Calculation of Waxy Crude Pipeline Temperature Field Based on Unstructured Grid

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Abstract. Because of the characteristics of high pour point and high viscosity of waxy crude, pipeline temperature must be calculated accurately in order to guarantee the safety of the pipeline operation. Therefore it is a crucial technical problem to simulate the temperature field precisely. In this paper, unsteady-state heat transfer model of normal operation, restrict time of shut down of waxy crude pipeline and restart process was proposed. And the two-dimensional temperature field of the pipeline is calculated by a numerical method based on unstructured grids. Then the temperature field distribution and contour map at 2℃ and 5℃ oil temperature are obtained, which plays a significant role for the safe transportation of pipeline.

Introduction

More than 80% of crude oil produced in China is waxy crude oil with a high percentage of wax, high pour point and high viscosity [1]. If the fluid temperature is low, the waxy crude pipeline would be possibly forced to shut down because of the non-Newton behavior of the high waxy crude. Heating the pipeline is a common measure used in waxy crude transportation. Due to the minimum flow-rate and restrict time of shut down of waxy crude pipeline changes a lot with the temperature field of pipeline required changing [2], it is crucial to obtain an accurate temperature field around the waxy crude pipeline.

The temperature field around the waxy crude pipeline is usually regarded as two-dimensional temperature field in calculation. Considering the physical property change of soil, the soil temperature field should be discretized by unstructured grids. Although the process of generating unstructured grid is complicated, the method has flexible data structure and is especially suitable for the boundary which is geometrical unstructure;. Therefore, the numerical method based on unstructured grid is used to obtain a temperature field [3].

The paper is organized as follows: the mathematical model of high waxy pipeline is given in the next section, including the governing equation of temperature of high waxy pipeline, restrict time of shut down of waxy crude pipeline and restart process. The discretization method to solve the model in numerical calculation is proposed thereafter. Then the numerical results are given by numerical simulation to mo-da line. Finally the conclusion remarks are addressed.

Mathematical model of high waxy pipeline

Mathematical models of the governing equation of high waxy pipeline, restrict time of shut down of waxy crude pipeline and restart process are proposed as follows:

Governing equation model of normal operation

For pipelines buried within the soil, there are three different parts of heat transfer, namely, the heat between the wax and tube, the heat between tube and coating, then the heat transfers from coating to soil and finally to atmosphere. The factors, which influence the heat dissipation of hot oil pipelines, can be divided into two types: internal factors and external factors. The internal factors include thermophysical properties of oil, etc. The external factors included physical properties of soil around the pipeline, thickness of covering soil, atmospheric temperature and wind speed etc. The physical model is shown in Fig. 1 and Fig. 2 separately.

