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Study on heat transfer characteristics of high water cut crude oil in FRP pipeline#

Yuanzhi Qin[1], Hanwen Zhang[2], Le Yu[3], Jingru Tian[1], Zhen Wei[1], Shishi Fei[1], Xingwen Zhong[1], Wenchen Liu[1], Xingyue Pu[1], Qiyu Huang[1*]

1 Beijing Key Laboratory of Urban Oil and Gas Distribution Technology/Surface Engineering Pilot Test Center, CNPC, China University of Petroleum, Beijing 102249, China

2 Research Institute of Science and Technology of PipeChina, Langfang 065000, Hebei, China

3 Changqing Oilfield Shale Oil Development Branch, PetroChina Company Limited, Qingyang 745000, Gansu, China
(Corresponding Author: ppd@cup.edu.cn)

ABSTRACT

When the high water cut crude oil is collected and transported at low temperature, a large amount of adhesive oil in the traditional stainless steel (SS) pipeline leads to the increase of wellhead back pressure, which seriously threatens the production safety of the oilfield. In this study, the heat transfer characteristics of fiberglass reinforced plastic (FRP) and SS pipe sections were tested with indoor loop experimental equipment, and the temperature drop and pressure drop of oil-water suspension in FRP pipe and SS pipe were studied. Simultaneously, the entire process involving convective heat transfer and heat conduction in FRP and SS pipes is characterized through heat transfer calculations. The experimental and calculation results show that the pressure drop in the SS pipe section is much greater than that in the FRP pipe section at the same temperature drop time, and the FRP pipe is more conducive to safe transportation. In addition, compared with the SS tube section, the temperature of the oil-water suspension in the FRP tube section takes longer to drop from 40 °C to 30 °C. FRP pipeline has better insulation performance, which is more conducive to the implementation of low temperature gathering and transportation (LTGT) technology of high water cut crude oil.

Keywords: FRP pipeline, high water cut crude oil, heat transfer characteristics, loop experiment, low temperature gathering and transportation.

NONMENCLATURE

Abbreviations	
SS	stainless steel
FRP	fiberglass reinforced plastic
LTGT	low temperature gathering and transportation
CHTC	convective heat transfer coefficient
THTC	total heat transfer coefficient
TTR	total thermal resistance
Symbols	
ρ	the density of oil-water suspension (kg/m^3)
v	the average flow rate of oil-water suspension in the pipeline (m/s)
d	the inner diameter of the pipeline (m)
μ	the dynamic viscosity of oil-water suspension (Pa·s)
C_p	the specific heat capacity of oil-water suspension (J/(kg·°C))
λ	the thermal conductivity of the oil-water suspension (W/(m·K))
Re_f	the Reynolds number of oil-water suspension at average temperature
Pr_f	the Prandtl number of oil-water suspension at average temperature
l	the pipeline length of the test section (m)
η_f	the kinematic viscosity of oil-water suspension at average temperature (Pa·s)
η_w	the kinematic viscosity of oil-water suspension at wall temperature (Pa·s)
Nu_f	the Nussel number of oil-water suspension at average temperature

1. INTRODUCTION

The majority of oil fields in China have entered the middle and late stage of exploitation [1-2], with the widespread testing and application of high water cut LTGT technology [3]. When the conveying temperature of the pipeline is reduced to the viscous wall temperature, crude oil will adhere to the inner wall of the

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pipeline and form a condensate layer, resulting in the increase of wellhead back pressure, which seriously threatens the safety of the oilfield gathering and transportation system [4]. FRP pipeline provides favorable conditions for the implementation of LTGT process with its excellent thermal insulation performance. As a result, it is critical to investigate the heat transfer properties of high water cut crude oil in FRP pipeline in order to broaden the application range of LTGT technology.

The LTGT of crude oil present a two-phase flow challenge involving oil and water, primarily addressed through experimental studies and model calculations. Wang et al. [5] believed that the low-temperature gelling and siltation process of water-bearing crude oil was the result of a variety of comprehensive action mechanisms such as wax evolution, wax formation and emulsification, and found through experiments that the siltation rate of water-bearing crude oil was the highest near the gelling temperature. Zheng et al. [6] found that the shear stress, water content and the difference between the freezing point and the pipe wall temperature affected the wall sticking rule of crude oil through the indoor loop experiment, and established the discrimination basis of the wall sticking temperature and the calculation model of the wall sticking rate. Zhang et al. [7] analyzed the adhesion process between condensate oil and the wall surface, and based on this, established a theoretical calculation model of the adhesion wall temperature.

