Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list.

For correction or revision of any artwork, please consult [http://www.elsevier.com/artworkinstructions](http://www.elsevier.com/artworkinstructions).

Any queries or remarks that have arisen during the processing of your manuscript are listed below and highlighted by flags in the proof.

<table>
<thead>
<tr>
<th>Location in article</th>
<th>Query / Remark: click on the Q link to go please insert your reply or correction at the corresponding line in the proof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Please check all author names and affiliations.</td>
</tr>
<tr>
<td>Q2</td>
<td>Please check the hierarchy of the section headings.</td>
</tr>
<tr>
<td>Q3</td>
<td>Please check the author name in Ref. [2].</td>
</tr>
<tr>
<td>Q4</td>
<td>Please provide 3—5 bullet points as Research Highlights, no more than 85 characters per bullet point for the article.</td>
</tr>
</tbody>
</table>

Thank you for your assistance.
Numerical simulation of a buried hot crude oil pipeline under normal operation

Bo Yu a,⁎, Chao Li a, Zhengwei Zhang b, Xin Liu a, Jinjun Zhang a, Jinjia Wei c, Shuyu Sun d, Jinping Huang e

a Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum-Beijing, Beijing 102249, PR China
b State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
c Department of Mathematical Sciences, Clemson University, Clemson, SC 29634-0975, USA
d Shengyang Dispatching Center, PetroChina Pipeline Company, Shenyang 110000, PR China

A B S T R A C T

A physical model is proposed to study the heat transfer and oil flow of a buried hot oil pipeline under normal operation. With certain physically reasonable assumptions, the governing equations for the thermal analyses are derived. An approach combining unstructured-finite-volume [1] and finite difference methods is applied to solve the governing equations, in which the soil domain was discretized by unstructured grids. Numerical simulations in a wide range of operating conditions are conducted. The operating conditions cover 5 months (April, May, June, October and November) with throughputs ranging from 15,007 tons per day to 27,451 tons per day and outlet temperatures varying from 40.6 °C to 64.8 °C. Measured data are provided for comparison. A good agreement between numerical simulations and field measurement suggests that the proposed numerical scheme is a suitable method to simulate the heat transfer and oil flow of buried hot crude oil pipelines. We also analyze a number of influential factors on the temperature distribution of oil along the pipeline.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Most crude oil produced in China is of high pour-point or highly viscous, which demands heating transportation. Heating transportation is a technology to reduce pressure-drop consumption, in which the crude oil is heated by a heating furnace to decrease its viscosity. During the transportation the oil temperature, though decreasing along the pipeline, is desirable to be kept above the gel point all the time. As an effective method to transport viscous heavy oils or high-pour-point crude oils, heating has the disadvantages of great energy-consumption. As a result, it is meaningful to study and gain a deep understanding of thermal and hydraulic phenomena, and it is important to develop better operation strategies to save energy, improve the automatic control and ensure operation safety.

Experimental and numerical studies have been reported on the thermal and hydraulic characterization of the hot oil pipeline. Compared to experiments, the numerical studies have the advantages of low cost and short research turnaround. With the development of the computer, numerical methods become increasingly popular, providing useful information for buried hot oil pipelines. As an early modeling effort on this subject, an analytical method was applied to study the buried hot oil pipeline [2]. However, the analytical solution usually deviates greatly from the real instance due to substantial simplifications that are required. Numerical methods can take more factors into account with fewer assumptions. A first step for numerical methods is the treatment of spatial domains. Strictly speaking, the influence region of the hot oil pipeline is semi-infinite soil region and we need to convert the domain into a finite computational domain in numerical simulations. Generally there are two approaches that can implement this conversion. One is the conformal transformation in a double polar coordinate [3] transforming the semi-infinite region into a rectangular or annular region, which requires complicated and tedious mathematical derivations and which also introduces a number of simplifications. The other approach is to introduce a thermal influence region of the pipeline [4]. The essence of the thermal influence region method is that the soil region far away from the hot oil pipeline is almost not affected by the oil and thereby the computational domain can be limited to the region close to the pipeline with an insulated boundary condition. The range of the thermal influence region depends on not only the soil properties, but also the buried depth, the diameter of the pipeline and the oil temperature. On the basis of the thermal influence region, a finite difference method and a finite volume method are proposed to make thermal analyses on the normal operation of the buried hot oil pipeline in this paper.

