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Thermal Characteristics Simulation of the Commissioning Process for New Buried Heated Oil Pipelines

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Abstract. For a new buried heated oil pipeline, the temperature field of the surrounded soil is natural. Therefore the temperature is usually low in this case. For the waxy crude oil whose pour point is higher than the ground temperature, if the new pipeline transports such oil directly after heating, crude oil may gel in pipeline because its temperature decrease dramatically due to heat exchange between the fluid and the surrounded soil. Hence, in practical situation hot water is often used to warm up the pipelines for most of the new long-distance buried pipelines. Crude oil transportation is determined after the soil temperature field around the pipeline is sufficiently high and the inlet water temperature meets the requirement.

This paper proposes a new way for the commissioning of new buried heated oil pipelines. With the new method, the safety of the pipeline is guaranteed and the economical use of hot water is also under the consideration. The method has already been applied for more than 10 pipeline commissioning.

Introduction

For a new buried heated oil pipeline or to restart a buried pipeline after long-time shutdown, the temperature field of the surrounded soil is natural. Therefore the temperature is usually low in this case. For the waxy crude oil whose pour point [1] is higher than the ground temperature, if the new pipeline transports such crude oil without heating, it may have to stop transportation because of the sharp increase of friction loss in pipeline due to dramatically temperature drop, or crude oil may even gel in pipeline. Hence, to avoid that in the practical field (even there might existed crude oil transported directly in new pipeline in the case that the pipeline is short enough or the physical properties of the crude oil are appropriate), a kind of liquid with high heat capacity and low viscosity (usually use hot water) is often used to warm up the pipelines for most of the new long-distance buried pipelines. Crude oil transportation is determined after the soil temperature field around the pipeline is sufficiently high and the inlet water temperature meets the requirement. Thus, during the starting process of heated oil pipeline, to calculate and predict the soil temperature field around the pipeline and the relations between inner fluid temperature and time, is the key part of determination of the oil transportation time and total quantity of warm up fluid.

At the stage of preheating pipeline, the thermodynamic process for the soil temperature field around the pipeline and the fluid flow temperature are unsteady thermal dynamic process. Heat continuously transfers from warm up fluid to the pipe wall, coat and soil around the pipeline. During this process, the temperature of warm up fluid is decreasing while the soil temperature field around the pipeline is increasing, and at last they are both in the heat equilibrium. Therefore a mathematical model is needed for obtaining the results.

Thermal dynamic calculation model

Having studied unsteady thermodynamic calculation of heated oil pipeline running starting from 80s last century, Ding [3] etc. have gotten a calculation formula which is close to practical situation, listed as follows:

T (z, t) = f(Tk,Q, z, t) (1) $T(z,t) = f(T_k, Q, z, t)$ (1)

where T, T_k, Q, z, t represent temperature of the fluid, station discharge temperature, throughput, location, and time respectively. This equation is a fundamental thermal dynamical equation for preheating of heated oil pipeline commissioning. During the commissioning process, the heat transfer coefficient α_2 between pipeline and soil plays a very important role on the heat loss of the fluid. Further, this coefficient will become smaller gradually and finally reach a new real number $\alpha_{2\infty}$. The following two equations are proposed by a Russian scientist based on field experience:

$$\alpha_2 = \frac{\alpha_{2\infty}}{1 - e^{\frac{4\alpha_s(\tau - z/\upsilon)}{5D_H D_H}}} \quad (2)$$

$$\alpha_2 = \alpha_{2\infty} + \frac{B_2 \lambda_s}{\sqrt{\alpha_s(\tau - z/\upsilon)}} \quad (3)$$

where α_s, D_H, λ_s, υ refer to temperature conduction coefficient of soil, pipe outside diameter, heat conduction coefficient of soil, fluid speed respectively. $B_2 = 0.3 + 0.06\frac{H}{D_H}$ where H denotes buried depth of the pipe.

