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Thermal impact of the products pipeline on the crude oil pipeline laid in one ditch – The effect of pipeline interval

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Abstract

Numerical simulations are carried out to study the thermal impact of the cold products pipeline on the hot crude oil pipeline of the steady state. The pipelines studied are those used in the West Pipelines in China. The physical properties of North Xinjiang crude oil and those of 90# gasoline were used in this study. The effect of pipeline interval on the thermal impact is studied in details at various conditions.

Keywords: Thermal impact; Crude oil pipeline; Products pipeline; Unstructured grid

1. Introduction

More than 80% of crude oils produced in China are either waxy crude oil with high pour points or viscous heavy crude oil, whose flowability is poor. One effective way to transport the poor flowability crude oil in the pipelines is to heat it at the station, which can decrease the viscosity of the oil and keep its temperature above the pour point along the pipelines [1,2]. This technique has been successfully used in China in the past 30 years.

As we know, before 2005, the crude oil pipelines were constructed independently in one ditch. In order to save the investment and protect the environment, a new technology of laying two pipelines in one ditch appears. In 2005, several hundred kilometers of the crude oil pipeline and the products pipeline in Western China were laid in one ditch. This is the first application of this technology in the long-distance oil pipeline's construction in China. Since the temperature of the crude oil is a key parameter for safe transportation, the most crucial problem in the design and operation of the double pipelines laid in one ditch is the thermal impact on the hot crude oil pipeline, which is a new problem in the construction of China Petroleum West Pipelines and one of the key technology problems [3].

Then in this study, numerical simulation method is applied to study the impact of the cold products pipeline on the hot crude oil pipeline of the steady state. In order to show the impact of the products pipeline on the crude oil pipeline laid in one ditch, hydraulic and thermal calculations of the single crude oil pipeline laid in the ditch under the same conditions are also performed for comparison. The achievements of this study will not only directly provide technical support for construction and operation optimization of the crude oil pipeline and the products pipeline, but also give some instructions to the transportation program of the imported Russian crude oil as well as the design, construction, operation and management of other pipelines in the future.

2. Mathematical model

The complete description of the thermal system of the buried pipelines, which are composed of the oil transported in the pipelines, soil and atmosphere etc, should contain the convective heat transfer of the oil in the pipelines and the

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Nomenclature

A	cross-section area of the pipeline (m^2)
C_i	heat capacity of the ith layer, including wax deposition, pipe wall and corrosion protective covering (J/(kg °C))
C_p	heat capacity under constant pressure (J/(kg °C))
C_s	heat capacity of the soil (J/(kg °C))
D	the inner diameter (m)
f	Darcy friction coefficient
g	gravity acceleration (m/s^2)
h	specific enthalpy (J/kg)
l_0	interval between the two pipelines (m)
p	average pressure along the pipeline (Pa)
q	heat flux density (W/m^2)
q_L	line heat flux density (W/m)
q_0	heat flux density of the crude oil along the pipeline (W/m^2)
r	radial direction (m)
s	specific entropy (J/(kg K))
T	temperature of the crude oil or the products oil (°C)
T_a	air temperature (°C)
T_i	temperature of the ith layer, including wax deposition, pipe wall and corrosion protective covering (°C)
T_0	temperature of the pipe inner wall (°C)
T_n	temperature of the constant temperature layer (°C)
T_s	soil temperature (°C)
u	specific energy of the crude oil (J/kg)
V	average velocity of the flow (m/s)
x	horizontal direction (m)
y	vertical direction (m)
z	axial direction of the pipeline (km)
Δz	grid spacing in the axial direction (km)
α	angle between the axis of the pipeline and the horizontal line
α_a	heat transfer coefficient at the ground surface ($W/(m^2$ °C))
α_0	heat transfer coefficient of the pipe flow ($W/(m^2$ °C))
β	expansion coefficient of the crude oil (°C^{-1})
θ	circumferential direction
λ_i	thermal conductivity of the ith layer, including wax deposition, pipe wall and corrosion protective covering (W/(m °C))
λ_s	thermal conductivity of the soil (W/(m °C))
ρ	density of the crude oil (kg/m^3)
ρ_i	density of the ith layer, including wax deposition, pipe wall and corrosion protective covering (kg/m^3)
ρ_s	soil density (kg/m^3)
τ	time (s)
∞y	single crude oil pipeline
∞c	single products pipeline

heat conduction outside the pipelines. The balance of heat flux is used to couple the convective heat transfer in the pipeline and the soil heat conduction. For simplification, following assumptions are made in the numerical simulations:

(1) The thermal influence region of a hot crude oil pipeline is within 10 m, which can be determined by measuring the soil temperature field or some test calculations. The temperature of the soil 5–10 m far away from the center of the pipeline, of which the outer diameter is 720 mm in northeast China, is almost not affected by the hot oil pipeline [4]. The measured soil temperatures in Tazhong area, Talimu Basin have shown that the maximum ranges of the thermal influence region of the insulated pipeline, of which the outer diameter is 273 mm and the buried depth is 1.6 m, are 2.0 m in the horizontal direction and 2.2 m in the vertical direction; while those of the non-insulated pipeline, of which the diameter is 426 mm and the depth is 1.7 m, are 5.0 m in the horizontal direction and 5.5 m in the vertical direction [5]. The soil temperature within the depth of 3 m varies notably according to the change of the air temperature; the variation of the soil temperature is smaller at the depth of 4–5 m; the effect of the air temperature on the soil temperature at the depth of 6 m is minor to be ignored while the soil 8 m down from the ground surface is free from the effect of the air temperature [6]. Apart from the experimental data, numerical simulation on the thermal influence region has been done in Ref. [7], where different boundary conditions were given. As a result, the calculation domain is selected as a rectangular region shown in Fig. 1, in which the crude oil pipeline is located on the Y-axis, the symmetry axis of the X-direction in the rectangular region, while the products pipeline is located to the left side of the crude oil pipeline with a certain distance. The ranges of the calculation domain are determined as $-10\,\text{m} \leqslant x \leqslant 10\,\text{m}$ and $-10\,\text{m} \leqslant y \leqslant 0\,\text{m}$.
(2) The oil temperature at the cross-section of a pipe is assumed to be uniform, that is to say, the oil temperature is only the function of time and axial position.
(3) The soil anisotropy outside the pipelines is simplified as isotropy.

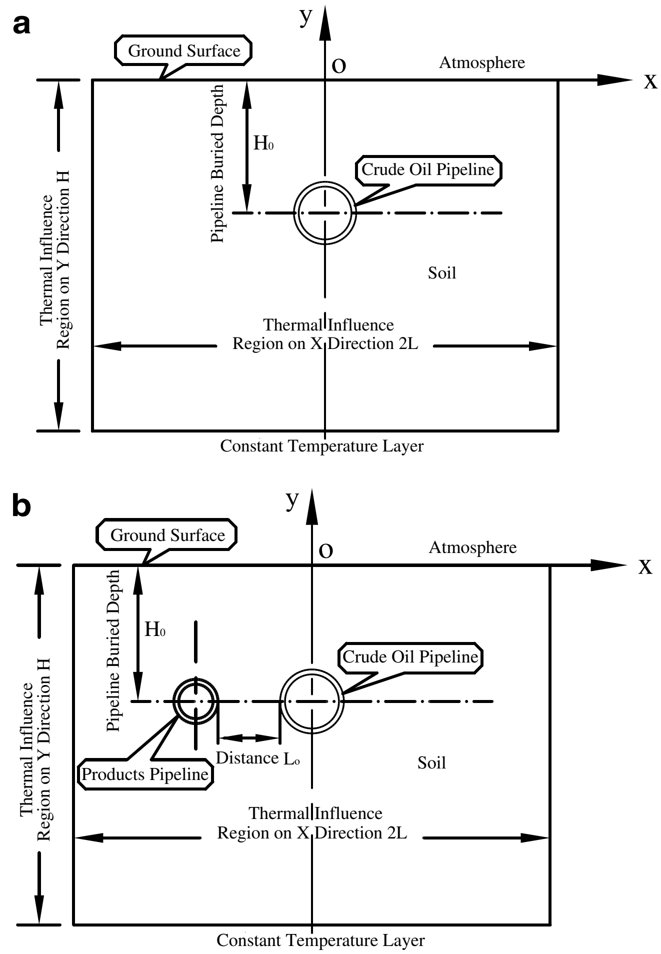

Fig. 1. Sketch of the buried pipelines: (a) single crude oil pipeline in the ditch and (b) double-pipeline system.

