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A NEW TECHNIQUE OF OIL TRANSPORTATION IN PIPELINE BY STEAM INJECTION*

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ABSTRACT: The direct contact heating of crude oil with steam is promising technique for improving crude oil transportation in pipelines. Crude oil temperature is increased greatly by a small quantity of steam due to the high steam latent heat and direct contact heat transfer. A jet pump was developed for injecting steam into oil in order to get a high efficiency by transferring momentum and energy from a high-velocity jet to ambient fluid. The jet pump was designed based on the free injection principle, which has no rotation parts and no converging mixing chamber, therefore it would not be blocked by the viscous crude oil. The technical feasibility of this method has been tested in the Liaohe Oilfeld, China.

KEY WORDS: heavy oil transportation, free injection, jet pump

1. INTRODUCTION

Pipelines are the most economical and feasible means for transportation of large quantities of crude oil (hereinafter, crude oil is called oil for short). Generally, oil viscosity less than 2×10^3 mPa·s is desirable for pipeline transportation. However, heavy oil accounts for a large fraction of potentially recoverable oil reserves in China. The viscosity of these oils at 25 ℃ varies from 10^4 mPa·s to more than 10^6 mPa·s. Conventional pipeines are not suitable for transporting the heavy oil from the reservoir to the refinery because of their high viscosity. Several alternative transportation methods were proposed, including dilution with lighter oil, reducing viscosity with chemicals, or preheating the oil before transporting in pipelines[1,2]. Each of these methods may have logistic, technical, or economic drawbacks for a given application. It is beneficial to dilute the heavy oils with lighter oil is produced in the same oil district. The effect of reducing viscosity by adding some chemicals into oil has some drawbacks, for there are no chemicals into oil has some drawbacks, for there are no chemicals that can matches all kinds of oils, and the refinement quality of oil will be affected.

Oil viscosity exponentially decreases with temperature, so it has a potential to improve heating method, but the efficiency of conventional heating methods by warm water or power is very low. A number of proposed empirical heat transfer correlations for direct condensation of steam jets in subcooled water pools[3,4]. These results show that the direct contact condensation heat transfer is very efficient heat transferring mechanism. Therefore, it is thought to apply this technology for heating oil.

Jet pumps are broadly used nowadays in industrial applications because they are capable of creating homogeneous single or two-phase mixture in the mixing chamber. Therefore, a jet pump is adopted for injecting steam into oil. Its velocity is very high, therefore its momentum and energy are transported instantly to the oil side through the interface between steam and oil. The main components of the conventional jet pump are a nozzle, a mixing chamber and a diffuser. This jet pump is not suitable for heating heavy oil because high viscosity oil may solidify at its throat. The objective of the present investigation is to design a new jet pump that is capable of immediate heating and transporting oil with the prevention of pump blockage. The jet pump is designed based on the free injection principle. The mixing chamber of the pump is not converging but cylindrical, and its diameter is the same as that of pipeline, which makes the blockages of the jet pump highly unlikely. The technical feasibility of this method was tested using a pipeline of 300m in length and 3 inches in diameter at the Liaohe Oilfield, China.

2. DESIGN OF THE JET PUMP

A new jet pump was designed based on parameters of transportation popeline at the Liaohe Oilfield (see Table 1). Schematic diagram of the jet

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pump is shown in Fig. 1. It is composed of three coaxal pipes. The inside diameter of the inner pipe is 3 inches, which is the same as that of the oil transportation pipeline. There are 4 titled holes on the pipe wall, one for each nozzle. The gap between the inner pipe and the middle pipe is used for heating, which is called heating section, while the gap between the middle pipe and the outside pipe is required to maintain temperature, which is called temperature preservation section. They are both connected with the steam pipelines. The steam in the heating section is injected into pipe through the four nozzles due to the pressure at this section being higher than that in inner pipe. The pressure ratio between heating section and pipe is close to the critical ratio, which means jet velocity is sonic at nozzle exit. There is a section of screw on the outside of the middle pipe. The steam in the temperature preservation section flows spirally along the screw, which keeps steam quality in the heating section.

Table 1 **Summary of Test Conditions**

Substance	Parameter
Inside Diameter	80mm
Pipe Length	300m
Pressure	0.16Mpa
Temperature	75 ℃
Flow rate	21.6m^3/d
Water Fraction	19 %