Adding equation 2 and 3 into the overall heat coefficient K equation [2], the following equations will be obtained:

$$K = \frac{K_\infty}{1 - \frac{K_\infty D}{\alpha_{2\infty} D_H} e^{\frac{4\alpha_s(\tau - z/\upsilon)}{5D_H D_H}}} \quad (4)$$

$$K = K_\infty \{1 + \frac{K_\infty D/(\alpha_{2\infty} D_H)}{b_3 + b_4\sqrt{\tau - z/\upsilon}}\} \quad (5)$$

Adding equation 4 and 5 into the thermal balance equation [2], the following equation will be obtained:

$$K\pi D(T - T_0)dz = -Q\rho_p c_p dT \quad (6)$$

The following equations would be addressed after integrating:

$$T = T_0 + (T_H - T_0)[\frac{1 - E \cdot e^{f2z}}{1 - E}]^{J_1} \cdot e^{(-m_y \frac{z}{L})} \quad (7)$$

$$T = T_0 + (T_H - T_0)[\frac{b_3 + b_4\sqrt{\alpha_s \tau}}{b_3 + b_4\sqrt{\alpha_s(\tau - z/\upsilon)}}]^{f_3} \cdot e^{(-m_y \frac{z}{L})} e^{[f_4(\sqrt{\alpha_s(\tau - z/\upsilon)} - \sqrt{\alpha_s \tau})]} \quad (8)$$

where

$$J_1 = \frac{5K_\infty D}{\alpha_s \rho_p C_p} \frac{{D_H}^2}{D} \qquad f_2 = \frac{4\alpha_s}{5D_H^2 V}$$

$$f_3 = \frac{\lambda_s B_2 b_3}{\alpha_{2\infty}} f_4 \qquad f_4 = \frac{8\lambda_s B_2 K_\infty^2}{\alpha_s \rho_p C_p D_H \alpha_{2\infty}^2}$$

$$b_3 = 1 - \frac{K_\infty D}{\alpha_{2\infty} D_H} \qquad b_4 = \frac{\alpha_{2\infty}}{B_2 \lambda_s}$$

and L, z, τ, T_H, T_0, Q, ρ_p, C_p denote for pipeline length, location of the node, time, station discharge temperature, natural soil temperature, throughput, crude density, crude heat capacity respectively.

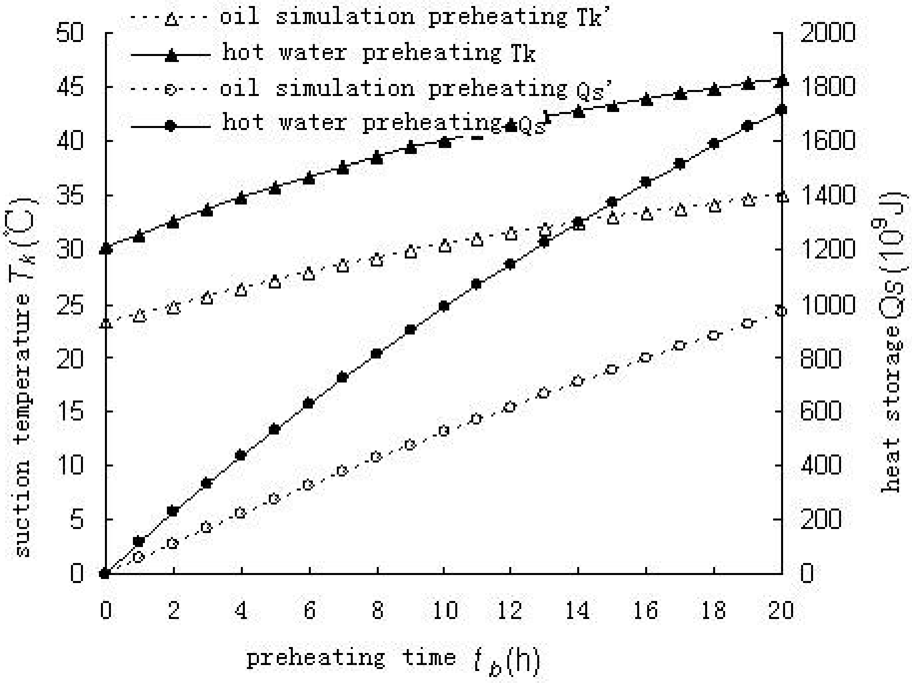

Fig. 1 The relationship between T_k, Q_s, t_b

Based on equation 7 and 8, the following presented computational equations are given with correction factors:

$$T(z,T) = T_0 + \theta(z,T)\delta(\theta) \qquad (9)$$

where

$$\theta(z,T) = (T_H - T_0)[\frac{1 - E \cdot e^{f2z}}{1-E}]^{J_1} \cdot e^{(-m_y \frac{z}{L})} + 8\times10^{-5} z\{1 - 1.5e^{[-\alpha_s(38.973(\tau - z/\upsilon) - 14.893\sqrt{\tau - z/\upsilon})]}\}$$

