CFD-Based Numerical Simulation for Soil Temperature Field Underground Hot Oil Pipelines

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Abstract. Soil temperature field underground hot oil pipelines are unsteadies that varies with season. In this paper, physical model and mathematical model for soil temperature field around buried oil pipelines was established. And soil temperature field underground oil pipelines with and without insulating layer in different seasons was simulated through the application of CFD software. Analysis indicates temperature field around buried pipelines has markedly difference in different seasons. And underground pipelines with and without insulating layer have a significant influence on soil temperature distributions. This paper proposes optimal burial depth for certain pipe and certain soil condition, which has great influence for the economic construction, optimal design, and safe operation of underground pipelines.

Keywords: Hot oil pipeline; Heat transfer; CFD; Numerical simulation.

1. Introduction

CFD (Computational Fluid Dynamics) calculates a certain fluid flow problems to obtain a flow field distribution with steady or unsteady state. It formed in 1960s. The flowchart is shown in Fig.1. The process of numerical simulation is establishing mathematical models and determining definite conditions according to working conditions firstly. It is the start point for numerical simulation. And then determining computational methods including discrete method and solution of differential equation, establishment of body-fitted coordinates, and treatment of boundary conditions. Then writing programs and iterative computation of discrete equation, which are the main body of simulation. Finally, outputting graphs and all needed data will be shown on it [1].

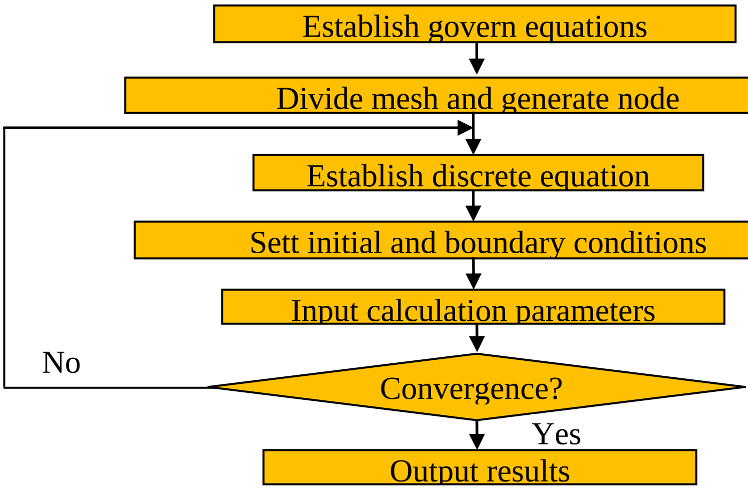

Fig. 1 CFD Flowchart

CFD has been widely applied in oil-gas storage and transportation industry, and it has gained a lot of achievements in operating modes, equipment and attachment and safety problem of pipeline [2]. Considering china oil is mostly high waxy content, high solidification point, so the best transportation way is underground hot-oil pipelines. Hence, a study of temperature distributions of the soil temperature field around the pipeline is crucial for design, construction and operation management of pipelines. For example, the depth of buried-pipe lying is obtained based on the design specifications, which present referential values of depth under different soil conditions [3]. And yet, the characteristics of China' vast territory, soil environment is complex and varied. A referential value for a certain area and condition is unscientific and irrational. In this context, this paper simulates the soil temperature distribution around oil pipeline with and without insulating layer in winter and summer condition, analyzes the difference of temperature distribution in different conditions and optimizes the depth of buried-pipeline.

2. Numerical model

2.1 Physical model.

Take an oil pipeline in Northeast China, for example [4]. Axial temperature drop can be neglected in calculation owing to temperature drop in axial direction are very small compared with radial direction. Physical model is shown in Fig.2. Burial depth is 1.5m, pipe radius is 426mm, steel pipe wall thickness is 7mm, insulating layer thickness is 40mm, and asphalt layer thickness is 6mm. Given the soil heat transfer involved, thermostat layer and horizontal boundary of temperature-affected area should be considered. Adopting burial depth 10m as thermostat layer with temperature 2℃ and thermodynamic radius 8m, see reference 3.

