Calculation of Soil Natural Temperature Field in Cold Region and Analysis of Influencing Factors

Lantian Yang\textsuperscript{1,2}, Pengli Ge\textsuperscript{1,2}, Yanyan Xu\textsuperscript{1,2}, Guangwen Zeng\textsuperscript{1,2}, Qingshan Liu\textsuperscript{1,2}, Wenwen Xiao\textsuperscript{1,2}, Xudong Jia\textsuperscript{1}, and Ying Xu\textsuperscript{3,*}

\textsuperscript{1}Key Laboratory of Enhanced Oil Recovery in Carbonate Fractured-vuggy Reservoirs, CNPC, Urumqi, Xin Jiang, China
\textsuperscript{2}Northwest Company of China Petroleum and Chemical Corporation, Urumqi, Xin Jiang, China
\textsuperscript{3}Northeast Petroleum University, Da Qing City, China

Abstract. Soil properties directly affect the temperature change of crude oil in buried pipelines in cold regions, and clarifying soil temperature field and its influencing factors is the key to production management in gathering and transportation field. In this paper, a mathematical model for calculating soil natural temperature field was established to analyze the influence of frozen and unfrozen soil physical properties on soil natural temperature field, and to clarify the influence of soil physical properties parameters on soil temperature, delay time, freezing time and starting time of freezing, so as to provide theoretical support for thermal calculation of buried pipelines.

Keywords: Buried pipelines, Cold region, Soil temperature field, Influence factor.

1 Introduction

Most hot oil pipelines are laid underground. The temperature drop along the medium inside the pipeline is not only affected by the temperature, flow rate and physical properties of the medium at the inlet of the pipeline, but also by the annual periodic change of soil temperature field, time delay and whether the soil is frozen or not. Especially in the cold region, the annual maximum and minimum temperature difference is about 70\degree C, and the soil natural temperature field in different depths of variable temperate zone also varies greatly throughout the year.

Soil thermal property parameters are the basis of soil temperature field and temperature drop calculation of buried geothermal oil pipeline. There have been relevant studies on soil thermophysical properties and freezing depth at home and abroad [1-4]. Zhang Guozhong [5], in his research on the soil temperature field around the buried geothermal oil pipeline, gave another calculation formula for the natural temperature distribution of soil. The third boundary condition which is closer to the actual situation was used to describe the heat exchange between the surface and the atmosphere, so the calculation formula was closer to the actual situation.
Xu [6-7] considered the influence of atmospheric annual cycle temperature change on soil temperature field and, on this basis, analyzed the influence of pipeline buried depth and soil thermal conductivity on the temperature field of crude oil in the shutdown pipeline. Fan [8] applied the mathematical model of heat and mass transfer in porous media to compare the daily temperature changes in a cylindrical soil bed with a height of 500mm and a radius of 250mm in summer and winter when the environmental wind speed was 4m/s and 1m/s respectively and the environmental relative humidity was 35% and 85% respectively. B Han [9]analyzed the difference of soil temperature before and after precipitation in Gobi region .

In this paper, a mathematical model of soil natural temperature field is established according to soil physical properties in cold regions, and the change law of soil natural temperature field under different soil physical properties is analyzed. Meanwhile, its influence on delay time, freezing time and starting time of freezing is analyzed.

2 Mathematical model for soil natural temperature field calculation

The calculation of soil natural temperature field can be simplified as a one-dimensional periodic unsteady thermal conduction problem for semi-infinite objects under the third boundary condition. Its mathematical description is

$$\frac{\partial t_0(x, \tau)}{\partial \tau} = a \frac{\partial^2 t_0(x, \tau)}{\partial x^2}$$

(1)

$$t_\tau = t_{am} + (t_{amax} - t_{am}) \cos \left(\frac{2\pi \tau}{\tau_0}\right)$$

(2)

Where $t_0$ is soil temperature, °C; $a$ is soil temperature conductivity coefficient, m²/s; $\tau$ is the time from the hottest atmospheric temperature, s; $t_\tau$ is the atmospheric temperature at any time starting with the maximum annual atmospheric temperature, °C; $t_{am}$ is Annual mean temperature of the atmosphere, °C; $t_{max}$ is Atmospheric maximum annual temperature, °C.