2. Mathematical model of the buried hot oil pipeline under normal operation

The thermal system of the buried pipeline contains the convective heat transfer of the oil in the pipeline and the heat conduction outside the pipeline, which is affected by a lot of parameters such as the air temperature, the thickness of wax, the properties of soil and the corrosion protective covering. To simplify the analyses, the following assumptions are made in the study.

(1) The oil temperature on a fixed pipeline cross section is assumed to be uniform; in other words, the oil temperature is only the function of time and axial position.
(2) The soil outside the pipeline is modeled as an isotropic medium, even though it is anisotropic in reality.
(3) The thickness of the wax deposition is assumed to be uniform along the pipeline.
(4) The heat conduction of the pipeline is assumed to be two-dimensional neglecting the axial temperature drop. Since the radial temperature gradient is much greater than the axial temperature gradient, the three-dimensional heat conduction of the wax deposition, the pipe wall, the corrosion protective covering can be simplified using two spatial dimensions.

How to determine the computational region is an important issue in numerical simulations. In this study we use a finite thermal influence region in place of the semi-infinite region to simplify the calculation. The idea is that the closer the soil is to the oil pipeline, the more it is affected by the pipeline, and when the soil is sufficiently far away from the hot oil pipeline the soil temperature is hardly affected by the oil. Generally, the thermal influence region can be determined by measuring the soil temperature field or by performing test simulations. The measured soil temperatures in Middle-Talimu have shown that the maximum ranges of the thermal influence region are 2.0 m in the horizontal direction and 2.2 m in the vertical direction for an insulated pipeline buried under 1.6 m with outer diameter 273 mm; while those of a non-insulated pipeline are 5.0 m in the horizontal direction and 5.5 m in the vertical direction, where the diameter of the pipeline is 426 mm and the burial depth is 1.7 m [5]. It has been reported that the hot oil pipeline has practically no influence on the temperature of the soil 5–10 m away from the center of the pipeline that has an outer diameter of 720 mm and was buried in northeast China [6]. As stated in the paper [7], the soil temperature within the depth of 3 m varies along the pipeline.

Based on the above assumptions and simplifications, a mathematical model describing the thermal system of the buried hot oil pipeline is established as follows [8].
following equations: the others. Their coupling interactions can be described by the protective covering and the soil are tightly coupled for the heat corrosion protective covering respectively.

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

\[ \frac{\partial V}{\partial t} + V \frac{\partial V}{\partial z} = -g \sin \alpha - \frac{1}{\rho} \frac{\partial p}{\partial z} - f \frac{V^2}{2} \]  (2)

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

The heat transfer equation of the oil flow (4) can be obtained from Equations (1) - (3) listed above [9].

\[ C_f \frac{dT}{dt} + \frac{T}{\rho} \frac{\partial p}{\partial t} + \frac{f V^3}{2D} = \frac{4q}{\rho D} \]  (4)

(2) Heat transfer equations of the wax deposition, the pipe wall and the corrosion protective covering:

\[ \rho_l C_w \frac{\partial T_k}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_k \frac{\partial T_k}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( \lambda_k \frac{\partial T_k}{\partial \theta} \right) \]  (5)

\[ k = 1, 2, 3 \text{ stand for the wax deposition, the pipe wall and the corrosion protective covering respectively.} \]

(3) Heat conduction equation of the soil

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

(4) Matching conditions

The crude oil, the wax deposition, the pipe wall, the corrosion protective covering and the soil are tightly coupled for the heat transfer process, with substantial effects from one component on the others. Their coupling interactions can be described by the following equations:

\[ -\lambda_l \frac{\partial T_l}{\partial r} \bigg|_{r=R_l} = \alpha_l (T - T_0) \]  (7)

\[ \lambda_k \frac{\partial T_k}{\partial r} \bigg|_{r=R_k} = \lambda_{k+1} \frac{\partial T_{k+1}}{\partial r} \bigg|_{r=R_{k+1}} \quad k = 1, 2 \]  (8)

\[ T_k \bigg|_{r=R_k} = T_{k+1} \bigg|_{r=R_{k+1}} \quad k = 1, 2 \]  (9)

\[ \lambda_s \frac{\partial T_s}{\partial r} \bigg|_{r=R_s} = \lambda_{s+1} \frac{\partial T_{s+1}}{\partial r} \bigg|_{r=R_{s+1}} \]  (10)

(5) Boundary conditions

Only the right half of the computational domain is taken into consideration due to its symmetry.