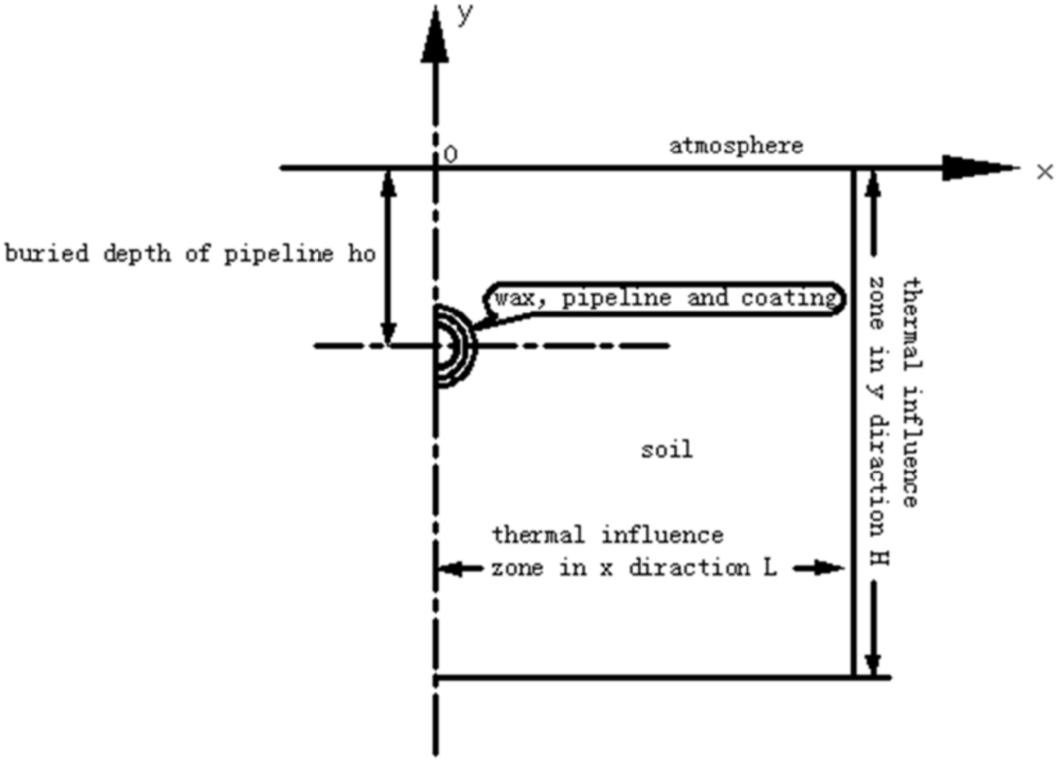


Fig. 1 Profile of buried pipeline

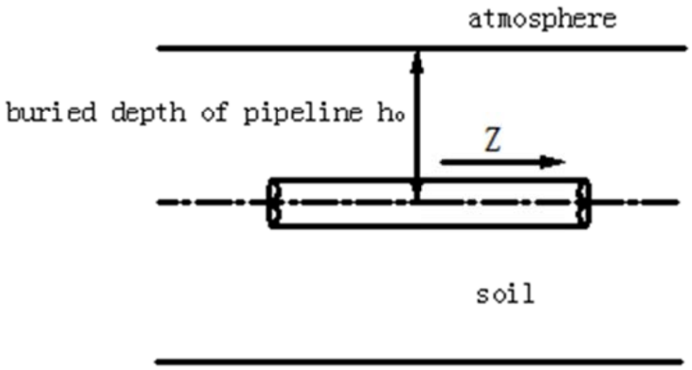


Fig. 2 Figure of buried pipeline

And the governing equation models of normal operation are shown as follows:

Flow equation:

Continuity equation: $\frac{\partial}{\partial \tau}(\rho A)+\frac{\partial}{\partial z}(\rho u A)=0$ (1)

Momentum equation: $\frac{\partial u}{\partial \tau}+V\frac{\partial u}{\partial z}=-g\sin\alpha-\frac{1}{\rho}\frac{\partial p}{\partial z}-\frac{f}{D}\frac{u^2}{2}$ (2)

Where v|v| is instead of v^2 as far as velocity direction of oil is concerned but it is not concerned in the paper.

Energy equation: $\frac{\partial}{\partial \tau}\left[(\rho A)\left(U+\frac{u^2}{2}+gs\right)\right]+\frac{\partial}{\partial z}\left[(\rho u A)\left(h+\frac{u^2}{2}+gs\right)\right]=-\pi D q$ (3)

By means of the continuity equation, momentum equation and energy equation, heat transfer equation of oil is established:

$$C_p \frac{\mathrm{d}T}{\mathrm{d}\tau} - \frac{T}{\rho}\alpha\frac{\mathrm{d}p}{\mathrm{d}\tau} - \frac{fu^3}{2D} = -\frac{4q}{\rho D} \tag{4}$$

$$\rho_k C_k \frac{\partial T_k}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda_k r \frac{\partial T_k}{\partial r}) + \frac{1}{r^2}\frac{\partial}{\partial \beta}(\lambda_k \frac{\partial T_k}{\partial \beta}) \tag{5}$$

Where $k = 1,2,3$ represents wax deposition, tube wall and coating separately.

