27.9, respectively, and the average cooling rate is 0.78/ h, 0.43/ h, 0.29/ h, 0.21/ h. At the end of the pipeline, stable operation and shutdown of 10h, 20h, 30h, 40h, the temperature of the oil flow are 25.5, 20.8 and 20.8, 17.1 and 15.9, The oil flow at the end of pipe cooling rate decreases, are 0.47/h, 0.23/h, 0.14/h, 0.12/h, which are less than the average cooling rate of the starting point, It is indicated that the axial cooling rate of pipeline oil flow decreases gradually, and the starting temperature decreases quickly and the end temperature decreases slowly. This is because the natural convection of crude oil is stronger when the pipeline has just stopped, The temperature difference between the internal oil temperature and the external soil is larger, the oil temperature in the pipeline is cooled to slightly higher than the temperature of the outside soil, and the oil temperature in the near wall is decreasing rapidly; After stopping for a period of time, the oil temperature in the pipeline gradually decreases, gradually from natural convection to the thermal control stage, The pipeline oil and the outer soil of the pipeline are slowly cooled as a whole, and the heat lost mainly comes from the soil around the pipe, which results in a gradual decrease in the rate of cooling of the hot oil pipeline from the starting point to the end point.

In FIG. 4b~d, the temperature gradient of soil at stable operation and at different time of shutdown is gradually reduced with the extension of the time of stop and loss, and the lower the soil temperature gradient is in the distance from the center of the pipeline, and the farther from the center of the pipeline, the lower the soil temperature gradient. This is because of the thermodynamic coupling of crude oil in the pipe and soil. The oil flow passes the heat through the paraffin layer, the pipe wall and the corrosion protection layer to the surrounding soil, and then the ground and the atmospheric heat exchange. The temperature difference between the starting position and the surrounding soil is greater than that of the end point. The soil at the starting point has more heat than the end of the soil, and the temperature of the crude oil in the pipe is large, which leads to a large gradient of soil temperature near the pipeline and a small gradient of soil temperature away from the pipeline. In addition, it can be seen from Fig. 4d that the soil temperature at 80cm from the center of the pipeline does not vary with the extension of the stopping time.

3.3. The temperature change inside and outside the pipeline during the restart

The numerical simulation of the temperature of the oil flow and the surrounding soil at different start-up times during the restart of the hot oil pipeline is shown in Figure5.

The change of oil temperature over time is shown in FIG. 5a, similar to the temperature recovery process under different start-up conditions. At the beginning of the start, the hot oil has just entered the cold pipe. As the temperature of the pipe wall and the nearby soil is low, the oil heat is released quickly, the oil temperature is drastically reduced, and the pipeline oil continues to move forward.The oil in the pipe continues to move forward while cooling off, and the temperature is lower than the oil flow temperature at the beginning of the restart. The calculation result

shows that with the development of hot oil into and remaining oil over backwards, hot oil section along the oil temperature rise faster, with time in the process of the pipeline restart, the temperature difference between start and end of the pipe gradually decreases, are 28.1, 28.0 and 27.2, 26.1 and 24.8, 21.6 and 20.8. This is because the high temperature oil flow slowly heating the surrounding soil, after the subsequent heat flow into the pipe section, and the temperature difference between the soil and the pipe is reduced, the soil loss quantity of heat also is reduced, so the pipeline across the board temperature, reduce the temperature gradient. Hot oil pipeline after 30 h restart process, the pipeline oil temperature gradually stabilized, indicating that cold oil are all top out, the pipeline fluid flow and heat transfer is not immediately into a stable state, but a gradual process, After a period of time to achieve the corresponding balance.