(4) The axial temperature drop outside the pipelines is small enough to be neglected, thus the heat conduction outside the pipelines can be assumed to be two-dimensional.

Based on the assumptions listed above, a mathematical model is obtained by taking into account the heat transfer of the oils, wax deposition, steel pipes, corrosion protective covering and soil. The mass conservation equation, momentum conservation equation and energy conservation equation of the crude oil are listed below [8]:

$$\frac{\partial}{\partial \tau}(\rho A) + \frac{\partial}{\partial z}(\rho VA) = 0 \tag{1}$$

$$\frac{\partial V}{\partial \tau} + V\frac{\partial V}{\partial z} = -g\sin\alpha - \frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{f}{D}\frac{V^2}{2} \tag{2}$$

$$\frac{\partial}{\partial \tau}\left[(\rho A)\left(u + \frac{V^2}{2} + gs\right)\right] + \frac{\partial}{\partial z}\left[(\rho VA)\left(h + \frac{V^2}{2} + gs\right)\right] = -\pi D q_0 \tag{3}$$

The heat transfer equation of the oil flow can be obtained from the three equations listed above [9].

$$C_p\frac{\mathrm{d}T}{\mathrm{d}\tau} - \frac{T}{\rho}\beta\frac{\mathrm{d}p}{\mathrm{d}\tau} - \frac{fV^3}{2D} = -\frac{4q_0}{\rho D} \tag{4}$$

q_0 in Eq. (4) represents the axial heat flux density of the oil flow, and it also stands for the heat loss of the oil flow on the cross-plane of the pipeline. As a result, we can couple the two heat transfer problem easily.

The heat conductive equations of the wax deposition, pipeline wall and corrosion protective covering are listed below:

$$\rho_i C_i\frac{\partial T_i}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_i r\frac{\partial T_i}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda_i\frac{\partial T_i}{\partial \theta}\right) \quad i = 1,2,3 \tag{5}$$

Boundary condition:

At $r = D/2$,

$$\lambda_1\frac{\mathrm{d}T_1}{\mathrm{d}r} = -\alpha_0(T - T_0) \tag{6}$$

The mass, momentum and energy conservation equations of the products oil are similar to those of the crude oil, which are not listed here for simplicity.

The heat conductive equation of the soil is as follows:

$$\rho_s C_s\frac{\partial T_s}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_s\frac{\partial T_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_s\frac{\partial T_s}{\partial y}\right) \tag{7}$$

Boundary conditions:

$$\text{At } y = 0, \quad \lambda_s\frac{\mathrm{d}T_s}{\mathrm{d}y} = \alpha_a(T_a - T_s) \tag{8}$$

$$\text{At } y = -H, \quad T_s = T_n \tag{9}$$

$$\text{At } x = \pm L, \quad \frac{\partial T_s}{\partial x} = 0 \tag{10}$$

3. Numerical method

A Delaunay triangulation method [10] is used to generate the grids of the soil domain automatically. After the input of the outer diameter of the pipelines, the buried pipeline depth (namely the distance between the center of the pipeline and the ground surface), and other control parameters, the software [11] can automatically divide the calculation domain into unstructured triangular grids of 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, meanwhile, the lesser the temperature gradient will be. In order to save computation time, denser grids are generated only in the region close to the pipelines as shown in Fig. 2. A structural grid generation in polar coordinates is applied to the steel pipe wall, wax deposition and corrosion protective covering. The local grid expanded view is shown as Fig. 3. The three layers of the crude pipeline's grids are wax deposition, steel pipe wall and corrosion protective covering from inside all the way to outside. However, there are only two layers of the products pipeline due to the absence of the wax deposition in the products pipeline.

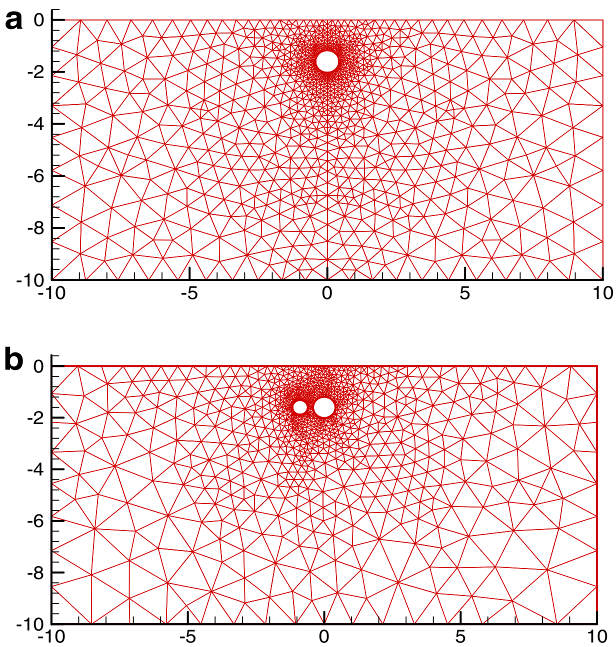

Fig. 2. Unstructured grids of the soil: (a) single crude oil pipeline in the ditch and (b) double-pipeline system.

Fig. 4 shows the grids used in the axial direction of the pipeline. The calculation starts at the outlet of a pumping station in the pipeline, shown as Point 1 in Fig. 4, and ends at the inlet of the next pumping station, shown as Point *n* in Fig. 4. Uniform grids along *z*-axis of the pipeline are employed with the grid spacing of 4 km which can satisfy the requirements of accuracy in engineering calculation.

A second-order finite volume method is used to discretize the heat conductive equations of the soil [12], the wax deposition, pipe wall and corrosion protective covering [13]. The governing equations in soil domains and the pipeline are discretized in different ways and coupled along their interfaces in an iterative procedure. An implicit method is used for time discretization. The discretized equations are solved by a Gauss–Seidel method.

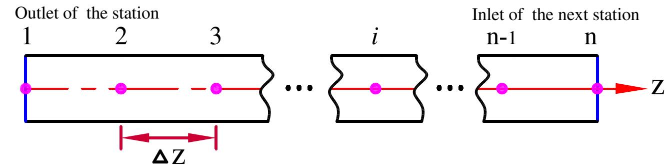

Fig. 4. Grids of the pipeline.

4. Computation and results

4.1. Results under a typical operating condition

It is obvious that the pipeline interval (The pipeline interval l_0 is defined as the minimum horizontal distance between the outer pipe wall of the crude oil pipeline and that of the products pipelines, as shown in Fig. 1) is a key factor to affect the heat transfer in the double-pipeline system. In this section, the effect of pipeline interval on the heat transfer is studied. Calculations are performed under six pipeline intervals, namely 0.2 m, 0.6 m, 0.9 m, 1.2 m, 2.4 m and 4.8 m, which cover the possible interval range in the real construction of the double-pipeline system. Fig. 5 shows the computation grids of the soil domain at the above pipeline intervals.