The integral of equations (1) and (2) is solved:

$$t_0(x, \tau) = t_{am} + (t_{amax} - t_{am}) \cdot \phi \cdot \exp \left(-\frac{\pi}{a \cdot \tau_0} \cdot x\right) \cdot \cos \left(\frac{2\pi \tau}{\tau_0} - \frac{\pi}{a \cdot \tau_0} \cdot x - \psi\right)$$

(3)

$$\phi = \left(1 + \frac{2}{h} \cdot \frac{\lambda_t}{a \cdot \tau_0} \cdot 2 \left(1 + \frac{\lambda_t}{h} \cdot \frac{\pi}{a \cdot \tau_0}\right)^2\right)^{-0.5}$$

(4)

$$\psi = t_g^{-1} \left(\frac{1}{1 + \frac{h}{\lambda_t} \cdot \frac{\pi}{a \cdot \tau_0}}\right)$$

(5)
Where \( t_0(x, \tau) \) is the soil temperature at depth \( X \) when the time from the hottest atmospheric temperature is \( \tau \), °C; \( \lambda_0 \) is thermal conductivity of the soil around the pipe, W/(m·K); \( h \) is convective heat transfer coefficient between the surface and the atmosphere, W/(m\(^2\)·K).

By referring to the definition of delay time and the solution results of delay time for semi-infinite problems under the first class boundary conditions, the delay time (\( \xi \)) under the third class boundary conditions is generalized to be

\[
\xi = \sqrt{\frac{\pi}{a \cdot \tau_0}} \cdot x + \psi
\]

(6)

3 Analysis of the influence of physical properties of frozen and unfrozen soils on soil natural temperature field

By using the above model and combining with the results of soil thermophysical property test in cold regions, the average thermal conductivity and temperature conductivity of silty clay in unfrozen and frozen state were calculated, and the natural temperature field of soil under unfrozen and frozen physical property parameters was compared and analyzed. The average thermal conductivity of unfrozen silty clay was 1.11w/(m·K), and the temperature conductivity was 4.15×10\(^{-7}\)m\(^2\)/s. The average frozen silty clay was 1.44w/(m·K), and the temperature conductivity coefficient was 5.05×10\(^{-7}\)m\(^2\)/s. The annual change curves of soil temperature calculated in various depth unfrozen and frozen state were shown in FIG. 1. The change of delay time, freezing days with depth and freezing depth with starting date of freezing were shown in FIG. 2 ~ FIG. 4. Detailed results are summarized in Table 1.

It can be seen from Figure 1 and Table 1 that, with the increase of soil depth, the difference of soil temperature field calculated by frozen and unfrozen parameters was the largest, and at 1.5m, the maximum difference was 1.05 °C per day. The maximum value of the absolute value of the average day difference was 0.67°C.

![Figure 1. Soil natural temperature field under frozen and unfrozen physical property parameters.](image)
Figure 2. Soil temperature delay time under frozen and unfrozen physical property parameters.