\[ \lambda_s \frac{\partial T_s}{\partial x} = 0, \text{ at } x = 0, 0 \leq |y| \leq H_0 - R_s \]  (12)

\[ \lambda_s \frac{\partial T_s}{\partial x} = 0, \text{ at } x = 0, H_0 + R_s \leq |y| \leq H \]  (13)

\[ \frac{\partial T_s}{\partial x} = 0, \text{ at } x = L \]  (14)

\[ T_s = T_n, \text{ at } y = -H \]  (15)

\[ T_s = T_n, \text{ at } y = -H \]  (16)

3. Numerical method

3.1. Discretization of the computational domain

A Delaunay triangulation method [10] is used to generate the grids of the soil domain automatically. After the input of the outer diameters of the pipelines and the buried pipeline depth (namely the distance between the center of the pipeline and the ground surface), the software can automatically divide the computational domain into unstructured triangular grids in Cartesian coordinate system, as Fig. 2 shows. The further the soil is away from the pipeline, the lesser it will be affected by the hot crude oil pipeline, and meanwhile, the lesser the temperature gradient will be. In order to simulate true temperature field, denser grids are generated in the region close to the pipeline. A structural grid generation in polar coordinates is applied to the steel pipe wall, the wax deposition and the corrosion protective covering. The local grid expanded view is shown as Fig. 3. A finite difference method is used in discretizing the pipeline, as Fig. 4 shows. The computational pipeline section begins at Point 1, the outlet of the pumping station, and ends at Point n, the inlet of the next pumping station.

3.2. Discretization of the governing equations

A finite difference method is applied to discretize the oil flow equation while a control volume integration method is employed to discretize the governing equations of the wax deposition, the
pipe wall, the corrosion protective covering and the soil. The discretization of the boundary conditions is almost identical and its discretization process is hence omitted.

### 3.2.1. Discretization of the oil flow equations

Since the methods are similar to treat different governing equations of the oil flow, we present only the discretization of the oil temperature equation as an example. The oil temperature equation is discretized with a finite difference method, in which the flow equations become

\[
\frac{\rho C_p}{\Delta t} \left( \frac{\partial T}{\partial t} \right) - \frac{\mathbf{v} \cdot \nabla T}{\rho} + \frac{\partial}{\partial z} \left( \alpha \frac{\partial T}{\partial z} \right) - \frac{\mathbf{v} \cdot \nabla T}{\rho} = -\frac{4q}{\rho D} \tag{17}
\]

In which, \( q \) represents the heat loss of the pipeline section between Point \( i-1 \) and Point \( i \) during the time interval of \( \Delta t \). Moreover, \( p_i \) and \( p_i^0 \) stand for the pressure at present time step and that at previous time step at Point \( i \), while \( T_i \) and \( T_i^0 \) represent the temperature at present time step and that at previous time step at Point \( i \).

When \( \Delta z = V \Delta t \), Equation (19) can be simplified as follows.

\[
T_i = \frac{\frac{V^3}{2D} \rho \frac{\partial T}{\partial z} - 4q_i}{\rho C_p} + \frac{\rho C_p}{\Delta t} \left( p_i^0 - p_i^0 \right) \tag{20}
\]

### 3.2.2. Discretization of the governing equations of wax deposition, the pipe wall and the corrosion protective covering

The heat conduction equations of wax deposition, the pipe wall and the corrosion protective covering can be expressed in a general form.

\[
\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{\partial \theta} \frac{\partial}{\partial \theta} \tag{21}
\]

Integrated on the control volume shown in Fig. 5, Equation (21) becomes

\[
\int_{r}^{r+\Delta r} \int_{n}^{n+e} \int_{w}^{w} r \rho C_p \left( \frac{\partial T}{\partial t} \right) \, dt \, d\theta \, dr + \int_{r}^{r+\Delta r} \int_{n}^{n+e} \int_{w}^{w} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) \, dt \, d\theta \, dr + \int_{r}^{r+\Delta r} \int_{n}^{n+e} \int_{w}^{w} \frac{1}{\partial \theta} \frac{\partial}{\partial \theta} \, dt \, d\theta \, dr = \int_{r}^{r+\Delta r} \int_{n}^{n+e} \int_{w}^{w} \mathbf{v} \cdot \nabla T \, dt \, d\theta \, dr \tag{22}
\]