In order to show the thermal effect of pipeline interval, calculations are first carried out under a typical operating condition. In the typical operating condition, some important operation parameters are listed below. The pipelines studied are the same as the ones actually used in the West Pipelines, that is, the outer diameter of the crude oil pipeline is 813 mm and the thickness of the pipe wall is 11 mm while the outer diameter of the products pipeline is 559 mm and the thickness of the pipe wall is 7 mm. The pipeline length is 240 km from the outlet of the pumping station

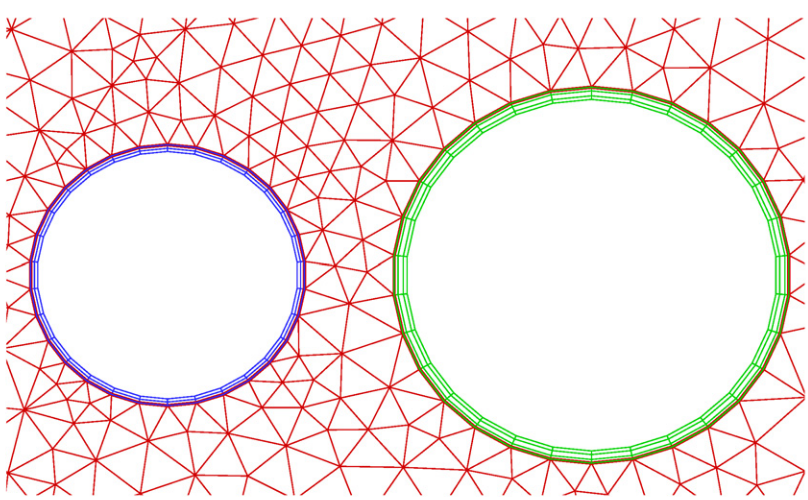

Fig. 3. Structural grids of the crude oil pipeline and the products pipeline in a polar coordinate system around by the unstructured grids of the soil.

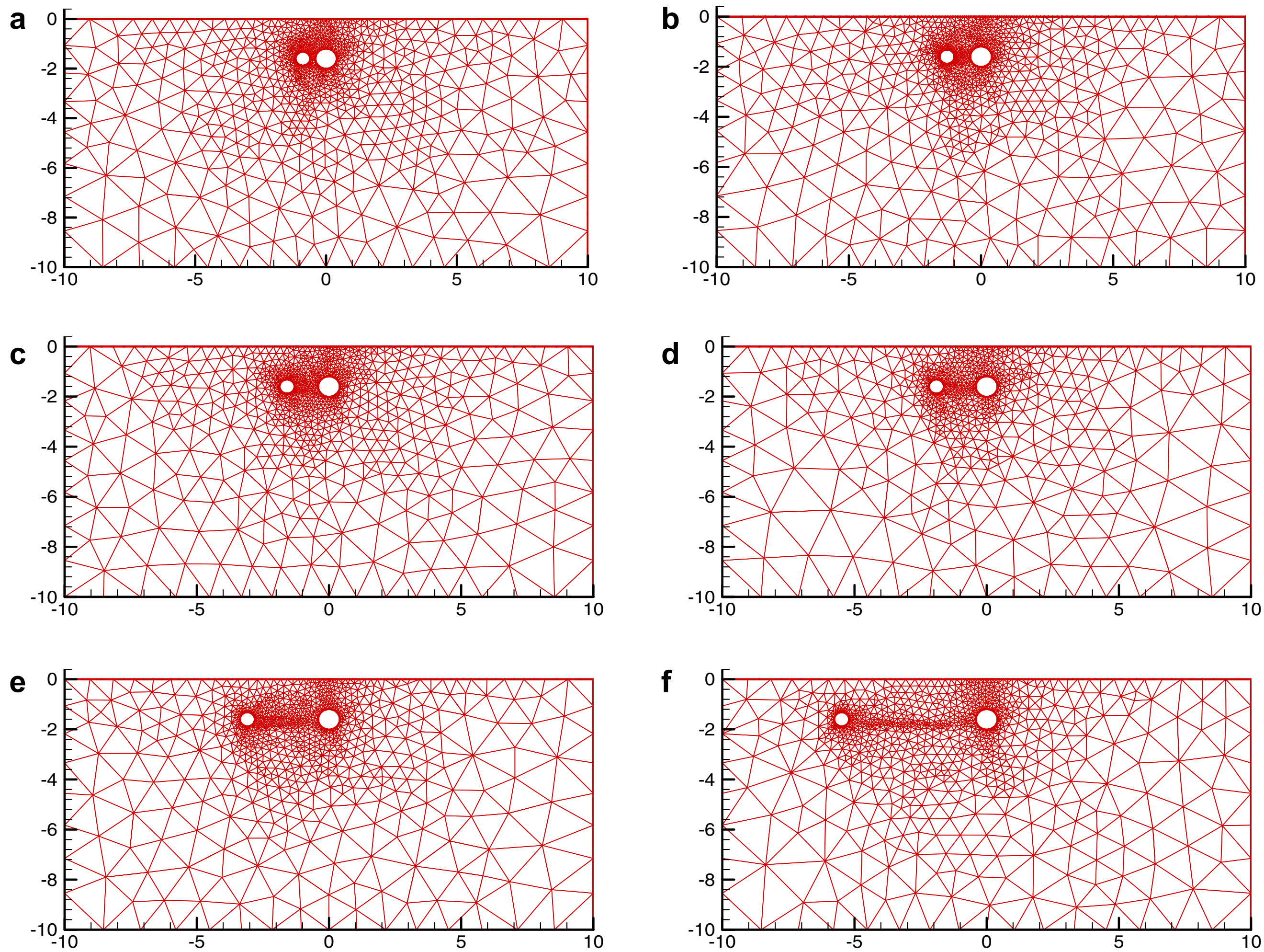

Fig. 5. The grids under a buried depth of $H_0 = 1.6$ m: (a) 0.2 m between two pipelines, (b) 0.6 m between two pipelines, (c) 0.9 m between two pipelines, (d) 1.2 m between two pipelines, (e) 2.4 m between two pipelines and (f) 4.8 m between two pipelines.

to the inlet of the next pumping station; the buried depth of the two pipelines is 1.6 m (the buried depth is defined as the distance from the ground to the axes of the two pipelines which are in the same horizon as shown in Fig. 1b); the temperature of the soil at the buried depth is 1.6 °C; the throughput of the crude oil pipeline is 1×10^7 t/a (1 t/a = 1 ton per annum) and its outlet temperature is 60 °C; the throughput of the products pipeline is 8×10^6 t/a and its outlet temperature is 5 °C; the thickness of the wax deposition and that of corrosion protective covering are 8 mm. The physical properties of North Xinjiang crude oil and those of 90# gasoline are used in this study.

By running the numerical code developed in a FORTRAN language and analyzing the output data, we obtain some results as follow.

4.1.1. Soil temperature fields at the outlet and the inlet of the pumping stations

The soil temperature fields at the outlet of the pumping station and at the inlet of the next pumping station at different pipeline intervals are, respectively, shown in Figs. 6 and 7.