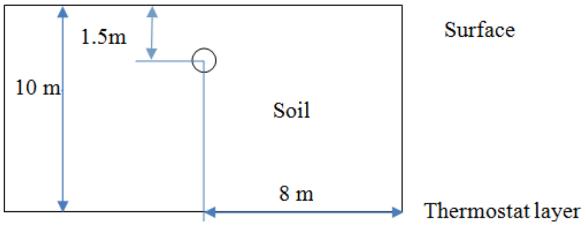

Fig. 2 Physical model of buried pipelines

2.2 Mathematical model.

Develop a mathematical equation based on the model mentioned above. To facilitate theoretical analysis and equation solution, this paper proposes some assumptions:

Pipelines total contact with the soil, neglecting of the contact thermal resistances.

Soil is continuous.

Thermostat layer has no horizontal heat flow.

The left and right borders of soil are the adiabatic boundaries.

Inner wall initial temperature is hot oil temperature and soil initial temperature is outside temperature of asphalt layer.

Solve heat conduction differential equations for individual layers and soil [3] as formula 3.

$$\frac{\partial T_n}{\partial \tau} = \frac{\lambda_n}{\rho_n c_{pn}}\left(\frac{\partial^2 T_n}{\partial x^2} + \frac{\partial^2 T_n}{\partial y^2}\right),\ n = 1, 2, 3 \tag{1}$$

N represents each layer: wax deposit layer, steel pipe layer and asphalt layer.

$$\frac{\partial T_t}{\partial \tau} = \frac{\lambda_t}{\rho_t c_{pt}}\left(\frac{\partial^2 T_t}{\partial x^2} + \frac{\partial^2 T_t}{\partial y^2}\right) \tag{2}$$

Where, t represents soil; T is temperature, ℃; τ is compute time; ρ is density, kg/m^3; c_p is specific heat capacity, J/ (K ·kg); λ is heat conductivity coefficient, W/ (m ·℃).

2.3 Meshing.

Establish the geometry model based on the fore treatment software GAMBIT and generate mesh. For the computation domain is symmetric structure, this model can simplified an area on the right. Fig.3 showed the mesh generation of computational domain and partial enlargement drawing of specific region. The grid division of a quarter of computational model adopts the Tri-Primitive method. Especially, the grid of meshes were increased for meeting the computational accuracy for that steel pipe, insulating layer and asphalt layer have considerable influence on the results. The grid division of soil adopts the Pave method, and the closer to the pipe center, the more mesh is. It accords with the logical law of heat transfer and can reduce the iteration times.

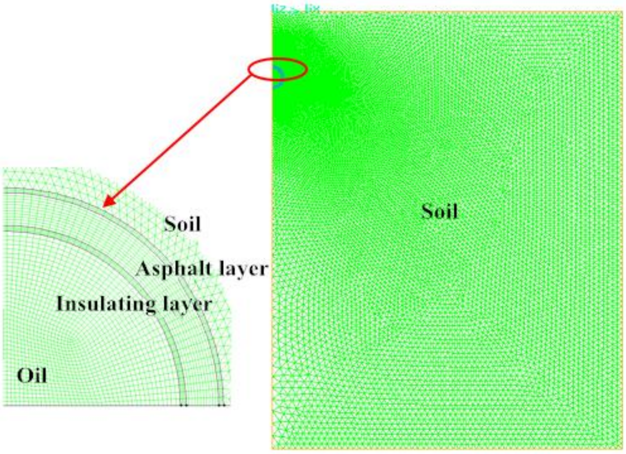

Fig. 3 Mesh generation of computational domain and partial enlargement drawing of specific region

2.4 Boundary and initial conditions.

It is assumed that oil temperature of cross section is uniformly distributed and heat transfer is neglected. The basic physical parameters are shown in table1 below, which are not given in database in FLUENT 6.3 and user-defined. It is known in winter average surface temperature is -20℃ and soil temperature is -3℃; and in summer average surface temperature is 24℃, soil temperature is 12℃ and oil temperature is 60℃. The SIMPLE algorithm of hydrokinetics calculating software FLUENT 6.3 is employed to make numerical simulation and the obtained image is further processed with Tecplot.