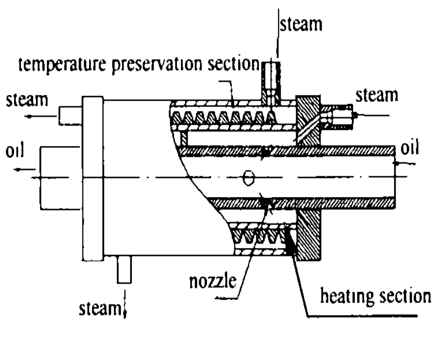


Fig. 1 Schematic diagram of jet pump

The major controlling parameter in the jet pump design is nozzle size because steam mass flow is a function of the steam pressure and the nozzle size. Steam mass flow is calculated based on the oil temperature increment, while steam pressure is decided according to transportation conditions, which is higher than that in oil pipe. With the consideration of above two conditions, small nozzle size is chosen. It is consistent with the results by Simpson and Chan[9]. Their experimental data clearly showed that the average heat transfer coefficient increases significantly as the nozzle diameter is reduced. In other words, the direct condensation heat transfer occurs more efficiently when the steam is injected through smaller diameter nozzles. Therefore, the small size of nozzles is a perfecting choice for obtaining high heat transfer coefficients.

The jet pump is made of alloy steel. Its surface was processed by nichrome for enduring high pressure and temperature. For operation safety, the jet pump was tested for having no leak by gas and ensuring its endurance of high pressure by water, whose pressures are 1.5 times larger than that of operation. The photograph of the jet pump is shown in Fig. 2.