As can be seen from Figs. 6 and 7: (1) The temperature distribution curves on the right side of the crude oil pipeline at the station outlet are much the same as each other at different pipeline intervals. So are the temperature distributions at the next station inlet. It means the effect of the products pipeline on the temperature field on the right side of the crude oil pipeline is minor. (2) The soil temperature field on the left side of the crude oil pipeline at the station outlet is affected notably by the products pipeline in the double-pipeline system at all pipeline intervals. This is because the cold products oil enlarges the low-temperature region near the ground surface on the left side and reduces the temperature gradient, which lessens the soil heat loss to the atmosphere on the left side of the crude oil pipeline at the station outlet. However, the effect of the products pipeline at the next station inlet is not as obvious as that at the station outlet. The reason is that the temperature of the crude oil at the station inlet has decreased significantly due to the long-distance pipeline transportation, therefore the temperature difference at the next station inlet between the crude oil and products oil decreases appreciably. (3) With the increase of the pipeline interval, the high-temper-

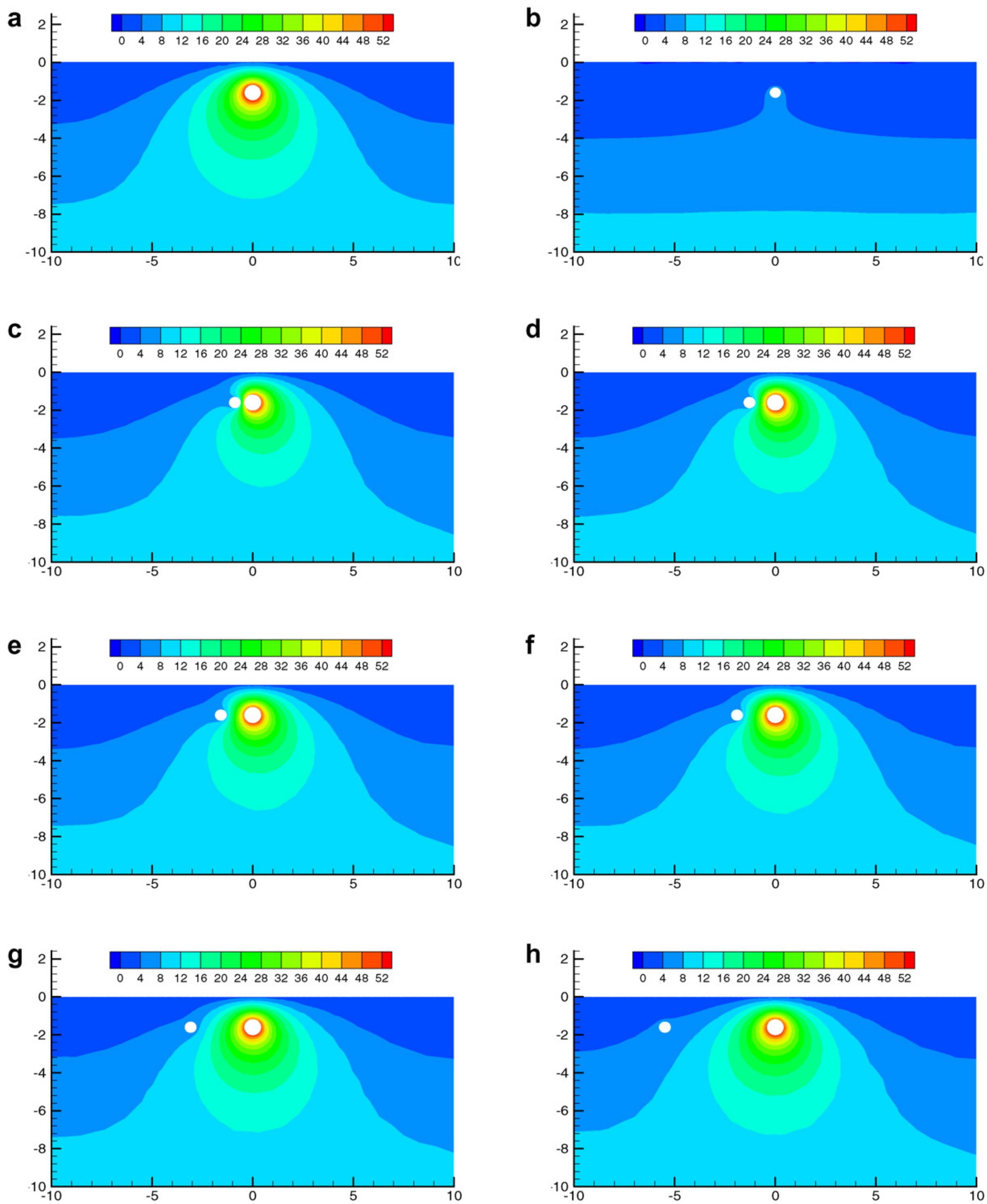

Fig. 6. Soil temperature field at the station outlet: (a) single crude oil pipeline, (b) single products pipeline, (c) 0.2 m between two pipelines, (d) 0.6 m between two pipelines, (e) 0.9 m between two pipelines, (f) 1.2 m between two pipelines, (g) 2.4 m between two pipelines and (h) 4.8 m between two pipelines.

ature region around the crude oil pipeline enlarges and the temperature field on both sides of the crude oil pipeline becomes more and more similar to each other, which means the heat absorption of the products pipeline from the crude oil pipeline has become lesser and lesser. When the pipeline interval is 4.8 m, the isothermals on the left side closely near the ground surface at the station outlet go 0.4 m upwards in average and the temperature gradient increases, which means the heat emission of the ground surface has become greater. It shows the products pipeline now loses heat instead of absorbing heat. It is favorable to the transportation of the crude oil.