Table 1 Physical parameters of steel pipe, insulation and soil

Name	Density (kg/m3)	Heat conductivity coefficient (w/m ·k)	Specific heat capacity (J/kg ·k)
Oil	870	2.1	2000
Steel Pipe	8030	48	500
insulation	50	0.04	700
Asphalt	360	0.15	1670
Soil	1680	1.21	2403

3. Results and discussion

3.1 Effects of insulating layer on temperature field distributions.

Fig.4 and Fig.5 show pipe simulation results with and without insulating layer in winter and summer, respectively, including soil temperature field distributions around pipe and partial enlargement drawing of specific region. From Fig.4, soil temperature field distributions have an elliptic form in winter, the closer to the pipe, the more concentration the isotherm is. And isotherm above along the pipes is more intensive than lower line. Since surface temperature is low in winter, there is a wide temperature difference between surface and oil, and hot-oil conducts more heat through soil, then temperature field exhibits a nearly cosine. Fig.5 shows simulation results with and without insulating layer in summer. It is clearly that in winner and summer soil temperature distributions vary considerably. With high summer surface temperature, there is no significant temperature difference between oil and upper soil. And soil temperature field distributions around pipe appear nearly circle radial distribution, temperature field in the center region exhibits a sine distribution, isotherm is linear distribution because of region around thermostat layer being not affected by hot-oil.

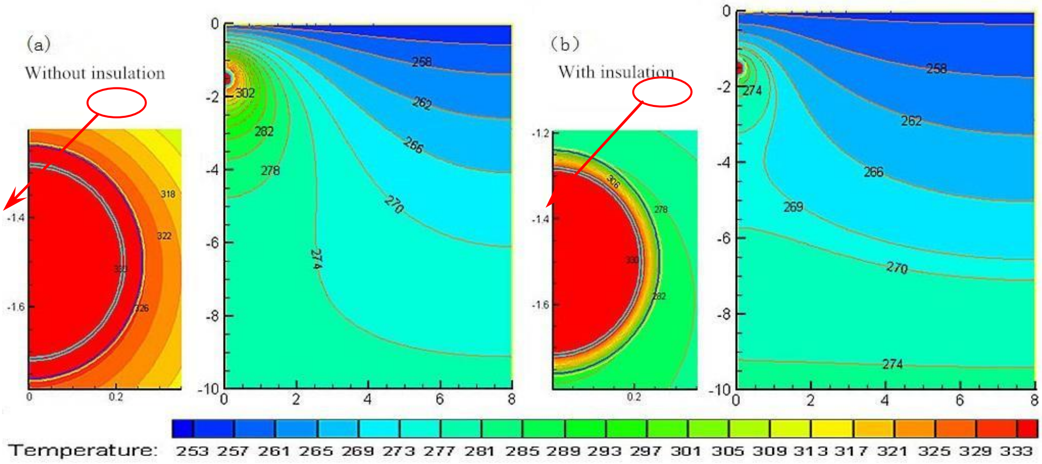

Fig. 4 Soil temperature field distributions around pipelines in winter
(a. With insulating layer; b. Without insulating layer)

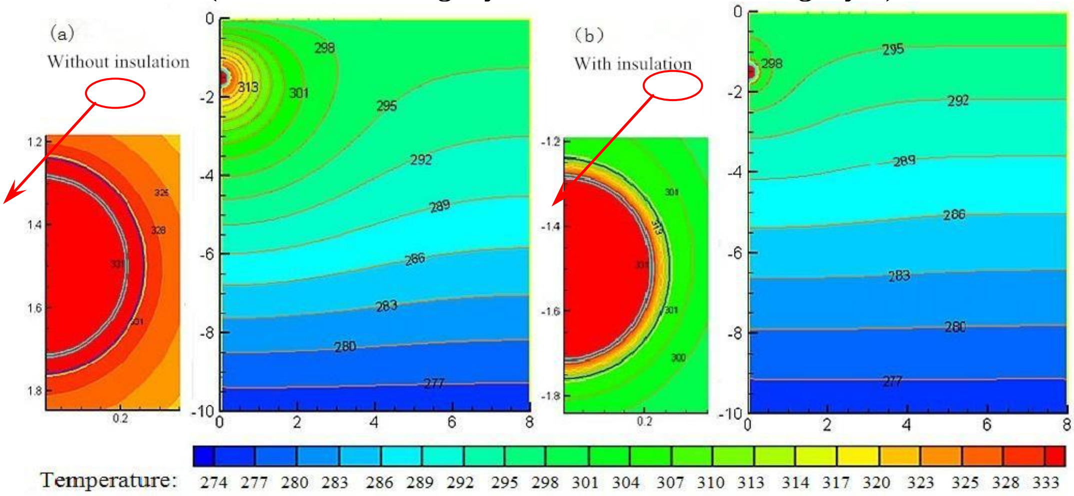

Fig. 5 Soil temperature field distributions around pipelines in summer
(A.with insulating layer; without insulating layer)