Restarting the average temperature of the surrounding soil along with changes over time are shown in Figure 5b~5d, With the extension of the start time, the soil temperature gradually increased, and the process of oil temperature is basically the same, and the same is 30h after the re-start, the soil temperature tends to be stable.It can be seen from Fig. 5b that the temperature difference between the starting point and the end point of the soil increases with the increase of the restart time before the formation of the stable soil temperature field.This is because the pipeline restart, near the starting point of the oil temperature, compared with near the end of the oil temperature rise is larger, the surrounding soil loss quantity of heat is more, resulting in near the starting point of the soil temperature fast, near the end of the soil temperature is slow. In addition, the average temperature of soil continued to decline after 1h at the distance of 40cm from the center of the distance. This is due to the pipeline start-up phase, hot oil has just entered the pipeline, the wall and the nearby soil temperature is low, oil flow heat quickly, the oil temperature dropped sharply, And in the top squeeze process, crude oil at the top of the squeeze is worse than the crude oil in the pipeline in physical properties , resulting in the inside and outside the temperature difference does not change, and the pipe around the soil continue to heat to the atmosphere, so there is a slow decline in the trend.

Along the oil temperature distribution can be divided into hot oil head first and after section, the front oil flow from the initial temperature 45 cooling rapidly, with the extension of the start-up time, gradually slow cooling process, the later period of oil temperature at different restart time always is rising steadily as a whole. Heating mechanism of the reason is that the two parts is different, the front of the heating mechanism is mainly: the restart process of hot oil, crude oil rapidly heating up, cooling oil temperature is low, cold and hot crude oil temperature difference is bigger, heat fast, at the same time, the accumulation of soil around heat, further accelerate the speed of heat transfer oil, which causes the crude oil was quickly cooling. The latter part of the heating mechanism on the one hand is due to the top of the hot oil squeeze, the cold oil continues to flow, the end of the cold oil is discharged; On the other hand, the temperature difference between the crude oil and the external soil is decreased, resulting in the decrease of the crude oil.

FIG. 5e is the change trend chart of hot oil head position and total heat transfer coefficient with start-up time.It can be seen from the figure that with the increase of

the starting time, the increase of the distance of the hot oil head from the starting point gradually decreases, showing a non-linear change, which is due to the increase of the oil temperature in the restart process is higher than the temperature of the surrounding soil, resulting in the pipeline inside and outside temperature difference is reduced, the total heat transfer coefficient decreases, and so on macro performance for heat dissipating capacity decreases, and hot oil head moving slow in the pipe.

4. Conclusion

The numerical simulation can precisely simulate the thermal change of the pipeline along the pipeline, and provide theoretical basis for the reasonable operation of the oil pipeline stopping and restarting.

During the process of stopping the pipeline, the temperature of the crude oil and the surrounding soil decreased exponentially with the thermodynamic coupling between the crude oil and the surrounding soil, and along the axial cooling rate decreases, beginning temperature drop quickly, the finish temperature drop slowly.The axial temperature drop of the surrounding soil decreases with the increase of the distance from the center of the pipeline. With the increase of the stopping time, the change of the soil temperature at 80 cm from the center of the pipeline is very small.

In the process of restarting the pipeline, the temperature recovery process is similar at different times. With the increase of start-up time, the temperature difference between the pipeline's starting point and the end point of the pipeline gradually decreases, and the temperature difference of the surrounding soil gradually increases. In this paper, we analyze the heating mechanism of the crude oil in the pipeline before and after the influence of the surrounding soil, and find that the distance of the hot oil head from the starting point is nonlinear with the increase of the time.

After 30 hours of shutdown and restart, the temperature of the crude oil and soil tends to be stable, and the pipeline oil and the soil outside the pipeline are changed as a whole. The flow and heat transfer of the fluid in the pipeline are a gradual process.