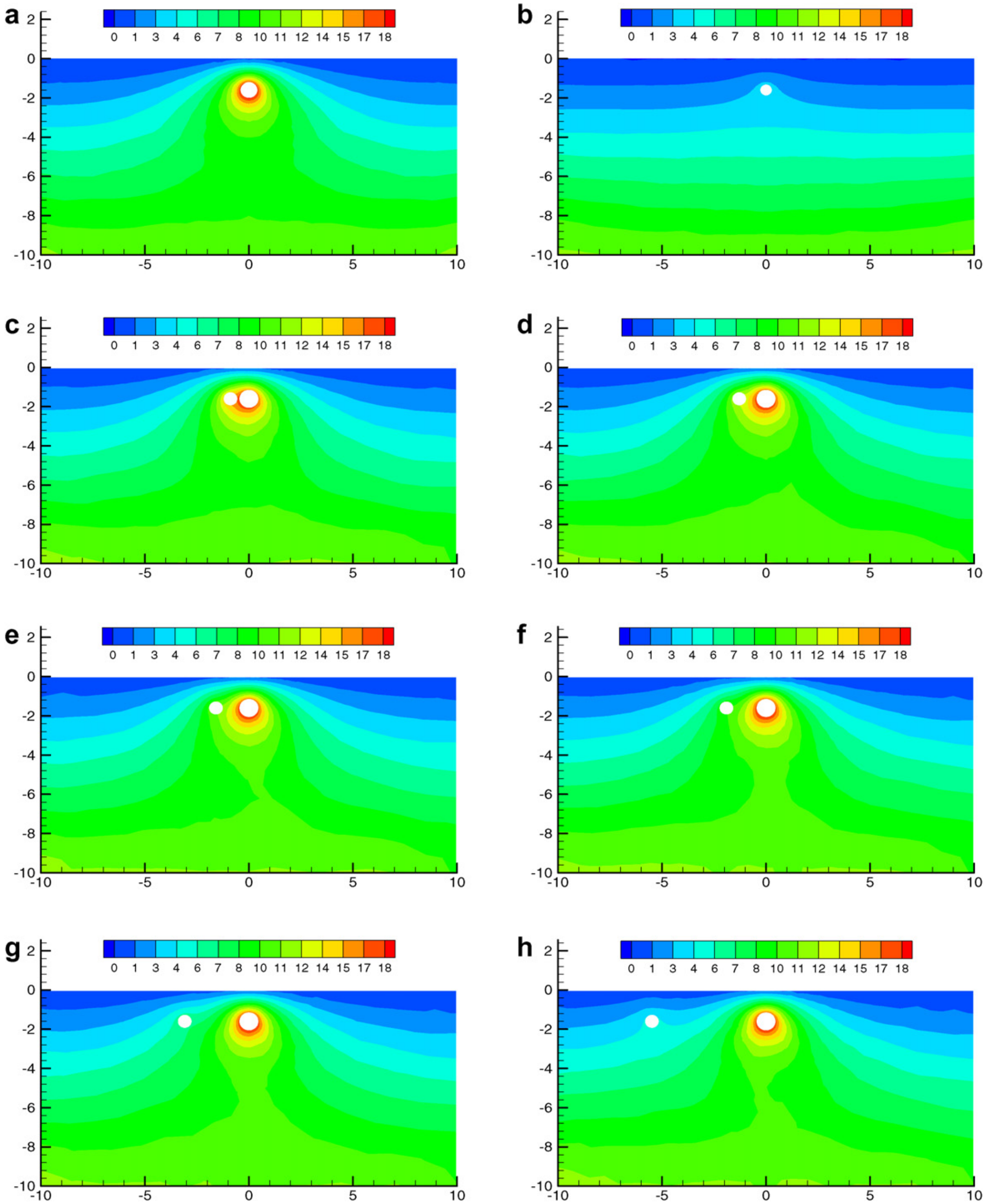

Fig. 7. Soil temperature field at the next station inlet: (a) single crude oil pipeline, (b) Single products pipeline, (c) 0.2 m between two pipelines, (d) 0.6 m between two pipelines, (e) 0.9 m between two pipelines, (f) 1.2 m between two pipelines, (g) 2.4 m between two pipelines and (h) 4.8 m between two pipelines.

4.1.2. Heat flux density of the ground surface at the station outlet and inlet

The heat flux density of the ground surface at the station outlet and inlet corresponding to different pipeline intervals are shown in Fig. 8a and b. As can be seen from the figure, the heat flux density curves of the ground surface on the right side corresponding to different pipeline intervals have good superposition with the curve when there is a single crude oil pipeline in the ditch. However, the curves on the left side are obviously different. It shows that at different pipeline intervals the products pipeline's effect on the right side of the crude oil pipeline of the ground surface is so minor as to be ignored while the effect on the left side should be taken into consideration.

As shown in Fig. 8a, the ground surface heat flux density on the left side of the crude oil pipeline at the station outlet decreases notably when the crude oil pipeline and the products pipeline are close to each other. With the increase of

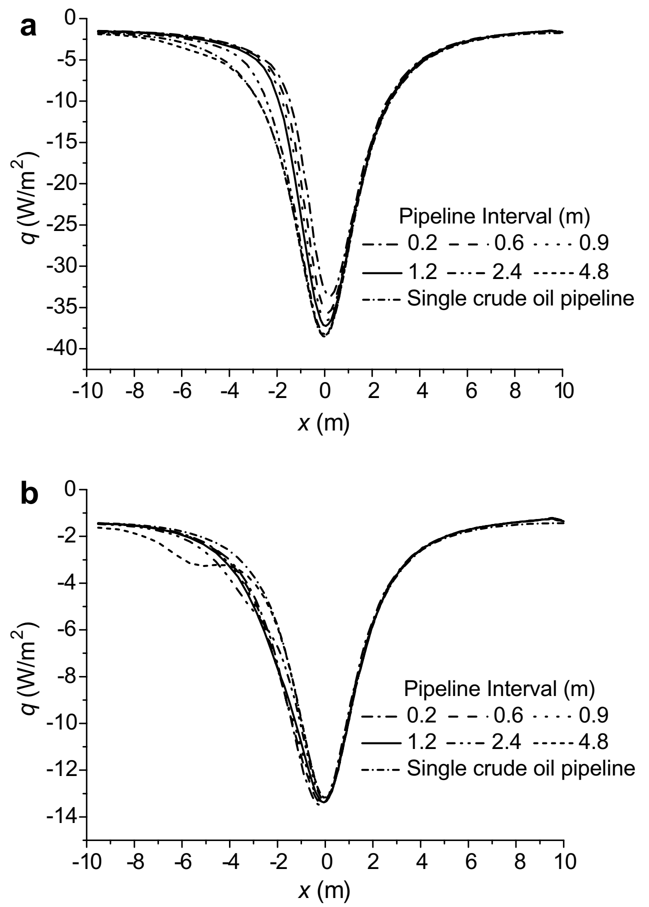

Fig. 8. Heat flux density of the ground surface: (a) heat flux density of the ground surface at the station outlet and (b) heat flux density of the ground surface at the next station inlet.

the pipeline interval, heat flux density of the double-pipeline system gets close to that of laying a single pipeline in the ditch. The heat flux density even has a little increase until the pipeline interval reaches 4.8 m. The increase is due to the products pipeline changing from the heat absorption to heat loss. When the products pipeline is far from the crude oil pipeline, the temperature of the products pipeline is higher than the local soil temperature and thus it loses heat. The heat flux density at the station inlet, as is shown in Fig. 8b, increases compared to the situation when there is a single crude oil pipeline in the ditch. The basic reason for this phenomenon is the heat loss of higher temperature products oil to the soil of the location.

It is apparent in Fig. 8 that the heat flux density of the ground surface at the station inlet is lesser than that at the outlet. The reason is that the crude oil continuously loses heat and thus its temperature decreases during the transportation between the station outlet and the next station inlet.

4.1.3. Line heat flux density and temperature along the pipelines

The heat loss is defined as positive while the heat absorption is defined as negative. The heat absorption of the atmosphere is equal to the heat flux density of the ground surface. The line heat flux density and the temperature along the pipelines are given in Tables 1–6. The line heat flux density of the crude oil pipeline is defined as $2\pi R q_1$, in which R is the distance between the center of the crude oil pipeline and the inner wall of the wax deposition and q_1 is the average heat flux density of the crude oil pipeline circumference. Then the line heat flux density of the products pipeline is defined as $2\pi r q_2$, in which r is the inner diameter and q_2 is the average heat flux density of the products pipeline circumference. The line heat flux of the ground surface is defined as $2qL$, in which q is the average heat flux density of the ground surface and $2L$ is as shown in Fig. 1. The comparison of the line heat flux density at different pipeline intervals is shown in Fig. 9 while the temperature along the pipelines is shown in Fig. 10. Some conclusions can be drawn by analyzing Tables 1–6 and the figures.

(a) As can be seen from Tables 1–3, at the station outlet when the pipeline interval is 0.2 m, the heat loss of the crude oil is 288.5 W/m, 38.2% more than the heat loss of the single crude oil pipeline in the ditch, which is

Table 1
Line heat flux density of the crude oil at the station outlet and the next station inlet (W/m)

Mileage (km)	Pipeline interval (m)						
	0.2	0.6	0.9	1.2	2.4	4.8	∞y
0 (outlet)	288.5	240.7	227.1	219.5	209.8	207.8	208.7
240 (inlet)	52.5	59.6	62.1	63.7	66.0	66.7	67.0

Table 2
Line heat flux density of the products oil at the station outlet and the next station inlet (W/m)

Mileage (km)	Pipeline interval (m)						
	0.2	0.6	0.9	1.2	2.4	4.8	∞c
0 (outlet)	−132.8	−75.1	−54.7	−40.6	−14.0	3.1	11.1
240 (inlet)	20.6	14.6	12.3	10.9	8.6	7.2	6.8

Table 3
Line heat flux density of the ground surface at the station outlet and the next station inlet (W/m)

Mileage (km)	Pipeline interval (m)							
	0.2	0.6	0.9	1.2	2.4	4.8	∞y	∞c
0 (outlet)	−139.0	−147.6	−153.1	−155.7	−171.3	−182.4	−181.2	−34.7
240 (inlet)	−79.1	−79.8	−80.0	−77.5	−79.8	−79.1	−75.1	−31.4

