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The study on temperature field variation and phase transition law after shutdown of buried waxy crude oil pipeline

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ABSTRACT

In the buried waxy crude oil pipeline, considering the change of physical properties with temperature and the latent heat of wax precipitation, based on the pipeline-soil-atmosphere coupled heat transfer, the temperature drop model after shutdown is established by apparent heat capacity method. Taking a waxy crude oil transportation pipeline in Daqing Oilfield as an example, under different initial oil temperatures, different environmental temperatures and different soil thermal conductivities, the distribution of temperature field in pipeline and soil is simulated, the influence mechanism on temperature field of these three cases is analyzed. In addition, the phase transition interface of wax precipitation in crude oil is traced, the variation law of interface position after shutdown is analyzed. This research could provide a theoretical basis for the establishment of pipeline shutdown engineering scheme.

1. Introduction

In China, more than 80% of crude oil is waxy crude oil, the transportation method of heating to ensure the safety operation is generally adopted [1,2]. If the accidents, maintenances and other factors occurred in buried hot oil pipeline, the transportation would stop, and the oil temperature would continuously decrease [3]. When it reduces to wax precipitation point, wax in crude oil gradually precipitates, the cross-linked structure will form, meanwhile, it releases latent heat of wax crystallization. With the further formation of wax crystals, the strength of crude oil will be greater than the start-up pressure of pump, the pipeline condensation accident will happen [4], thus the safety and economy operation of pipeline is seriously affected [5]. Therefore, the study on temperature distribution and temperature drop of buried waxy crude oil pipeline after shutdown has great significance on guiding optimizing the operation of pipelines.

For the scientific research of shutdown process in buried waxy crude oil, scholars in various countries had carried out a large number of experimental and theoretical studies, the law of temperature field distribution inside and outside pipeline was explored. Guozhong [6] studied the shutdown cooling process, then summarized the law of crude oil temperature changed with shutdown time and other factors affecting temperature drop rate. Kaufmann [7] took the shutdown process as a quasi-static process, established the heat conduction equation by coupling the crude oil, pipe wall and external environment, then studied the oil temperature variation in pipeline. Xiuguo et al. [8] utilized the finite element method to quantitatively analyze the relationship between horizontal thermal influence range and ground temperature, oil temperature, pipe diameter, buried depth, soil thermal conductivity, and calculated the thermal influence range of pipeline in horizontal direction. Xiaoyan et al. [9] built an unsteady heat transfer model according to the periodic variation of ambient temperature, and carried out the numerical simulation, the external environmental factors such as changes of atmospheric temperature and soil thermal conductivity that affected the temperature field were analyzed. Liping et al.

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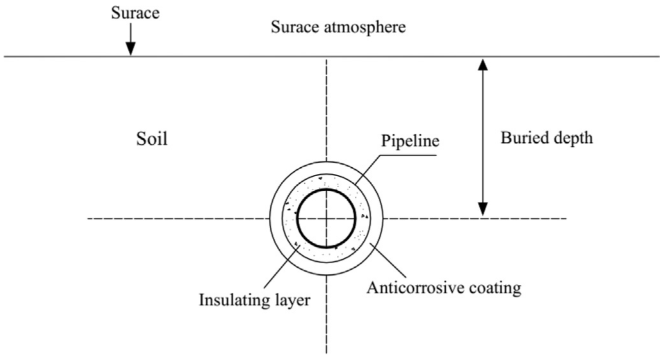

Fig. 1. Physical model for buried hot oil pipeline.

[10] took into account the heterogeneity of soil physical properties around pipe, and considered the other factors such as air temperature and soil constant temperature layer which could affect the temperature field distribution, a mathematical model of coupled heat transfer between pipe and soil was then established.

To sum up, many experts and scholars had done a great deal of work on the study of heat transfer model and temperature field after shutdown. However, to author's knowledge, they may not fully consider the latent heat of wax precipitation, the temperature change process of crude oil and the change of thermal conductivity mode in their work, but treated the crude oil in pipeline as a whole, which hindered the continuous development of this field. In fact, the shutdown process of waxy crude oil involves latent heat of wax crystallization, solid-liquid interface movement, physical properties change with temperature and other multiple problems. In this paper, considering these factors, a reasonable shutdown temperature drop model was established, numerical simulation of oil and soil temperature distribution was carried out, then the main factors and mechanisms which could affect the temperature distribution were analyzed. This research could lay the foundation for further research on the establishment of pipeline shutdown scheme.

2. Theoretical model

2.1. Physical model

The axial temperature drop gradient of pipe is smaller than the radial, so the problem can be simplified as a two-dimensional problem on cross section of pipe [11]. Around the hot oil pipeline, the soil temperature field is greatly affected by it, with the increase of distance, this effect will be gradually weakened, when it reaches a certain distance, the soil temperature field will not be affected by pipeline, a limited spatial region will be formed, which is called thermal influence zone. A solving regional physical model for buried pipelines was established by the method of heat affected zone [12], which was shown in Fig. 1:

Atmospheric temperature changes periodically with season, in fact, the heat exchange between soil and atmosphere also makes the soil temperature show a periodic variation trend. But due to the property of soil heat storage, the variation of soil temperature is slower than that of atmospheric temperature, with the increase of depth, the effect of atmospheric periodic variation on the soil temperature field gradually weakens, after reaching a certain depth, the effect could be neglected, this depth is defined as the soil constant temperature layer [13]. The formula for the periodic variation of soil temperature with time and depth could be written as:

$$T(h_t, \tau) - T_{a_m} = (T_{a_{max}} - T_{a_m})\phi \exp\left(-h_t\sqrt{\frac{\pi}{a_t\tau_0}}\right)\cos\left(2\pi\frac{\tau}{\tau_0} - h_t\sqrt{\frac{\pi}{a_t\tau_0}} - \psi\right) \tag{1}$$

$$\phi = \left[1 + 2\frac{\lambda_t}{\alpha_a}\sqrt{\frac{\pi}{a_t\tau_0}} + 2\left(\frac{\lambda_t}{\alpha_a}\sqrt{\frac{\pi}{a_t\tau_0}}\right)^2\right]^{-0.5} \tag{2}$$

$$\Psi = \tan^{-1}\left[\frac{1}{1 + \frac{\alpha_a}{\lambda_t}\sqrt{\frac{a_t\tau_0}{\pi}}}\right] \tag{3}$$

Where:

T_{a_m}——Annual average temperature, K.
$T_{a_{max}}$——Maximum daily average temperature, K.
τ——The time to begin the calculation from the day of the maximum average temperature, h.
α_a——Heat transfer coefficient between soil and atmosphere, W/(m^2 K).
h_t——The depth vertically downward from the surface of earth, m.
a_t——Thermal conductivity of soil, m^2/h.