and $\delta(\theta)$ =1 if θ>0, $\delta(\theta)$ =0 if θ<=0. A further explanation is listed as follows: only in the case that the preheating material is light oil (the density and heat capacity of this oil is relatively low) and the pipeline is quite low, δ has the possibility to be zero. Under normal condition, δ = 1. So if the hot water is used as the preheating medium, δ = 1. Therefore, when calculating the soil heat storage capacity, the following equation can be obtained:

$$f(L,\tau) = T_0 + \theta(L,\tau) \qquad (10)$$

A. Determination of commissioning time. Commissioning time determination should meet two requirements: one is thermodynamic condition that the lowest suction temperature of crude oil should be 2-3C higher than pour point, the other one is hydraulic condition that the friction loss must not exceed the pressure that transportation bump offered and the pipeline can bear.

The commissioning time which use water to pre-heat should be determined by these steps: to meet the industrial requirement, such as the requirement on the suction temperature Tk and hydraulic condition, pre-heating is first simulated based on the crude oil in order to obtain the expected heat storage capacity of the surrounding soil Q_s'. Then pre-heating is simulated again but based on the hot water. When the heat storage capacity of the soil Q_s meets the expected heat storage capacity Q_s', it means that the commissioning process is ready to start. That is fundamental theory of the commissioning time determination–Theory of Soil Heat Equation.

Numerical examples

One buried heated oil commissioning pipeline is taken as an example, the physical property parameters of this pipeline are listed as follows:

Pipeline length *L*	60km
Inner Diameter *D*	0.515m
Pipe Thickness	0.007m

Outside Diameter D_H 0.544m
Buried Depth H 1.50m
Natural Temperature T_0 21C
Discharge Temperature T_k 50 − 80C
Throughput Q 300 − 1000m^3/h

The suction temperature T_k and heat storage capacity of soil Qs were simulated based on the crude oil and hot water with the same throughput and warm up time t_u (i.e. commissioning time - till warm up fluid full of pipeline to commissioning conditions achieved). Discharge temperature was 65C, and the natural soil temperature T_0 = 21C. The pour point of crude oil is 33C, and the soil temperature field around the pipeline is warmed enough to commissioning when the suction temperature of warm up fluid T_k reached 35.

Table1 Relation among throughput Q, t_u, T_k, Q_s

Throughput	t_0	t_u	$T'_k(H)$	$T'_k(C)$	Q_s(C)	Q_s(H)
300	41.6	137.0	34.9	47.7	2451.8	4176.6
500	25.0	47.0	35.0	46.8	1454.6	2514.4
800	15.6	20	35.0	45.8	964.5	1714.5
1000	12.5	13	34.9	45.1	770.6	1375.5

where (*C*), (*H*) represents the terminology of using crude oil to preheat, using hot water to preheat respectively. Table 1 indicated that the suction temperature and heat storage capacity which simulated by water are higher than crude oil, because the heat capacity of water is larger than crude oil. Thus, hot water transferred more heat to soil than crude oil when suction temperature and volume of the fluid in pipeline are the same. When the throughput Q = 800m^3/h, T0 = 21C Th =65C, the relation between warm up time $t_b(t_b t - L/v))$ and T_k, Qs is listed in Fig. 1. Fig. 1 shows that T_k is continuously increasing with warm up time longer, but the increasing velocity is turning small until balance because of the equilibrium between warm up fluid and surrounding soil at last. The heat transfer coefficient and suction temperature of heat oil pipeline tended to be stable when the soil temperature field is warm enough.

Based on the theory of equivalent heat storage capacity, the crude oil is firstly used as preheating medium to do the simulation. When the station suction temperature meets the commissioning requirement, the computed soil heat storage capacity Q'_s will be recorded. Then the hot water will be used as preheating medium to do the second numerical simulation. Once the soil heat storage capacity for the new medium Q_s equals Q'_s, then the preheating time is the needed commissioning time t_y.

The following figure and table show the relationship between the commissioning time t_y and heat storage capacity Q_s, throughput Q at the condition that T_0 = 21C, T_k = 65C

Table 2. Relationship between t_y, Q_s, T_k at different throughput

Throughput	T_k(C)	T_k (HW)	t_y(C)	t_y (HW)	Q_s (10^7 J)
300	31.9	42.5	137	66	2451.8
400	35.0	41.5	75	36	1805.3
500	35.1	40.8	47	23	1454.6
600	35.1	40.1	34	16	1238.9
700	35.0	39.8	25	12	1064.1
800	34.9	40.1	20	10	964.5
900	35.0	40.1	16	8	861.5
1000	35.1	39.2	13	7	770.6

where (C), (HW) represents using crude oil, hot water respectively From Table 2 and Fig. 2, it can be seen that the commissioning time will be shorter if the throughput becomes larger. It also shows that the commissioning time of using hot water is smaller than that of using crude. When the commissioning requirements is satisfied, the suction temperature of hot water must be above 40*C* in order to guarantee the crude oil suction temperature will be higher than 35*C*.