In the study of wall adhesion, it is believed that oil composition, comprehensive water content, shear strength and other factors will affect the wall adhesion behavior of crude oil. Shi et al. [8] discovered that asphaltene deposited at the oil-water interface causes spatial repulsion between oil droplets and inhibits agglomeration of oil droplets. Zheng et al. [6] supposed that the increase of comprehensive water content maked it difficult for gelled crude oil to aggregate, and the viscosity of crude oil decreased with the increase of water content. Hoffmann et al. [9] studied the wax deposition law of oil-water two-phase flow through the loop device and found that the thickness of the sediment layer was negatively correlated with the shear action of the pipe flow.

The aforementioned researchers have investigated the influencing elements and the sticky wall model of crude oil, but there is no comprehensive theoretical advice on the heat transfer characteristics of pipelines. In this paper, the heat transfer characteristics of high water cut crude oil under different pipe conditions were studied by using indoor loop device, and the changes of temperature drop and pressure drop in FRP and SS pipelines during LTGT were studied. Through the calculation of heat transfer, the whole process of convection heat transfer and heat conduction of the pipeline is revealed, and it is clear that the FRP pipeline has better insulation performance, which provides an significant guide for the LTGT of the pipeline.

2. MATERIAL AND METHODS

2.1 Properties of crude oil

In this study, the sample oil used for the experiment was taken from the Jilin oilfield block in northeast China. Dehydration and solids removal are performed before the crude oil is used in the experiment. The basic physical properties of the sample oil are shown in Table 1.

Table 1. Basic physical properties of crude oil.

Density (kg/m^3)	Gel point (°C)	Wax appearance temperature (°C)	Cumulative wax precipitation amount (%)
824	35	58.10	25.97

2.2 Experimental apparatus

In this work, the heat transfer properties of high water content crude oil in various pipes were evaluated utilizing an indoor loop experimental setup, as seen in Fig. 1. The device is composed of a stirrer, a storage tank, two test tube sections, a gear pump, a flow meter, a pressure transmitter, a temperature transmitter, two circulating water baths and other components. The storage tank adopts a double-layer structure to form an annular water jacket, and the speed control range of the stirrer is 0-1500 r/min. The inner diameter of the test pipe is 29 mm, which contains two detachable test pipe sections made of FRP and SS.

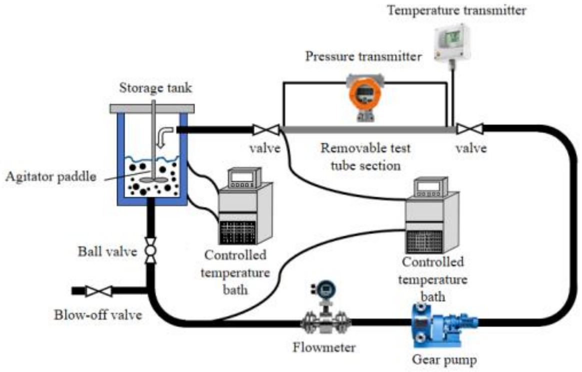

Fig. 1 Schematic diagram of the experimental device of the indoor loop.

2.3 Loop experiment

The specific steps of the loop test for different pipes of high water cut crude oil are as follows:

1) Prepare oil-water emulsion close to the liquid phase produced at the wellhead, measure a certain volume of oil-water emulsion and deionized water respectively, and place the oil-water emulsion and water sample in a constant temperature water bath at 40 °C for use;
2) Open the water bath, set the temperature to 30 °C, and keep the temperature of the exterior wall of the storage tank and pipeline at 30 °C;
3) When the temperature of the outer wall of the storage tank and pipeline is stable, turn on the agitator, and then pour the prepared water sample and oil-water emulsion into the storage tank in turn, start the pumping system and adjust to the set flow rate;
4) Real-time monitoring of the fluid temperature and pipeline pressure drop in the test pipe section during the cooling process, while recording the time taken when the fluid temperature drops to 30 °C;
5) Discharge the oil-water mixture, clean the experimental device, replace the test tube section and repeat the above steps.