Soil thermal conductivity:

$$\rho_s C_s \frac{\partial T_s}{\partial \tau} = \frac{\partial}{\partial x}(\lambda \frac{\partial T_s}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T_s}{\partial y}) \tag{6}$$

Connection condition:

Heat-transfer process of oil in the pipeline, wax deposition, tube wall, coating and soil is the interdependence, it satisfies:

$$-\lambda_1 \frac{\partial T_1}{\partial r}\bigg|_{r=R_0} = \alpha_0 (T - T_0) \tag{7}$$

$$\lambda_k \frac{\partial T_k}{\partial r}\bigg|_{r=R_k} = \lambda_{k+1}\frac{\partial T_{k+1}}{\partial r}\bigg|_{r=R_k} \quad k = 1,2 \tag{8}$$

$$T_k\bigg|_{r=R_k} = T_{k+1}\bigg|_{r=R_k} \qquad k = 1,2 \tag{9}$$

$$\lambda_3 \frac{\partial T_3}{\partial r}\bigg|_{r=R_3} = \lambda \frac{\partial T_s}{\partial r}\bigg|_{r=R_3} \tag{10}$$

$$T_3\bigg|_{r=R_3} = T_s\bigg|_{r=R_3} \tag{11}$$

Boundary conditions:

Due to symmetry of computational domain, it only researches the right half part of the pipeline. The boundary conditions are:

当 $x=0$，$0 \le |y| \le H_0 - R_3$ 时，$\lambda \frac{\partial T_s}{\partial x} = 0$ (12)

当 $x=0$，$H_0 + R_3 \le |y| \le H$ 时，$\lambda \frac{\partial T_s}{\partial x} = 0$ (13)

当 y=0 时，$\frac{\partial T_s}{\partial y} = \frac{\alpha_a}{\lambda}(T_a - T_s)$ (14)

当 $|x|$ =L 时，$\frac{\partial T_s}{\partial x} = 0$ (15)

当 $|y|$ =H 时，$T_s = T_n$ (16)

Variables of the equations are illustrated as follows: ρ is oil density, kg/m^3; A is sectional area of pipeline flow, m^2; τ is time, s; u is average velocity of pipeline flow, m/s; z is axial position of tubing, m; g is acceleration of gravity, m/s^2; α is angle between axial and horizontal direction of tubing; p is average pressure of sectional area of pipeline flow, Pa; f is darcy friction factor；C_p is heat capacity at constant pressure of crude oil, J/(kg·℃); U is specific internal energy of crude oil, J/kg; s is specific entropy of crude oil, J/(kg· K)； h is specific enthalpy of crude oil, J/kg; D is inner diameter of pipeline, m; q is heat dissipating capacity of crude oil in tube wall unit area per unit time, w/m^2; π is circumference ratio; T is temperature of crude oil, ℃； α is expansion coefficient of crude oil, ℃$^{-1}$; ρ_i is density of the i layer(wax deposition, tube wall and anticorrosion coating), kg/m^3; C_i is heat capacity of the i layer(wax deposition, tube wall and anticorrosion coating), J/(kg·℃); T_i is temperature of the i layer(wax deposition, tube wall and anticorrosion coating), ℃; λ_i is thermal conductivity of the i layer(wax deposition, tube wall and anticorrosion coating), W/(m·℃); r is radial position, m; β is radian of the ring; α_0 is heat transfer coefficient between oil and internal tube wall, W/(m^2·℃); T_0 is temperature of internal tube wall, ℃. ρ_s is density of soil, kg/m^3; C_s is heat capacity of soil, J/(kg·℃); T_s is temperature of soil, ℃; λ is thermal conductivity of soil, W/(m·℃); x is horizontal position perpendicular to axial direction, m; y is depth, m; α is heat transfer coefficient between soil surface and atmosphere, W/(m^2·℃); T_a is temperature of atmosphere ℃, T_n is temperature of constant temperature strata, ℃.

Mathematical models of shutdown temperature dropping

Shutdown temperature dropping of waxy crude oil is a three-dimension unsteady heat transfer with phase transition, natural convection and moving boundary. During transportation stopping, heat loss to the surroundings to combine the pipeline, coating, soil around the pipeline and atmosphere into a complete thermal system and combine crude oil of pipeline and each layer medium into different thermal subsystem [4].

Heat conduction equation of crude oil in the pipeline:

$$\rho C\frac{\partial T}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial \beta}\left(\frac{\lambda}{r}\frac{\partial T}{\partial \beta}\right) \tag{17}$$

The thermal conductivity in Ep. 17 should be truly selected for retaining state according to different states of crude oil and an equivalent thermal conductivity for natural convection station.

$$\lambda_{eff}=\frac{-\alpha_y(Ty-Tw)}{\left(\frac{\delta Ty}{\delta r}\right)_w} \tag{18}$$

Heat conduction equation of wax deposition, tube wall and coating and heat conduction equation of soil are the same as Eq. 5 and Eq. 6.