\[
\left( \rho C_p \frac{\partial T}{\partial t} \right)_{n}^{n+e} + \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right)_{n}^{n+e} + \frac{\partial}{\partial \theta} \frac{\partial T}{\partial \theta} \, \Delta r \Delta \theta = \left( \frac{\partial}{\partial t} \right)_{n}^{n+e} + \left( \frac{\partial}{\partial t} \right)_{e}^{e+e} + \left( \frac{\partial}{\partial \theta} \right)_{n}^{n+e} + \left( \frac{\partial}{\partial \theta} \right)_{e}^{e+e} \frac{\partial}{\partial \theta} \frac{\partial T}{\partial \theta} \, \Delta r \Delta \theta \tag{23}
\]
where $P_{t0}$ denotes the area of triangle $P_0$; $T_{t0}$ and $T_{t0}'$ represent the temperature at the present time step and that at the previous time step respectively; $\nabla T$ is the average temperature gradient on the interface $j$, which can be obtained by a linear interpolation of the temperature gradients of the two nodes neighboring to interface $j$. $\nabla T = w_{P_0} \nabla T_{P_0} + w_{P_1} \nabla T_{P_1}$.

As can be seen from the above derivation, the algebraic equation can be obtained provided the temperature gradients of the nodes have been given. The temperature gradient is determined using a least square method [11].

$$\frac{\partial}{\partial t} \nabla T_{P_0}^i - \frac{3}{|d_j|} \left( T_{t0} - T_{t0}' \right) \frac{d_j}{|d_j|}^2 = 0, \quad i = 1, 2$$

Here $\nabla T_{P_0}^i$ stands for the component on coordinate $i$ of the temperature gradient of node $P_0$. $d_j$ is a vector directed from $P_0$ to $P_j$. Algebraic equation (30) can be expressed in a matrix form below.

$$\nabla T_{P_0} = G^{-1} h$$

In which, the four components of matrix $G$ and the two components of column vector $h$ are respectively shown as follows.

$$g_{kl} = \frac{\sum_{j=1}^6 |d_j|^2}{|d_j|^2} \quad k = l = 1, 2$$

$$h_k = \frac{\sum_{j=1}^6 (T_{t0} - T_{t0}') \frac{d_k}{|d_j|^2}}{\frac{1}{|d_j|^2}} \quad k = 1, 2$$
the application of equation (29) may lead to a non-physical oscillate temperature gradients of the nodes have been obtained. However, the interface can be easily solved with equation (29) after the explicit modi-

\[ \frac{d}{d_j} = \begin{pmatrix} d_{i1} \end{pmatrix} \]

The final discretized equation can be obtained from Equations (28) and (33) as follow.

\[ \begin{align*}
\nabla T_j = & \left( w_{p_j} \nabla T_{p_j} + w_{p_j} \nabla T_{p_j} \right) \\
& - \left( w_{p_j} \nabla T_{p_j} + w_{p_j} \nabla T_{p_j} \right) \cdot \frac{d_i}{d_j} + \frac{d_i}{d_j} + T_{p_j} - T_{p_j} = d_j
\end{align*} \]

This concludes the construction of the algebraic equations for the oil, the wax deposition, the pipe wall, the corrosion protective

\[ a_{p_j} T_{p_j} = \sum_{i=1,2,3} a_{p_i} T_{p_i} + b \\
abla T_j = \left( w_{p_j} \nabla T_{p_j} + w_{p_j} \nabla T_{p_j} \right) \cdot \frac{d_i}{d_j} + \frac{d_i}{d_j} + T_{p_j} - T_{p_j} = d_j
\]

\[ a_{p_j} = \frac{A_j}{\Delta x} + \frac{A_j}{\Delta x} \sum_{i=1,2,3} \left( w_{p_j} \nabla T_{p_j} + w_{p_j} \nabla T_{p_j} \right) \cdot \frac{d_i}{d_j} + \frac{d_i}{d_j} + T_{p_j} - T_{p_j} = d_j
\]

covering and the soil. To solve these equations we use an iterative Gauss-Seidel method.

4. Numerical simulation and analysis

The hydraulic loss, the inlet temperature and the soil temperature field can be measured experimentally. We first verify our numerical method and the code, by carrying out the calculations in a wide range of operating conditions and making a comparison between the measured values and the numerical results. We then analyze a number of important influential factors on the temperature distribution of the oil along oil pipelines.