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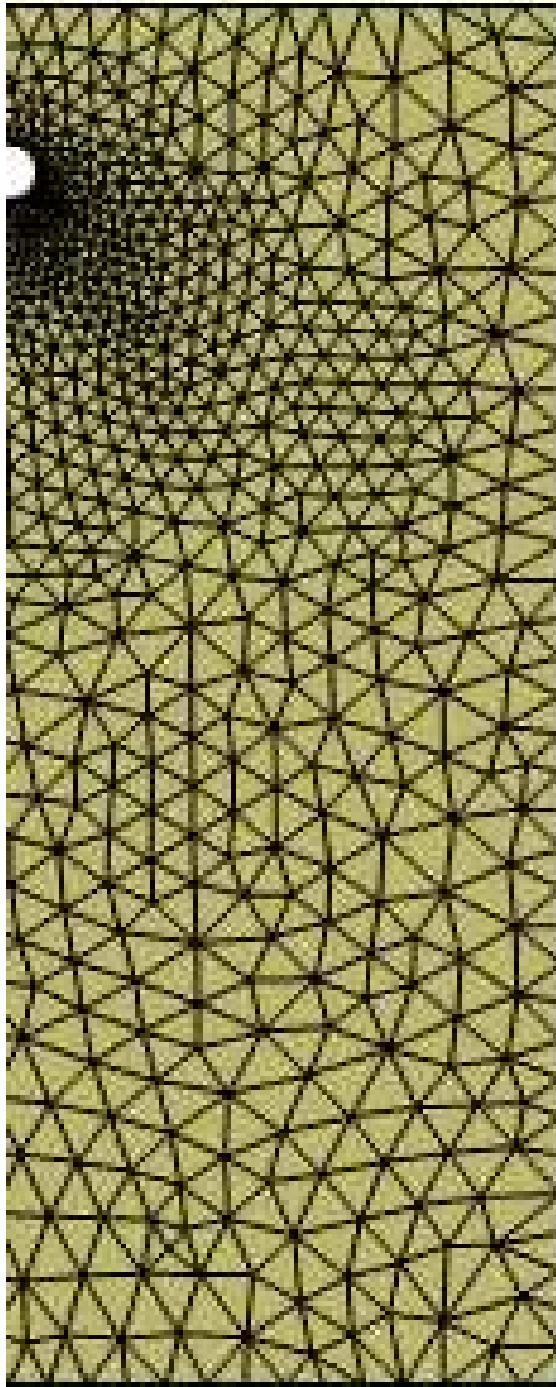
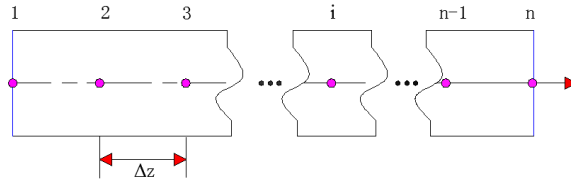Fig. 2. Meshing of wax layers, wall and anti-corrosive layers and surrounding soils
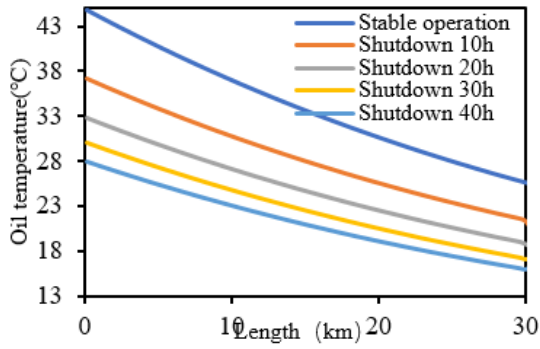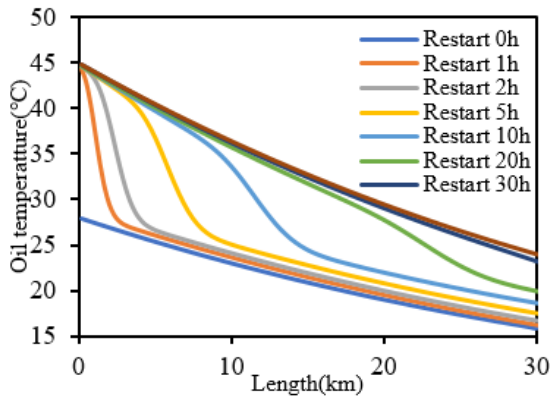
Fig. 3. Pipeline discrete schematic

Fig. 4

Fig. 5