Mathematical models of restart process

Restart process of buried hot oil is an unsteady process with hydraulic and thermodynamic interacting each other. Governing equation to crude, heat conduction equation of wax deposition, tube wall and coating and heat conduction equation of soil are the same as previous [5]. But if shutdown time is too long and all or part of crude shows thixotropy, the momentum equation of crude is different. More details can be found in the equations proposed by Tianyou Liu and Jingnan Zhang [6,7].

Computational domain discretization and numerical method

Computational domain discretization

Computational domain should be a semi-infinitely large soil temperature field, heat loss of pipeline is analytic solved by source method. In analytic solution, the question needs to be simplified a lot and deviation between results and true value is large [8]. So the solution can be brought out more accurately by controlling grid division. In the paper, computational domain is thermal influence zone of crude oil pipeline and method is numerical method. Before taking numerical method, the calculation region should be discretized (grid division), as shown in Fig. 3.

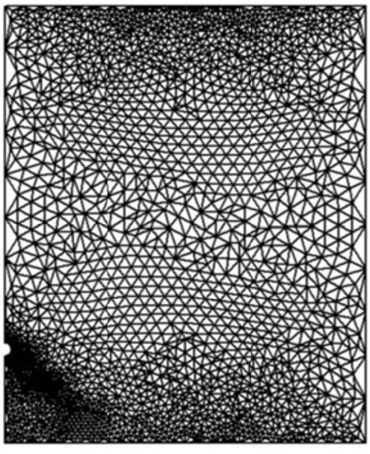


Fig. 3 Dense grid division of soil area

Governing equation discretization

Oil flow equation is discretized by finite difference method, wax deposition, tube wall and anticorrosion coating and soil is studied by control volume method.

Continuity equation, momentum equation and heat transfer equation of oil have the same discretization method. We illustrate oil flow equation discretization by heat transfer oil flow equation. Unsteady hydraulic-thermodynamic pipe flow equation is discretized by finite difference method. As shown in Fig. 3, pipeline is divided into several stags and both sides of Eq. 4 are discretized within $\Delta\tau$ time:

$$C_p\left(\frac{\partial T}{\partial \tau}+\frac{\partial T}{\partial z}\frac{\partial z}{\partial \tau}\right)-\frac{T}{\rho}\beta\left(\frac{\partial p}{\partial \tau}+\frac{\partial p}{\partial z}\frac{\partial z}{\partial \tau}\right)-\frac{fV^3}{2D}=-\frac{4q}{\rho D} \tag{19}$$

$$C_p\left(\frac{T_i-T_i^0}{\Delta\tau}+\frac{T_i^0-T_{i-1}^0}{\Delta z}V_i\right)-\frac{T_i}{\rho}\beta\left(\frac{p_i-p_i^0}{\Delta\tau}+\frac{p_i^0-p_{i-1}^0}{\Delta z}V_i\right)-\frac{fV_i^3}{2D}=-\frac{4q_i}{\rho D} \tag{20}$$

Numerical Example

A typical pipeline namely mo-da line in northeast is chosen to proceed numerical simulation for the temperature field of it. According to parameters given (burial depths of the pipeline top) and scientific research achievements obtained that soil layered structure (0-3m of sandy loam within 20 percent water, 3-10m of silty clay within 25 percent water, 10-20m of bedrock) , thermal influence zone is 20*15m; no insulating layer. Assuming that the thickness of frozen soil is 6m, the temperature is respectively 2℃and 5℃, the temperature field and freeze-thaw of soil is predicted.

Results are as shown in Fig. 4-Fig. 6. The region bordered by green lines around the pipeline is melting region without frozen soil and the lower line close to horizontal line is the lower limit of permafrost. The paper uses empirical data of parameters of soil, boundary conditions of the rock surface, field condition of frozen soil and history of oil temperature to carry out numerical simulation and obtained a result, which plays a guiding role for safe operation.