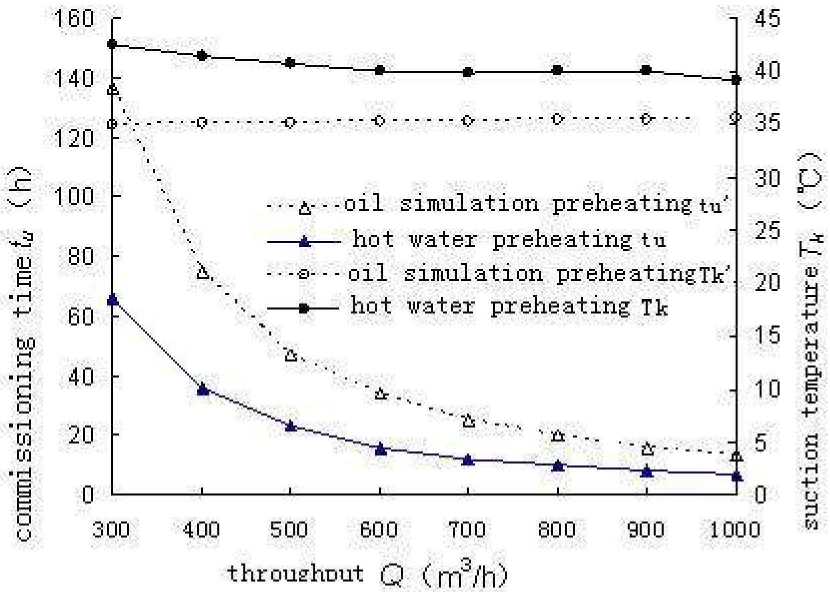

Fig.2 The relationship between t_y, T_k and throughput

The following figure shows the relationship between the commissioning time t_y and heat storage capacity Q_s, discharge temperature of the preheating medium T_k at the condition that T_0 = 21C, Q = 800m^3/h Fig. 3 shows that the preheating time will be smaller if the station discharge temperature is higher provided that the throughput keeps unchanged.

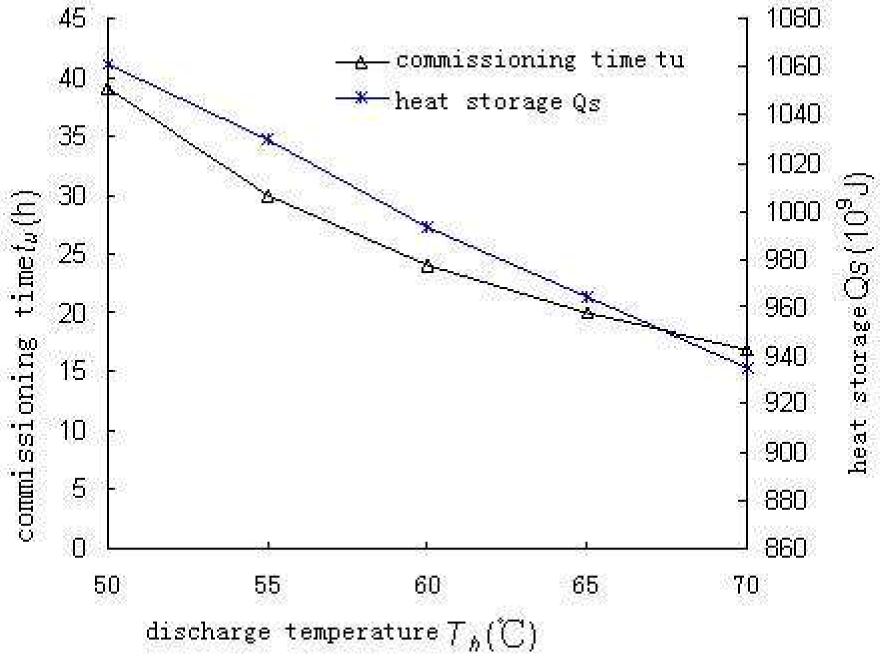

Fig.3 The relationship between t_y, Q_s, T_k

Fig. 4 shows the relationship between the overall heating coefficient K and the preheating time using different preheating medium (crude and hot water) at the following condition : T0 = 21C, Q = 800m3/h, Tk = 65C. From Fig. 4, it can be seen that K decreases exponently as the preheating time increase linearly. At the initial preheating stage, K decreases dramatically, however, as preheating time elapses, K decreases smaller and reaches a real number around 3.0.