Table 4
Temperature of the crude oil along the pipeline (°C)

Mileage (km)	Pipeline interval (m)						
	0.2	0.6	0.9	1.2	2.4	4.8	∞y
0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
4	58.5	58.7	58.8	58.8	58.9	58.9	58.9
8	57.0	57.5	57.6	57.7	57.8	57.8	57.8
12	55.5	56.2	56.5	56.6	56.7	56.7	56.7
16	54.2	55.1	55.3	55.5	55.7	55.7	55.7
20	52.8	53.9	54.2	54.4	54.6	54.7	54.6
24	51.5	52.8	53.1	53.3	53.6	53.7	53.6
28	50.3	51.7	52.1	52.3	52.6	52.7	52.6
32	49.1	50.6	51.0	51.3	51.6	51.7	51.7
36	47.9	49.6	50.0	50.3	50.7	50.7	50.7
40	46.8	48.5	49.1	49.4	49.7	49.8	49.8
44	45.7	47.5	48.1	48.4	48.8	48.9	48.8
48	44.7	46.6	47.2	47.5	47.9	48.0	47.9
52	43.7	45.7	46.3	46.6	47.0	47.1	47.1
56	42.8	44.8	45.4	45.7	46.2	46.3	46.2
60	41.8	43.9	44.5	44.9	45.3	45.4	45.4
64	40.9	43.0	43.7	44.0	44.5	44.6	44.5
68	40.1	42.2	42.8	43.2	43.7	43.8	43.7
72	39.2	41.4	42.0	42.4	42.9	43.0	42.9
76	38.4	40.6	41.2	41.6	42.1	42.2	42.2
80	37.7	39.8	40.5	40.9	41.4	41.5	41.4
84	36.9	39.0	39.7	40.1	40.6	40.7	40.7
88	36.2	38.3	39.0	39.4	39.9	40.0	39.9
92	35.4	37.6	38.3	38.7	39.2	39.3	39.2
96	34.8	36.9	37.6	38.0	38.5	38.6	38.5
100	34.1	36.2	36.9	37.3	37.8	37.9	37.8
104	33.4	35.5	36.2	36.6	37.1	37.2	37.1
108	32.8	34.9	35.6	36.0	36.5	36.6	36.5
112	32.2	34.2	34.9	35.3	35.8	35.9	35.8
116	31.6	33.6	34.3	34.7	35.2	35.3	35.2
120	31.0	33.0	33.7	34.1	34.6	34.7	34.6
124	30.5	32.4	33.1	33.5	34.0	34.1	33.9
128	29.9	31.8	32.5	32.9	33.4	33.5	33.3
132	29.4	31.3	31.9	32.3	32.8	32.9	32.7
136	28.9	30.7	31.4	31.7	32.2	32.3	32.2
140	28.4	30.2	30.8	31.2	31.7	31.7	31.6
144	27.9	29.7	30.3	30.6	31.1	31.2	31.0
148	27.5	29.1	29.8	30.1	30.6	30.6	30.5
152	27.0	28.7	29.2	29.6	30.0	30.1	30.0
156	26.6	28.2	28.7	29.1	29.5	29.6	29.4
160	26.2	27.7	28.3	28.6	29.0	29.1	28.9
164	25.7	27.2	27.8	28.1	28.5	28.6	28.4
168	25.3	26.8	27.3	27.6	28.0	28.1	27.9
172	25.0	26.3	26.9	27.2	27.6	27.6	27.5
176	24.6	25.9	26.4	26.7	27.1	27.1	27.0
180	24.2	25.5	26.0	26.3	26.6	26.7	26.5
184	23.9	25.1	25.6	25.9	26.2	26.2	26.1
188	23.5	24.7	25.2	25.4	25.8	25.8	25.7
192	23.2	24.3	24.8	25.0	25.4	25.4	25.2
196	22.9	24.0	24.4	24.6	24.9	25.0	24.8
200	22.5	23.6	24.0	24.2	24.5	24.6	24.4
204	22.2	23.2	23.6	23.9	24.2	24.2	24.0
208	21.9	22.9	23.3	23.5	23.8	23.8	23.6
212	21.7	22.6	22.9	23.1	23.4	23.4	23.2
216	21.4	22.2	22.6	22.8	23.0	23.0	22.9
220	21.1	21.9	22.3	22.4	22.7	22.7	22.5
224	20.8	21.6	21.9	22.1	22.3	22.3	22.2
228	20.6	21.3	21.6	21.8	22.0	22.0	21.8
232	20.3	21.0	21.3	21.5	21.7	21.7	21.5
236	20.1	20.7	21.0	21.2	21.4	21.3	21.2
240	19.8	20.5	20.7	20.9	21.0	21.0	20.9

Table 5
Temperature of the products oil along the pipeline (°C)

Mileage (km)	Pipeline interval (m)						
	0.2	0.6	0.9	1.2	2.4	4.8	∞c
0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
4	6.0	5.6	5.4	5.3	5.1	5.0	5.0
8	7.0	6.2	5.9	5.7	5.3	5.0	4.9
12	7.9	6.7	6.3	6.0	5.4	5.0	4.9
16	8.7	7.2	6.6	6.3	5.5	5.1	4.8
20	9.5	7.7	7.0	6.5	5.6	5.1	4.8
24	10.2	8.1	7.3	6.8	5.8	5.1	4.8
28	10.9	8.5	7.7	7.0	5.9	5.1	4.7
32	11.5	8.9	8.0	7.3	6.0	5.1	4.7
36	12.1	9.3	8.3	7.5	6.0	5.1	4.7
40	12.7	9.7	8.5	7.7	6.1	5.1	4.6
44	13.2	10.0	8.8	7.9	6.2	5.1	4.6
48	13.6	10.3	9.0	8.1	6.3	5.1	4.6
52	14.1	10.6	9.3	8.3	6.4	5.1	4.5
56	14.5	10.9	9.5	8.4	6.4	5.1	4.5
60	14.9	11.1	9.7	8.6	6.5	5.1	4.5
64	15.2	11.4	9.9	8.7	6.6	5.1	4.4
68	15.5	11.6	10.0	8.9	6.6	5.1	4.4
72	15.8	11.8	10.2	9.0	6.7	5.1	4.4
76	16.1	12.0	10.4	9.1	6.7	5.1	4.3
80	16.3	12.2	10.5	9.2	6.8	5.1	4.3
84	16.5	12.4	10.6	9.4	6.8	5.1	4.3
88	16.7	12.5	10.8	9.4	6.8	5.1	4.3
92	16.9	12.7	10.9	9.5	6.9	5.1	4.2
96	17.0	12.8	11.0	9.6	6.9	5.1	4.2
100	17.2	12.9	11.1	9.7	6.9	5.1	4.2
104	17.3	13.0	11.2	9.8	6.9	5.1	4.2
108	17.4	13.1	11.2	9.8	7.0	5.0	4.1
112	17.5	13.2	11.3	9.9	7.0	5.0	4.1
116	17.5	13.3	11.4	9.9	7.0	5.0	4.1
120	17.6	13.3	11.4	10.0	7.0	5.0	4.1
124	17.6	13.4	11.5	10.0	7.0	5.0	4.1
128	17.7	13.4	11.5	10.1	7.0	5.0	4.0
132	17.7	13.5	11.6	10.1	7.0	5.0	4.0
136	17.7	13.5	11.6	10.1	7.1	5.0	4.0
140	17.7	13.6	11.6	10.1	7.1	5.0	4.0
144	17.7	13.6	11.6	10.2	7.1	4.9	4.0
148	17.7	13.6	11.7	10.2	7.1	4.9	3.9
152	17.6	13.6	11.7	10.2	7.1	4.9	3.9
156	17.6	13.6	11.7	10.2	7.1	4.9	3.9
160	17.6	13.6	11.7	10.2	7.1	4.9	3.9
164	17.5	13.6	11.7	10.2	7.0	4.9	3.9
168	17.5	13.6	11.7	10.2	7.0	4.9	3.9
172	17.4	13.6	11.7	10.2	7.0	4.9	3.8
176	17.3	13.5	11.6	10.2	7.0	4.8	3.8
180	17.3	13.5	11.6	10.2	7.0	4.8	3.8
184	17.2	13.5	11.6	10.1	7.0	4.8	3.8
188	17.1	13.4	11.6	10.1	7.0	4.8	3.8
192	17.0	13.4	11.6	10.1	7.0	4.8	3.8
196	16.9	13.4	11.5	10.1	6.9	4.8	3.8
200	16.9	13.3	11.5	10.0	6.9	4.8	3.7
204	16.8	13.3	11.5	10.0	6.9	4.7	3.7
208	16.7	13.2	11.4	10.0	6.9	4.7	3.7
212	16.6	13.2	11.4	10.0	6.9	4.7	3.7
216	16.5	13.1	11.3	9.9	6.9	4.7	3.7
220	16.4	13.1	11.3	9.9	6.8	4.7	3.7
224	16.3	13.0	11.3	9.9	6.8	4.7	3.7
228	16.1	12.9	11.2	9.8	6.8	4.7	3.7
232	16.0	12.9	11.2	9.8	6.8	4.6	3.6
236	15.9	12.8	11.1	9.7	6.7	4.6	3.6
240	15.8	12.7	11.1	9.7	6.7	4.6	3.6