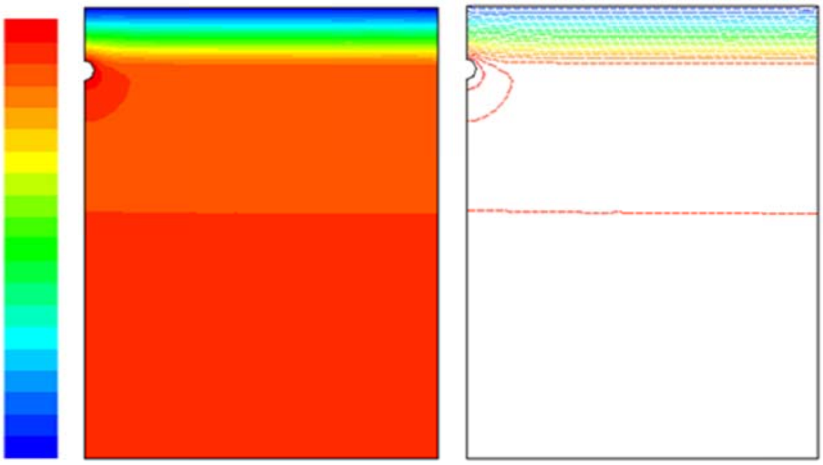


Fig. 4 Temperature field distribution and contour map at 2℃ oil temperature

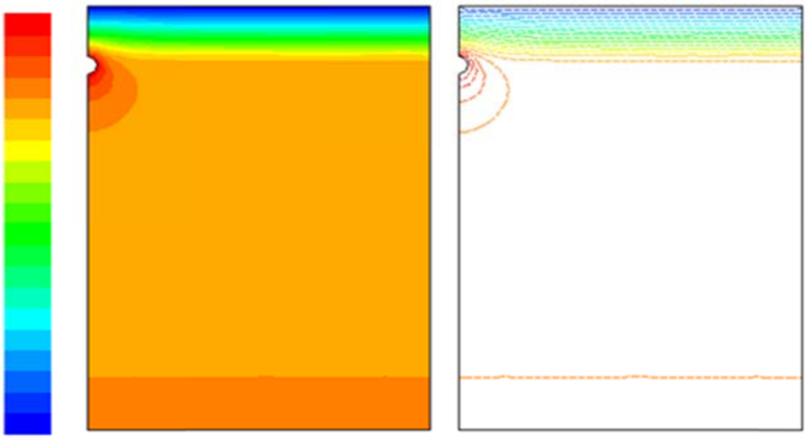
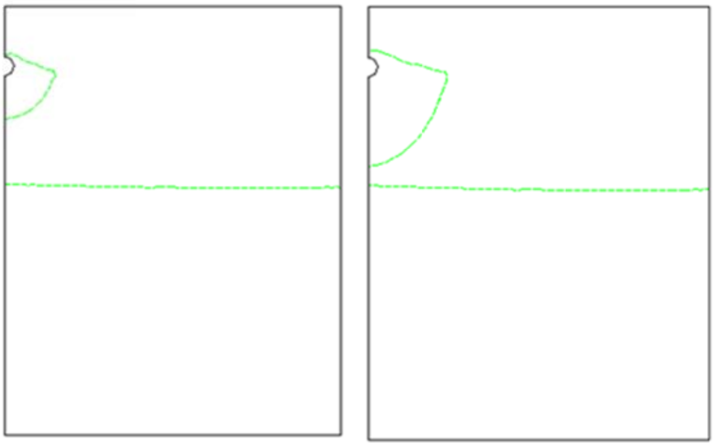


Fig. 5 Temperature field distribution and contour map at 5℃ oil temperature



（a）2℃ Oil temperature （b）5℃ Oil temperature

Fig. 6 Contour map at 0℃

Summary

The paper proposes an unsteady-state heat transfer model for temperature field around waxy crude pipeline. The semi-infinitely large temperature field of the soil is transformed to a finite rectangular field by the methods of confor-mal transformation. The soil temperature field around the pipeline of waxy oil is calculated by discretization method in transporting process. Through proceeding numerical simulation to the certain pipeline, the temperature field distribution and contour map at 2℃ and 5℃ oil temperature are obtained.

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