Table 1. The calculation results of soil natural temperature field at different depths of silty clay under the condition of unfrozen and frozen physical property are summarized.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Unfrozen soil</th>
<th>Frozen soil</th>
<th>Unfrozen soil</th>
<th>Frozen soil</th>
<th>Unfrozen soil</th>
<th>Frozen soil</th>
<th>Unfrozen soil</th>
<th>Frozen soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2m</td>
<td>24.74</td>
<td>24.85</td>
<td>21.88</td>
<td>22.23</td>
<td>17.95</td>
<td>18.56</td>
<td>14.87</td>
<td>15.62</td>
</tr>
<tr>
<td>0.5m</td>
<td>7.27</td>
<td>7.27</td>
<td>8.4</td>
<td>8.3</td>
<td>8.19</td>
<td>8.16</td>
<td>9.2</td>
<td>8.29</td>
</tr>
<tr>
<td>1.0m</td>
<td>-17.14</td>
<td>-17.25</td>
<td>-14.28</td>
<td>-14.63</td>
<td>-10.35</td>
<td>-10.96</td>
<td>-7.27</td>
<td>-8.02</td>
</tr>
<tr>
<td>1.5m</td>
<td>1.25</td>
<td>1.25</td>
<td>2.3</td>
<td>2.2</td>
<td>2.17</td>
<td>2.15</td>
<td>3.3</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>6.90</td>
<td>6.57</td>
<td>15.44</td>
<td>14.31</td>
<td>29.67</td>
<td>27.21</td>
<td>43.90</td>
<td>40.11</td>
</tr>
<tr>
<td></td>
<td>11.6</td>
<td>11.6</td>
<td>11.16</td>
<td>11.15</td>
<td>12.4</td>
<td>12.1</td>
<td>12.23</td>
<td>12.18</td>
</tr>
<tr>
<td></td>
<td>161</td>
<td>161</td>
<td>158</td>
<td>158</td>
<td>151</td>
<td>152</td>
<td>142</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>0.16</td>
<td>0.50</td>
<td>0.86</td>
<td>1.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.10</td>
<td>12.18</td>
<td>1.1</td>
<td>1.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.32</td>
<td>0.55</td>
<td>0.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from Fig. 2, with the increase of depth, the delay time of soil temperature increases. At the same depth, the delay time of unfrozen was longer than that of frozen physical parameters. With the increase of depth, the delay time difference between the two parameters increased. As can be seen from Table 1, the delay time calculated by unfrozen and frozen physical properties at 0.2m was 6.90 and 6.57 days, at 0.5m was 15.44 and 14.31 days, at 1.0m was 29.67 and 27.21 days, and at 1.5m was 43.90 and 40.11 days.
It can be seen that at the buried depth of 1.5m, the maximum delay time difference calculated by unfrozen and frozen physical parameters of silty clay was 3.79 days, accounting for 8.6% of the total delay time.

![Figure 3. Freezing days with depth under frozen and unfrozen physical parameters.](image)

![Figure 4. Freezing depth with freezing date under frozen and unfrozen physical parameters.](image)

As can be seen from Fig. 3, with the increase of depth, the freezing time of soil temperature decreases, and no freezing occurred when a certain depth was reached. At the same depth, the freezing time was shorter in the case of unfrozen property parameters than in the case of frozen property parameters. With the increase of depth, the difference of freezing time calculated under two physical parameters increased. As can be seen from Table 1, the freezing time (days below 0℃) calculated by unfrozen and frozen physical properties at 0.2m was 161 days, at 0.5m 158 days, at 1.0m 151 and 152 days, and at 1.5m 142 and 144 days, respectively. It can be seen that at the buried depth of the hot oil pipeline of 1.5m, the maximum delay time difference calculated by the average unfrozen and frozen physical parameters of silted clay was 2 days, accounting for 1.4% of the total delay time.

As can be seen from Fig. 4, with the increase of depth, the starting date of soil temperature freezing was delayed. At the same depth, the unfrozen physical parameters occurred later than the frozen physical parameters. With the increase of depth, the difference of the starting date of freezing calculated under the two physical parameters increased. As can be seen from Table 1, at the buried depth of the hot oil pipeline of 1.5m, the maximum difference of the starting date of freezing calculated by the average unfrozen and frozen physical parameters of silted clay was 4 days.
4 Conclusions

In this paper, a mathematical model of soil natural temperature field in severe cold region was established, and relevant influencing factors are analyzed. In conclusion, the annual periodic change and time delay of soil temperature must be taken into account when calculating soil temperature. But the same silty clay, according to the average physical parameters calculation of soil freezing and frozen temperature, delay time and freeze time, freeze starting time difference is very small, so the thermodynamic calculation analysis of hot oil pipeline operation management, cannot consider freezing and not under the frozen property nature the difference of soil temperature field, the soil press often physical processing.

5 Acknowledgements

This work was financially supported by National Natural Science Foundation of China (No. 51176024), and Natural Science Foundation of Heilongjiang Province (No. LH2020E017).

References