Table 6
The maximum temperature difference of the crude oil between the double-pipeline system and a single crude oil pipeline (°C)

Original example						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	3.8	1.6	1.0	0.6	0.1	0.0
Location (km)	76	84	84	84	84	–
The thermal conductivity of the soil increased to 1.8						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	3.3	1.5	0.9	0.5	0.1	0.0
Location (km)	62	68	62	60	28	–
The buried depth of the two pipelines reduced to 1.0 m						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	2.5	0.7	0.3	0.1	0.0	0.0
Location (km)	80	92	48	16	16	–
Air temperature reduced to −7.9 °C						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	3.2	1.2	0.5	0.3	0.0	0.0
Location (km)	76	66	66	46	–	–
Air temperature increased to 7.6 °C						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	1.0	0.0	0.0	0.0	0.0	0.0
Location (km)	38	–	–	–	–	–
Outlet temperature reduced to 45 °C						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	2.6	1.1	0.6	0.4	0.0	0.0
Location (km)	80	80	82	92	46	–
Outlet temperature increased to 75 °C						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	5.0	2.2	1.3	0.8	0.1	0.0
Location (km)	94	96	94	74	160	–
Double throughput of the crude oil						
Pipeline interval (m)	0.2	0.6	0.9	1.2	2.4	4.8
Maximum temperature difference (°C)	2.9	1.3	0.8	0.5	0.1	0.0
Location (km)	128	130	130	128	122	–

208.7 W/m. This is due to the heat absorption of the cold products, 132.8 W/m at the station outlet. The heat absorption of the cold products is much more than the increase of the heat loss of the crude oil. The energy balance calls for 42.2 W/m decrease of the heat emission of the ground surface (Table 3) and smaller heat transfer to the constant temperature layer. With the increase of the pipeline interval, the heat absorption of the cold products gradually decreases. When the interval is 1.2 m, the heat absorption of the cold products oil reduces to 40.6 W/m while the heat loss of the crude oil, 219.5 W/m, only increases 10.8 W/m compared to that of laying a single crude oil pipeline in one ditch. When the interval becomes 2.4 m, the heat absorption of the products oil, 14.0 W/m, is approximately equal to the reduced heat emission of the surface, while the heat loss of the crude oil, 209.8 W/m, is the same as that of laying the single one in one ditch. When the interval is 4.8 m, the heat loss of the products, 3.1 W/m, lessens the heat loss of the crude oil to 207.8 W/m by heating the soil around it. Because of the temperature drop along the crude oil pipeline, the heat loss of the crude oil gradually decreases, as is shown in Fig. 9a, and the heat absorption of the products oil also gradually decreases as is shown in Fig. 9b.

(b) The average increase rate of the heat loss along the crude oil pipeline, compared to the single crude oil pipeline in the ditch, reaches the maximum value of 2.6% when the pipeline interval is 0.2 m, which decreases with the increase of the pipeline interval. Though the total heat loss of the crude oil is basically the same, the heat transfer has changed notably. The heat loss of the single crude oil pipeline is totally absorbed by the environment, however, the heat loss of the crude oil in the double-pipeline system is partly absorbed by the environment and is partly absorbed by the products oil.

(c) As shown in Fig. 9a, when the pipeline interval is less than 2.4 m and the mileage of the pipeline is less than 80–100 km or so, the heat loss of the crude oil pipeline is more than that of a single crude oil pipeline. When the mileage is larger than 80–100 km or so, the heat loss contrarily becomes less. The contrary is due to two main reasons, one of which is that the significant temperature difference between the crude oil and products oil results in the abundant heat

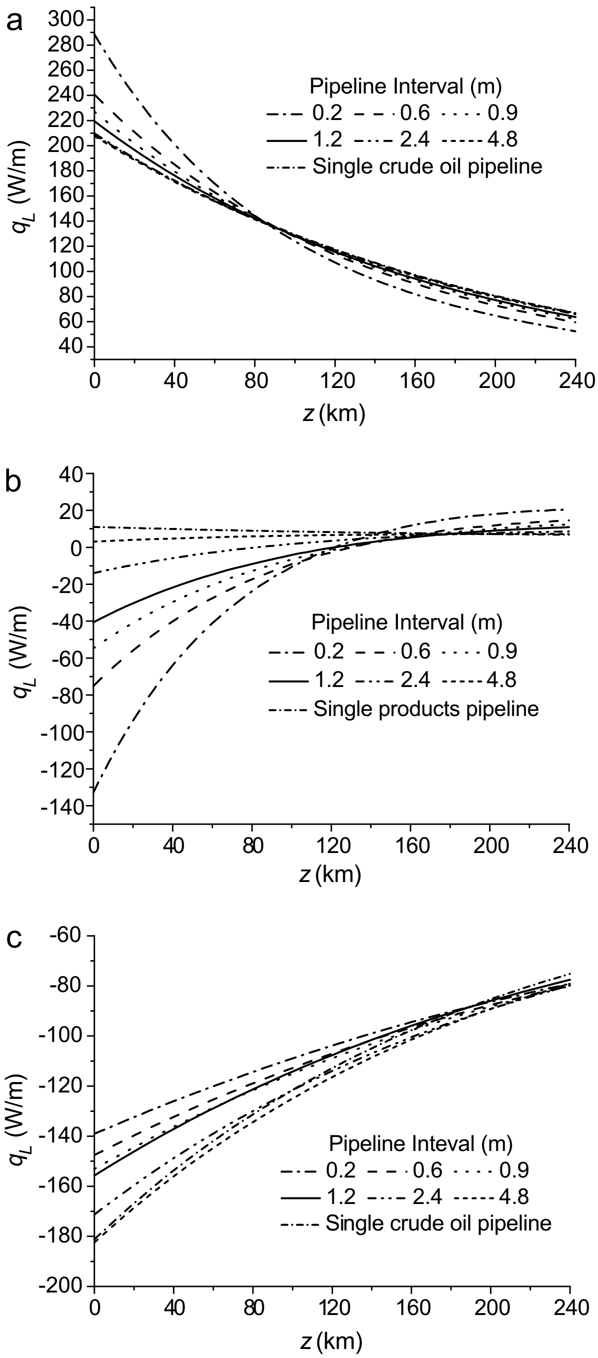

Fig. 9. Line heat flux densities along the pipeline: (a) heat loss of the crude oil along the pipeline, (b) heat absorption of the products oil along the pipeline and (c) heat absorption of the atmosphere along the pipeline.

absorption of the products oil when the mileage of the pipeline is less than 80–100 km or so and the products oil lose heat when the mileage is larger than about 140–160 km, as shown in Fig. 9b. The other reason is that before the 80–100 km the temperature drop and heat loss of the crude oil in the double-pipeline system are greater than those when laying the single crude oil pipeline, making its heat capacity becomes smaller.