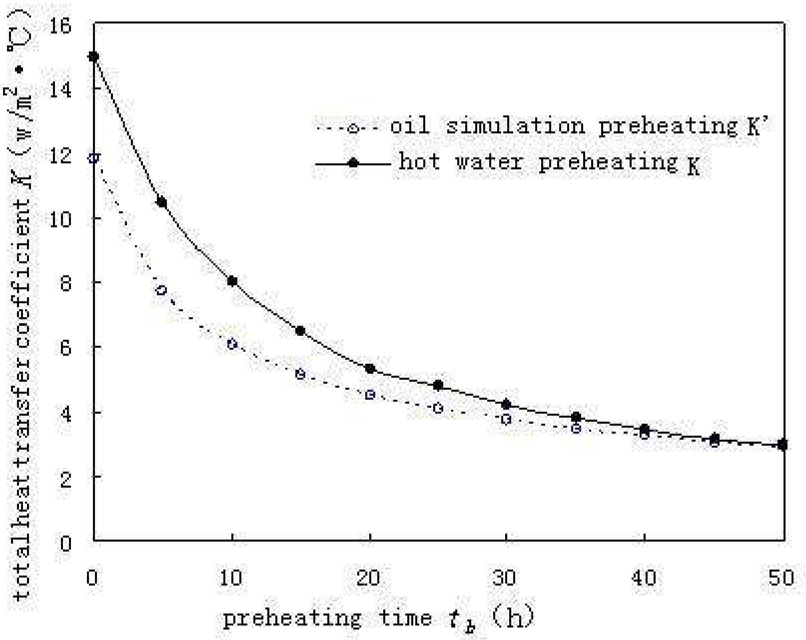

Fig.4 The relationship between the overall heating coefficient K and the preheating time

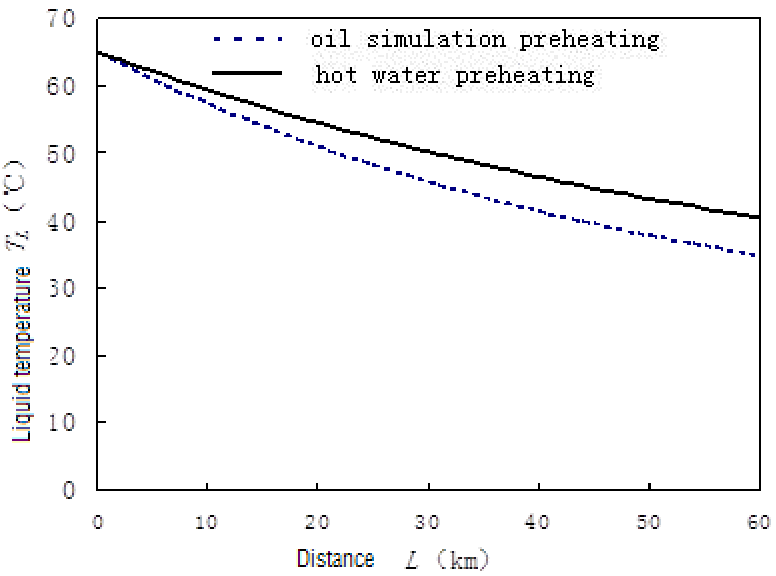

Fig. 5 Shows the temperature plot when the commissioning requirement is satisfied at the following conditions: T_0 = 21C, Q = 800m^3/h, T_k = 65C.

Conclusions

This paper proposes a new way for the commissioning of new buried heated oil pipelines. With the new method, the safety of the pipeline is guaranteed and the economical use of hot water are also under the consideration. The proposed method has been successfully applied in more than 10 new pipelines. Here are a few listed conclusions for field works:

- the heat storage capacity using hot water as heating medium is much larger than that of using crude oil at the exactly same condition.
- Based on the theory of equivalent heat storage capacity, the commissioning time will be shorter if the throughput is larger. At the same condition, the commissioning time of using hot water is much smaller than that of using crude oil. The consumed time for the previous one is only about half of the later one.

- The preheating time is shorter if the station discharge temperature is higher provided that the throughput keeps unchanged.
- The overall heating coefficient K decreases exponent and finally reaches a real number.

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