Compare the temperature distributions of affected area with and without insulating layer (affected area is with a temperature higher than 278K in winter and 298K in summer). In winter and without insulating layer(Fig.4a), the affected area is with horizontal distance ranging from -2m to 2m and vertical distance ranging from -4.8m to 3.5m; with insulating layer(Fig.4b), horizontal affected distance is -0.5~0.5m and vertical distance is -1~2.5m. 71% area is reduced. At the same time, temperature drop from pipe walls to asphalt layer is 7K and 51K, respectively. And heat loss reduced 86%. In summer and without insulating layer(Fig.5a), the affected area is with horizontal distance ranging from -3m to 3m and vertical distance ranging from 0m to 4m; with insulating layer(Fig.5b), horizontal affected distance is -0.7~0.7m and vertical distance is -0.6~2m. 92% area is reduced. At the same time, temperature drop from pipe walls to asphalt layer is 5K and 32K, respectively. And heat loss reduced 84%. Thus it can be seen that: insulating can effectively block heat transfer and assure the hot-oil transportation successful and safe.

3.2 Optimization of burial depth.

In summary, the pipe heat dissipating mainly occurs in winter. In winter with insulating condition, a numerical simulation for soil temperature field with burial depth 0.8m, 1.2m, 1.5m and 1.8m is performed. Simulation results of local isotherm figure are shown in Fig.6. Fig.6 (a) is isotherm figure under 0.8 burial depths. The figure above pipe has an elliptical shape and horizontal isotherm does not exist. This is resulted from shallow buried depth; soil temperature is influenced by air temperature and oil temperature. Extrapolating, temperature field has an obvious seasonal variation characteristic with this depth. Under 1.8m burial depth (Fig.6d), about 0 to 1m in vertical direction is horizontal isotherm. This is resulted from deep burial depth; soil temperature is influenced only by air temperature. Excess burial depth is wasteful when considering the exorbitant cost of great workload.

Compare the 1.2m burial depth (Fig.6b) with 1.5m burial depth (Fig.6c).Temperature distribution above pipe are similar basically. Especially in range of 0~0.8m the temperature field is almost exactly the same. It indicates burial depth is not impacting the soil temperature within 1.2~1.5m. Hence the final burial depth is 1.2m.

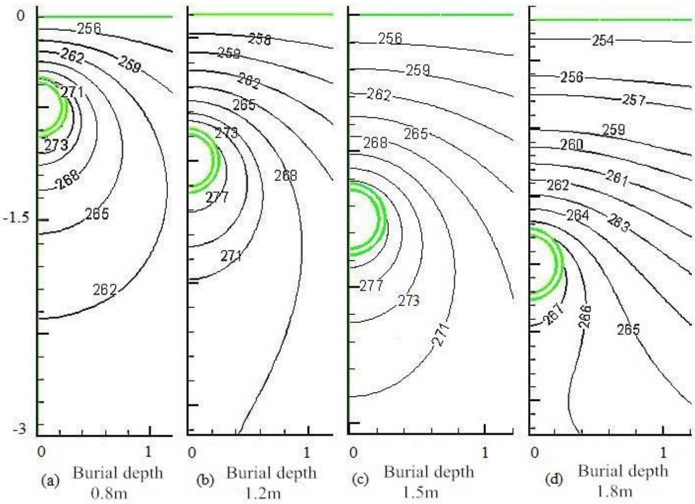

Fig. 6 Isotherm with different burial depth

4. Conclusions

The heat transfer process of underground hot-oil pipelines is complicate. So, analysis of change rules for soil temperature of underground pipelines is very important. By numerical simulation on the soil temperature field with and without insulating layer in two season and results analysis, this paper concludes soil temperature distributions around hot oil pipelines are very different in different temperature conditions. There will be a 70~90% reduction of the affected areas and 84%~96% oil heat loss by using insulating layer. Isotherm figures under different depth are also achieved. Through the analysis, the optimal burial depth is 1.2m. In this paper, numerical simulation for oil temperature field can assure oil pipeline transport safe and economic.

Acknowledgements

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