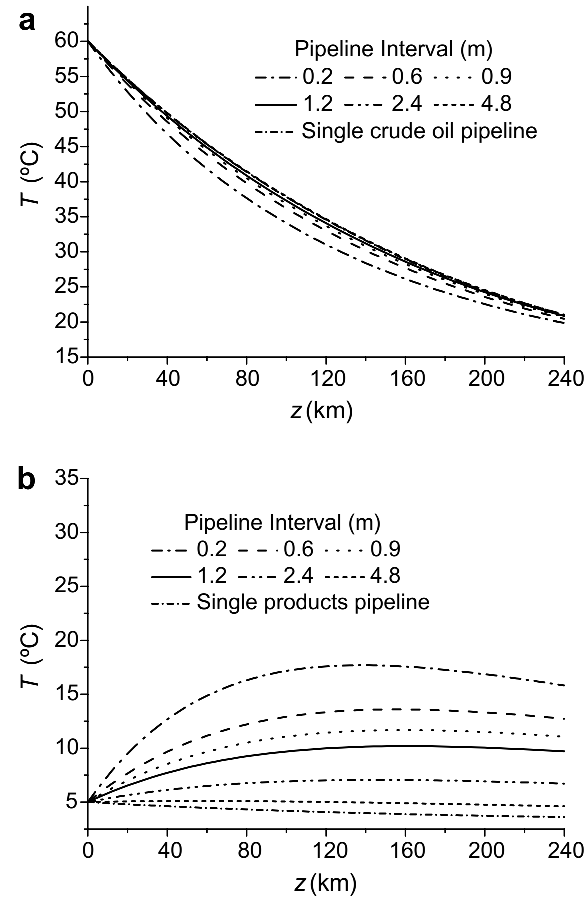

Fig. 10. Temperature along the pipeline: (a) temperature of the crude oil along the pipeline and (b) temperature of the products oil along the pipeline.

(d) When the pipeline interval is 2.4 m or 4.8 m, the heat flux density curve of the crude oil has good superposition with that of the single crude oil pipeline, which means the products pipeline has little impact on the crude oil pipeline. As a result, the temperature along the crude oil pipeline in the double-pipeline system is generally the same as the temperature along the single crude oil pipeline. As can be seen in Tables 2 and 4, when the interval is 4.8 m, the minor heat loss of the products oil has a favorable effect on the crude oil pipeline, which makes the next station inlet temperature of the crude oil 0.1 °C higher.

(e) The temperature difference is defined as the difference of the oil temperature at the same pipeline location between the double-pipeline system and single pipeline system. When the temperature difference reaches its maximum value, we call it the maximum temperature difference $\Delta T_{\max}$. As can be seen from Tables 4–6 and Fig. 10a, $\Delta T_{\max}$ appears at about 80 km and the temperature difference decreases gradually along the pipeline. The heat absorption of the products before 80 km aggravates the temperature decrease of the crude oil. Meanwhile, the significant decrease of the heat absorption or even the conversion to heat loss of the products oil after this location, shown in Fig. 9, slows down the temperature decrease of the crude oil. When the pipeline interval is not less than 1.2 m, ΔT_{max} is not more than 0.6 °C. However, when the pipeline interval is 0.2 m, ΔT_{max} at 76 km is 3.8 °C, which will jeopardize the safe operation. As a result, the two pipelines in one ditch should not be too close to each other.

(f) As can be seen from Fig. 10b, the temperature along the products pipeline firstly goes up and then falls down in most cases. When the interval is 4.8 m, the temperature decreases at the beginning of the station outlet, just similar to the single products pipeline. This shows that the products pipeline has no longer absorbed the heat from the crude oil pipeline and has a favorable effect on the operation of the crude oil pipeline. When the pipeline interval is 4.8 m, the heat loss of the products oil pipeline is less than that of the single products pipeline due to the effect of the hot crude oil. The hot crude oil has a great effect on the products pipeline and the highest temperature rise is 13.8 °C when the interval is 0.2 m.

4.2. Results under other typical operating conditions

It has shown that when the pipeline interval is not less than 1.2 m, the crude oil temperature of laying double pipelines decreases not more than 0.8 °C compared to that of laying single pipeline, which may not deteriorate the safe operation too much and can be acceptable in the engineering application. Is it a general result under other operation conditions? To answer this question, we need to do calculations for more typical operating conditions. As we know, physical properties of the soil such as thermal conductivity, the buried depth, air temperature, outlet temperature and throughput are the major factors to affect the heat transfer, therefore it is necessary to show whether and how the results obtained from the typical operating conditions in Section 4.1 changes by variation of the important parameters. For such a purpose, calculations under other operating conditions are made.

(1) The properties of the soil. The thermal conductivity of the soil was increased from 1.28 W/(m °C) (original example) to 1.8 W/(m °C).
(2) The depth was changed from 1.6 m of the original example to 1.0 m.
(3) The air temperature. The temperature was changed from 0 °C (original example) to −7.9 °C or 7.6 °C.
(4) The outlet temperature of the crude oil. The temperature was separately increased or reduced 15 °C compared to the 60 °C (original example).
(5) The throughput of the crude oil pipeline. The throughput was increased from 1×10^7 t/a (original example) to 2×10^7 t/a.

To our surprise, by analyzing the output data of the calculations under the above conditions, very similar results are obtained. For simplicity we no longer show the details and list only what seriously concerned in the engineering application, i.e. the maximum temperature difference (ΔT_{max}) between the double-pipeline system and the condition of laying single pipeline in Table 6. As can be seen from the table, following results are obtained. Firstly, when the pipeline interval is 4.8 m, the temperature of the crude oil actually increases no matter how the other parameters change, which shows that the products pipeline has a favorable effect on the crude oil. Secondly, when the pipeline interval is 1.2 m or 2.4 m, ΔT_{max} caused by the variation of each parameter is not more than 0.8 °C and the changing magnitude is not significant. Thirdly, when the pipeline interval is less than 1.2 m, ΔT_{max} caused by the variation of each parameter is generally more than 1 °C and ΔT_{max} reaches 5 °C under the most unfavorable condition. In a word, when the pipeline interval is less than 1.2 m, the products pipeline has a great impact on the crude oil pipeline.

5. Conclusions

On the basis of the results above, general conclusions can be drawn as follows:

(a) The existence of the products pipeline changes the soil temperature field on one side of the crude oil pipeline and changes the heat transfer. That is to say, when there is only a single crude oil pipeline, the heat is totally absorbed by the soil. When the products pipeline coexists in one ditch with the crude oil pipeline, the heat is partly absorbed by the soil and partly absorbed by the products oil. The gradient of the soil temperature on the very side of the products pipeline decreases and the heat loss to the environment lessens.
(b) The effects of each parameter on the temperature drop are not notable when the pipeline interval is not less than 1.2 m. However, the temperature decreases a lot when the pipeline interval is less than 1.2 m. Therefore, generally speaking the pipeline interval more than 1.2 m is relatively safe for the pipeline operation while the interval less than 1.2 m should carefully be chosen in pipeline construction.

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