3. DESCRIPTION OF HEAT TRANSFER CALCULATION METHODS

3.1 Convection heat transfer calculation method

Reynolds numbers and Prandtl numbers are calculated as shown in Eqs. (1)-(2).

$$Re = \frac{\rho v d}{\mu} \tag{1}$$

$$Pr = \frac{\mu c_p}{\lambda} \tag{2}$$

The calculation method of Nusselt number for laminar heat transfer in the pipe wall is shown in Eqs. (3)-(6).

$$Nu_f = 1.86(\mathrm{Re}_f \, \mathrm{Pr}_f \, \frac{d}{l})^{1/3} \left(\frac{\eta_f}{\eta_w}\right)^{0.14} \tag{3}$$

Applicable conditions:

$$0.48 < \mathrm{Pr}_f < 16700 \tag{4}$$

$$0.0044 < \frac{\eta_f}{\eta_w} < 9.75 \tag{5}$$

$$\left(\mathrm{Re}_f \, \mathrm{Pr}_f \, \frac{d}{l}\right)^{1/3} \left(\frac{\eta_f}{\eta_w}\right)^{0.14} \geq 2 \tag{6}$$

Eq. (7) can be used to calculate the convective heat transfer coefficient (CHTC) between oil-water suspension and tube wall.

$$h = \frac{\lambda}{d} Nu_f \tag{7}$$

3.2 Thermal conductivity calculation method

The heat conduction process of the fluid in the pipe to the outside of the pipe includes the heat conduction of the condensate adhesive layer and the heat conduction of the solid wall of the pipe. The calculation method is shown in Eq. (8).

$$R = \frac{1}{\lambda_1} \ln\left(\frac{d_2}{d_1}\right) + \frac{1}{\lambda_2} \ln\left(\frac{d_3}{d_2}\right) \tag{8}$$

Where λ_1 is the thermal conductivity of the adhesive layer, λ_2 is the thermal conductivity of the pipe wall, d_1 is the pipe flow diameter after condensate adhesion, d_2 is the inner diameter of the pipeline, d_3 is the outer diameter of the pipeline.

3.3 Calculation method of total heat transfer

The total heat transfer coefficient (THTC) of the pipe is calculated in Eq. (9). The heat transfer process of gathering and transportation pipeline mainly consists of the following three parts: Convective heat transfer between oil flow and tube wall; Heat conduction of condensate adhesive layer, pipe wall and insulation layer; Heat transfer between the outer wall of the insulation layer and the surrounding soil. The third process is ignored because of the heat pipe on the outer wall of the test tube section.

$$K = \frac{1}{\frac{1}{h_1} + \sum_{i=1}^{n} \frac{1}{\lambda_i} \ln \frac{d_{i+1}}{d_i} + \frac{1}{h_2}} \tag{9}$$

Where h_1 is the CHTC from the oil flow to the inner wall of the pipe, h_2 is the CHTC from the outer wall of the insulation layer to the soil.

4. RESULTS AND DISCUSSION

4.1 Temperature drop experiment

The temperature drop experiments of high water content crude oil were carried out under the conditions of SS and FRP test pipe sections for sample oil with a combined water content of 70% using an indoor loop channel experimental setup.

Fig. 2 shows that it takes 20min and 22.4min respectively for the fluid in the SS pipe section and the FRP pipe section to drop from 40 °C to 30 °C. In the temperature drop process above the freezing point (40 °C-35 °C), the cooling rate of FRP pipes is about 1.40 °C/min, and the cooling rate of SS pipes is about 1.48 °C/min. There is no condensate adhesion on the inner wall of the pipeline, and the thermal conductivity process is only determined by the material of the pipeline. In the temperature drop process below the freezing point (35 °C-30 °C), the cooling rate of FRP pipes is about 0.24 °C/min, and the cooling rate of SS pipes is about 0.27 °C/min. Condensate adhesion appears on the inner wall of the pipeline, and the thermal conduction process is determined by the material of the pipeline and the thickness of the condensate layer. Overall, the cooling rate of oil-water suspension in FRP pipeline is slow, resulting in better insulation effect.