4.1. Comparison between the measured values and numerical results

We study the pipeline between Huludao station and Suizhong station of Tieling-Qinhuangdao Pipeline of Northeast Pipeline Company, where the Daqing crude oil is transported. The pipeline length, its outer diameter and pipe wall thickness are 71.47 km, 720 mm and 8 mm, respectively. The average buried depth of the pipeline is 1.6 m; the elevation difference between the stations is 4.57 m; the thermal conductivity of the pipe wall, the wax deposition, the corrosion protective covering and the soil are 62.5 W/(m°C), 0.2 W/(m°C), 0.2 W/(m°C) and 1.4 W/(m°C) respectively; the thickness of the corrosion protective covering is 8 mm; the convective heat transfer coefficient of the ground surface is 25.6 W/

Calculations are made for 29 operation cases, which cover 5 months (April, May, June, October and November) as shown in Table 1. The simulated throughput ranges from 15,077 to 27,451 tons/day and the outlet temperature varies from 40.6 to 64.8°C. These operations cover most of the typical operating conditions which can be measured.

The comparisons of the inlet temperature and of the hydraulic loss between the calculated values and the measured values under the same operating condition are shown in Figs. 7 and 8 respectively. As shown in Table 1, Figs. 7 and 8, the inlet temperature and hydraulic loss agree well with the measured data. Though the maximum difference of inlet temperature between the numerical and measured values is as large as 2.5°C, the average difference is only 0.737. Most deviations of the temperature are within 1.0°C except those under particular operating conditions. Similarly, though the maximum hydraulic loss deviation is 0.22 MPa, the average hydraulic loss deviation is only 0.0229 MPa. For both the inlet temperature and the hydraulic loss, most calculations have quite a good agreement with the measured values. To quantitatively show the difference, we introduce a relative error (E(%)) defined as
With this definition, we can calculate the relative errors of the inlet temperature and the hydraulic loss. These relative errors are shown in Figs. 9 and 10 respectively. Fig. 9 shows that the absolute maximum relative error does not exceed 8% and most of the relative errors are within 2% and 2%. Fig. 10 shows that there is only one big deviation but not more than 23% and the relative error of the hydraulic loss is less than 10% except 3 cases. From the engineering application opinion the agreement is quite good.

Soil temperature is also a key parameter for safe transportation. It is necessary to show the comparison between the measured soil temperatures and the numerical ones to further verify the code developed based on the numerical method. One case on June 19th, 2006 is shown below.

Four temperature-sensing devices were set between the two stations, which located 20 km, 34 km, 42 km and 62 km from the outlet of Huludao station respectively. In each measuring device 35 platinum resistances were fixed up in five directions to measure the soil temperature as shown in Fig. 11, where there are 5, 5, 9, 8 and 8 resistances respectively set in Direction A, B, C, D and E.

The locations of the resistances are shown below (Note that the value in each direction is the distance from the resistance to the outer wall of the pipeline).

![Fig. 13. Temperature at the location of 42 km away from the station outlet.](image1)

![Fig. 14. Temperature at the location of 62 km away from the station outlet.](image2)

![Fig. 15. Relative errors at different locations.](image3)

![Fig. 16. Temperature distribution in winter.](image4)

Direction A: 0.0 m, 0.1 m, 0.2 m, 0.3 m, 0.5 m
Direction B: 0.1 m, 0.2 m, 0.3 m, 0.5 m, 0.7 m
Direction C: 0.0 m, 0.1 m, 0.2 m, 0.3 m, 0.5 m, 0.7 m, 0.9 m, 1.1 m, 5.0 m
Direction D: 0.016 m, 0.1 m, 0.2 m, 0.3 m, 0.5 m, 0.7 m, 0.9 m, 1.1 m
Direction E: 0.0 m, 0.1 m, 0.2 m, 0.3 m, 0.5 m, 0.7 m, 0.9 m, 1.1 m.

The soil temperatures at different locations on June 19th, 2006 are shown in Figs. 12–14. The relative errors of the calculated value of the soil temperature are shown in Fig. 15. Generally speaking, the numerical results have a good agreement with the measured values as shown in Figs. 12–14. The platinum resistances on the outer pipe wall, numbered as #1, #11 and #28, are selected as the measuring points since the temperatures there are close to that of the oil flow. The maximum difference is within 1.2°C. The platinum resistance on the corrosion protective covering is labeled as 20#, whose temperature deviation is within 2.9°C. One reason for the deviation is that the thickness of the corrosion protective covering we use in this program is 8 mm, which is equal to the thickness of the new pipeline in Northeast Pipeline Networks. However, the actual
thickness is less than 8 mm due to the aging after more than 30 years' operation. The platinum resistance numbered as 19# is the farthest one from the pipeline; the temperature difference between the measured values and the numerical results is as great as 3.7 °C. However, the relative errors as shown in Fig. 15 are acceptable in typical engineering applications.