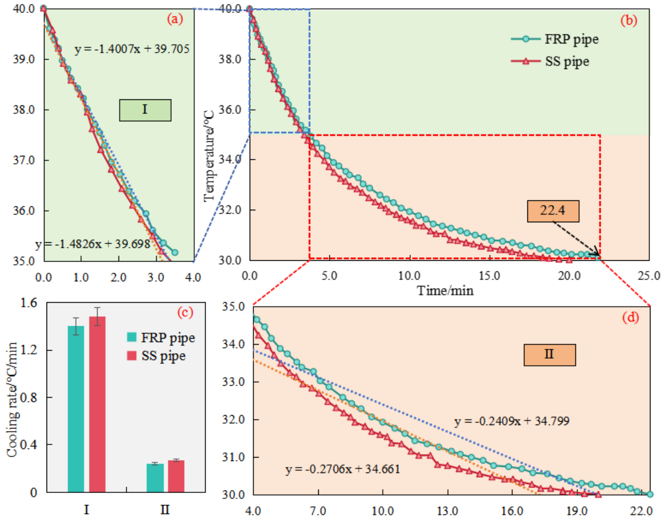

Fig. 2 (a) Temperature drop in interval Ⅰ, (b) temperature in the test tube section under different cooling times, (c) cooling rate, (d) temperature drop in interval Ⅱ.

4.2 Pressure drop experiment

By using the indoor loop test device, the sample oil with a comprehensive water content of 70% was tested under the conditions of SS and FRP pipe, and the pressure drop experiment of high water cut crude oil was carried out.

Fig. 3 reveals that the pressure drop of different pipe test sections varies with temperature. When the temperature is reduced from 40 °C to 35 °C, the pressure drop in the SS pipe section is nearly increased from 0.12 kPa to 0.22 kPa, and the pressure drop in the FRP pipe section is approximately increased from 0.12 kPa to 0.19 kPa. When the temperature is reduced from 35 °C to 30 °C, the pressure drop in the SS pipe section is almost increased from 0.22 kPa to 2.10 kPa, and the pressure drop in the FRP pipe section is probably increased from 0.19 kPa to 0.71 kPa. With the decrease of temperature, the pressure drop in the test section of SS pipe is much greater than that in the test section of FRP pipe. On the one hand, the friction coefficient of FRP pipeline is small, resulting in the flow resistance of oil-water suspension is relatively small; On the other hand, the condensate oil adhering to the surface of FRP is more likely to fall off under the action of pipe flow shear because of the higher temperature in the tube section within the same temperature drop time. Therefore, compared with SS pipelines, the use of FRP pipelines is more conducive to the safe production of oil fields.

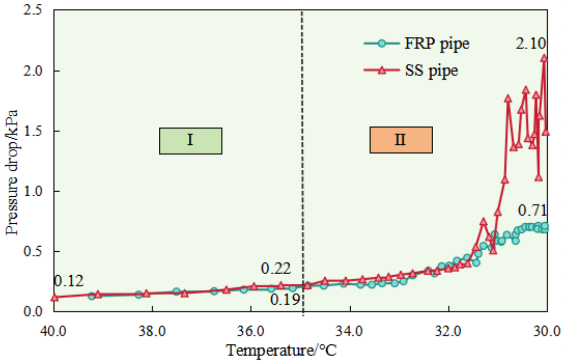

Fig. 3 Pressure drop of the test tube section at different temperatures.

4.3 Convection heat transfer calculation

The calculation results of the convection heat transfer coefficient of the fluid in the test tube section are shown in Fig. 4.

The CHTC of the fluid in the test tube section increases continuously during the cooling process, and the CHTC of the fluid in the FRP pipe is small. The CHTC of the fluid in the SS pipe approximately increased from 553.25 W/(m^2·°C) to 1345.69 W/(m^2·°C), and the CHTC of the fluid in the glass fiber reinforced plastic pipe nearly increased to 1052.61 W/(m^2·°C). In the two test tubes, the adhesive behavior of sample oil in SS pipe is more significant. The thickness of the condensate adhesive layer in the pipeline is large, which leads to the decrease of the effective flow section in the pipeline, and the convective heat transfer of the fluid in the pipeline is strong. However, the thickness of condensate adhesive layer in FRP pipeline is relatively small, and the increasing of adhesive layer thickness has little effect on the convective heat transfer.

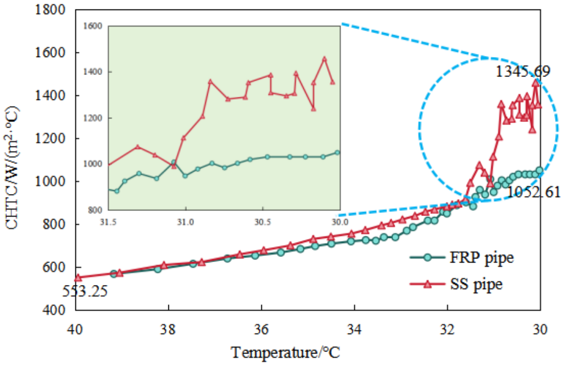

Fig. 4 The CHTC of the test tube section at different temperatures.

4.4 Thermal Conductivity Calculation

The calculation results of total thermal resistance (TTR) between condensate adhesive layer and pipe wall in FRP and SS pipe section are shown in Fig. 5.

As the temperature of oil-water suspension decreases, the TTR of the two materials increases slowly at first and then abruptly. The TTR of SS pipe section increases from 0.05 °C/W to 1.63 °C/W, and the TTR of FRP pipe section increases from 0.51 °C/W to 1.34 °C/W. In the range of 35 °C-40 °C, the adhesive layer of the two pipe test sections is thin, and the thermal conductivity of the FRP pipe is small, the TTR of the FRP pipe section is significantly greater than that of SS, and the thermal insulation effect of the FRP pipe section is better. When the temperature is reduced to 35°C, the condensate oil forms an adhesive layer on the tube wall. Due to the low thermal conductivity of condensate layer, the increase of adhesive layer thickness plays a certain role in the insulation of oil-water suspension in the pipeline, resulting in the gradual increase of the TTR of the pipe section.

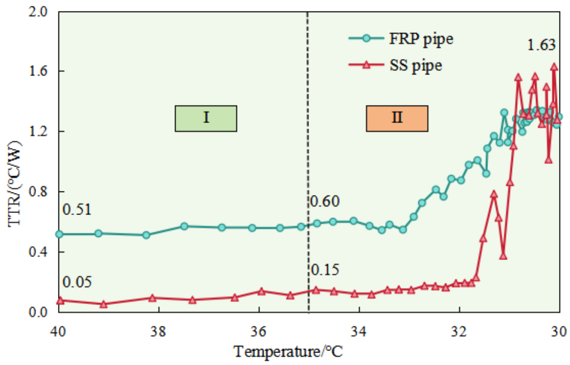

Fig. 5 The TTR between the adhesive layer and the pipe wall in the test pipe section at different temperatures.

4.5 Calculation of total heat transfer

Fig. 6 shows the THTC of the fluid in the FRP pipe section and the SS pipe section. With the decrease of temperature, the THTC of the fluid in the SS pipe is probably reduced from 16.50 W/(m^2·°C) to 0.79 W/(m^2·°C), while the THTC of the fluid in the FRP pipe is approximately reduced from 1.94 W/(m^2·°C) to 0.77 W/(m^2·°C). The phenomenon is due to the increase of the thickness of condensate adhesive layer in the pipeline, and the strengthening of the insulation effect of pipe flow. At the same time, under the same conditions, the heat flow of the FRP test tube section is less than that of the SS test tube section. Therefore, in the case of the same outbound temperature, the FRP pipeline has a better insulation effect, which is conducive to the low-temperature transportation of the gathering pipeline.

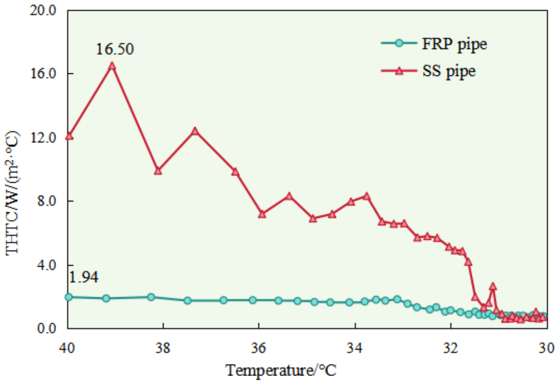

Fig. 6 The THTC of fluid in the test tube section at different temperatures.

5. CONCLUSIONS

In the same cooling time, the pressure drop in the FRP pipe section is much less than that in the SS pipe section, and the FRP pipe is more conducive to safe transportation.

Compared with the SS test pipe section, it takes longer time for the oil-water suspension temperature in the FRP test pipe section to drop from 40 °C to 30 °C. FRP pipeline has better thermal insulation performance in gathering pipeline because of the smaller THTC, which is more conducive to the implementation of LTGT technology of high water cut crude oil.

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