4.2. Analysis of certain influential factors on the axial temperature drop under normal operation

In the transportation of the crude oil of high viscosity or high pour-point, the oil temperature is what we mostly concern. There are many factors which can affect the axial temperature drop of the buried hot oil pipeline under normal operation such as seasons, throughputs, outlet temperatures and the thicknesses of the wax deposition and so on. In this section four important factors are studied.

4.2.1. The effect of seasons

Mathematical simulations of the soil temperature field are performed for different seasons. Two-dimensional temperature distributions are plotting with the Tecplot software according to the calculated temperatures, which gives an illustration of the real temperature field. The temperature field outside the pipeline in winter is shown in Fig. 16 while that in summer is shown in Fig. 17.

As can be seen from Figs. 16 and 17, the closer the soil is to the pipeline, the more it is affected by the oil and the higher the soil temperature will be. The further the soil is away from the pipeline, the less it is affected and the temperature is much the same as the natural soil temperature. The isothermals in Fig. 16, which are denser above the pipeline in winter, are in elliptic shapes around the pipe. The great temperature gradients observed here are due to the significant temperature difference between the hot oil and the atmosphere. Consequently, we see that the heat flux density upwards is greater than that downwards. However, this phenomenon is less pronounced in summer because of the relatively high air temperature then, as shown in Fig. 17.

The axial temperature drop curves are shown in Fig. 18 in different seasons when other conditions are the same. It can be seen that the oil temperature drops slowly in summer because of higher soil temperature.

4.2.2. The effect of throughputs

The axial temperature drop curves are shown in Fig. 19 when the throughput is 26,000 tons/day or 18,000 tons/day. As can be seen
from the figure, the more the throughput is, the less steep the temperature curve is.

4.2.3. The effect of outlet temperatures

The axial temperature drop curves are shown in Fig. 20 when the outlet temperature is 60°C or 48°C. As can be seen from the figure, the higher the outlet temperature is, the quicker the temperature drops. The reason is that higher outlet temperature leads to greater temperature difference between the oil and the soil, which results in a quicker temperature drop.

4.2.4. The effect of thicknesses of wax deposition

The axial temperature drop curves are shown in Fig. 21 when the thickness of the wax deposition is 10 mm or 0 mm. As can be seen from the figure, the thicker the wax deposition is, the more slowly the temperature drops, and the more flattened the temperature curve is, which is due to the heat preservation effect of the wax deposition on the oil flow. A thicker deposition provides greater thermal resistance and leads to a slower temperature drop. Therefore, frequent pigging is unnecessary in the oil transportation if the pump stations can provide enough pressure to fulfill the transportation task.

From the analysis above some conclusions can be drawn. Due to economical concerns, it is inadvisable to raise the outlet temperature for increased inlet temperature in order to ensure the operating safety, especially in the cold winter. The decrease of the outlet temperature on the basis of safe operation is recommended for saving the energy consumption. Another feasible way for energy saving is to increase the pipeline oil throughput in winter.

5. Summary

A simplified mathematical model for a buried hot oil pipeline under normal operation has been established. A finite difference and finite-volume combined approach has been proposed to discretize the governing equations. Simulations under different operating conditions were performed and the comparisons between the calculation results and the measured data were made. These comparisons include a number of key parameters such as the inlet temperature, the hydraulic loss between two stations and the soil temperature field around the pipeline, and a good agreement in the comparison has verified our program for hydraulic and thermal simulations. These data comparisons also suggested that our approach yields accurate simulations under operating conditions in different months of a year, at various throughputs and with diverse outlet temperatures; this success has been made possible through introduction of the thermal influence region of the pipeline and utilization of finite volume methods on unstructured grids. Using our numerical model, a number of insightful conclusions have been drawn by analyzing various influential factors on the axial temperature drop under the normal operation of the buried hot oil pipeline.

Acknowledgement

The study is supported by National Science Foundation of China (No. 50876114, No. 50944030, No. 10602043), the Program for New Century Excellent Talents in University (NCET-07-0843), and the State Key Laboratory of Multiphase Flow in Power Engineering (Xi’an Jiaotong University).

References