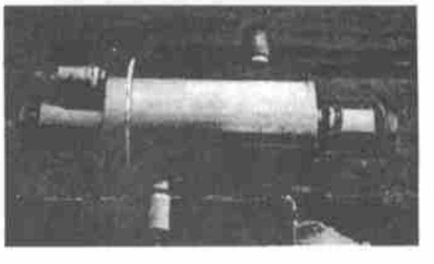


Fig. 2 Photograph of jet pump

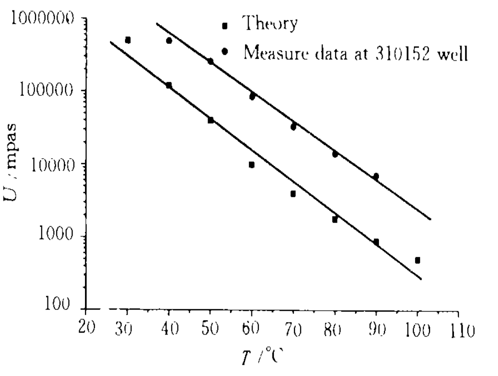


Fig. 3 Relationship between oil viscosity and temperature

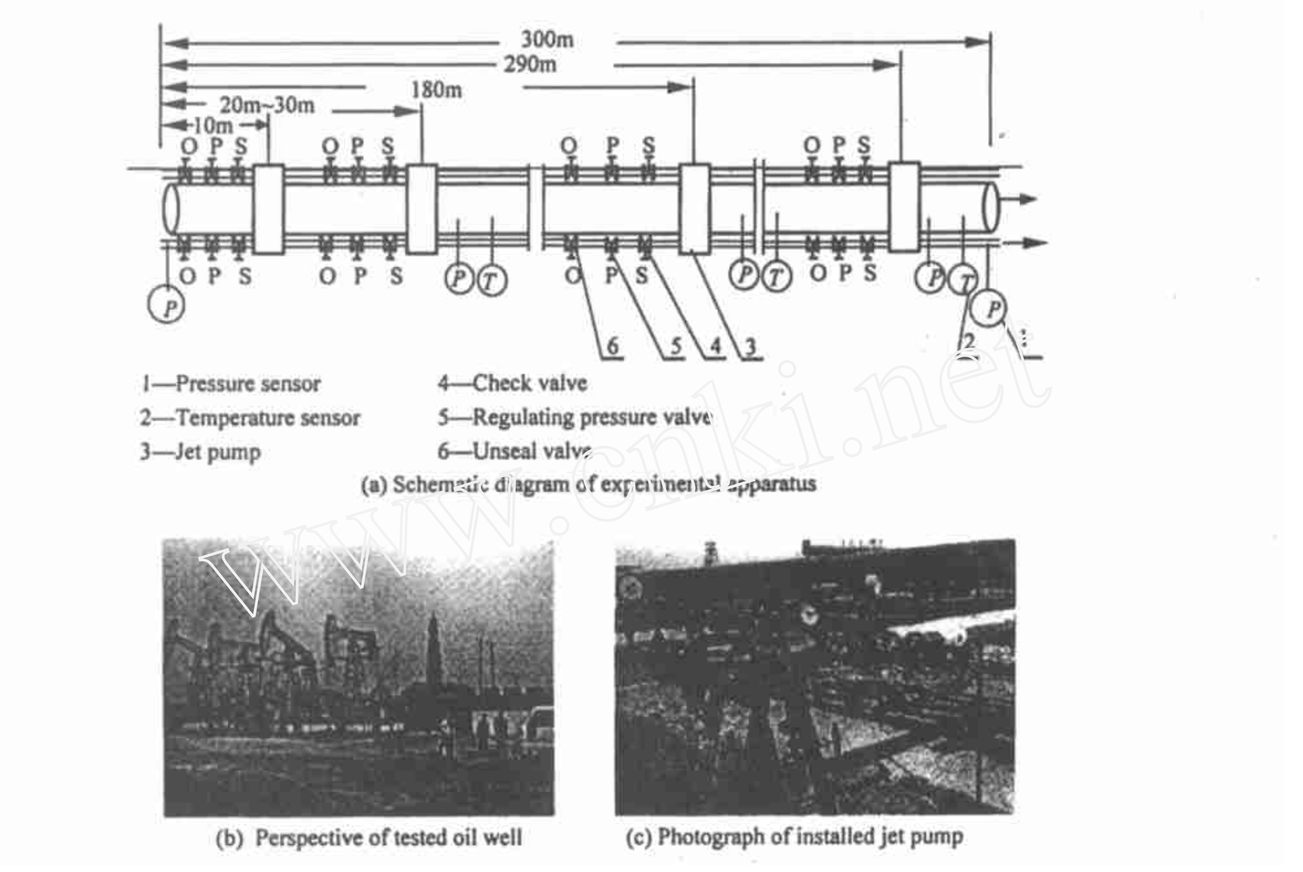


Fig. 4 Schematic diagram and photograph of the experimental apparatus

3. EXPERIMENTS

Table 1 is a summary of the test conditions of oil well 310152 at the Liaohe oilfield, China. The oil viscosity as a function of temperature is illustrated in Fig. 3.

A schematic diagram and photographs used for the oil pipeline transportation experiment are shown in Fig. 4. Four jet pumps were installed in a 300m oil pipeline with a distance of 5m, 15m, 180m and 290m from the start of the pipeline. The roles of these four jet pumps are as follows. The temperature of heavy crude oil increased to an appointed value after passing through the first two jet pumps. The third jet pump offsetted the heat loss caused by the heat conduction effects on the pipe wall. The last jet pump was used to clear oil remnants in the pipeline after transportation was stopped. The oil temperature transportation was stopped, The oil temperature was measured by the use of a Centigrade thermometer protruding through sealed penetration on the walls. The pressures were measured by pressure-meters mounted on both sides of the jet pumps.

Steam was supplied by a steam pipeline the pressure of which was controlled by three gate valves. Two checking valves were installed at steam inlets of the jet pumps to prevent oil back flowing through the nozzle to the steam pipeline.

3.1 *Risetime of crude oil temperature*

Risetime of oil temperature is a key criterion in heating transportation because it is not cost-efficient if the risetime is too long. A number of experimental studies were performed in order to establish the empirical correlations of the heat transfer coefficients for various steam mass fluxes and pool temperatures. The heat transfer areas were obtained with the assumption of a smooth interface between steam and water in the calculation of heat transfer coefficients since it is extremely difficult to estimate the exact surface area contributed to the heat transfer. As the indicated relationship by several researchers [3~7] the average heat transfer coefficient was defined by

$$Q = GA_e(h_s - h_f) = hA(T_s - T_f) \tag{1}$$

where G, A_e, h_s, and h_f are the steam mass flow, nozzle exit area, steam enthalpy and water enthalpy, respectively and h, A, T_s and T_f, are the average heat transfer coefficient, jet surface area, steam temperature and water temperature, respectively. The average heat transfer coefficient in the experiment is in the range of 1. 24-2. 05 $MWm^{-2}C^{-1}$, which is head and shoulders above that by warm water or power.

Although the difference between crude oil and water may cause some errors, it is believed that the order of the magnitude in the heat transfer coefficient does not change significantly.

Fig. 5 given a correlation between the oil temperature and pipeline length. It is clear from these results that the heating effect of the jet pump is very high because oil temperature increases quickly from 75 °C to 103 °C (case 1) affter oil passes through the first two jet pumps at a distance of 15m from the pipeline inlet. Transportation is nearly isothermal because the heat insulation material of oil pipe is very good. oil temperature drops no more than 2 °C when it flows through 180m pipeline.

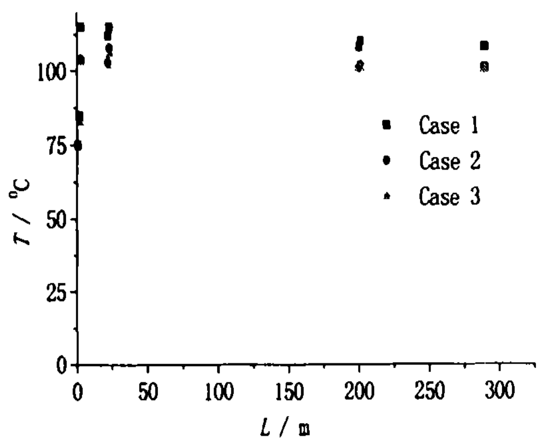
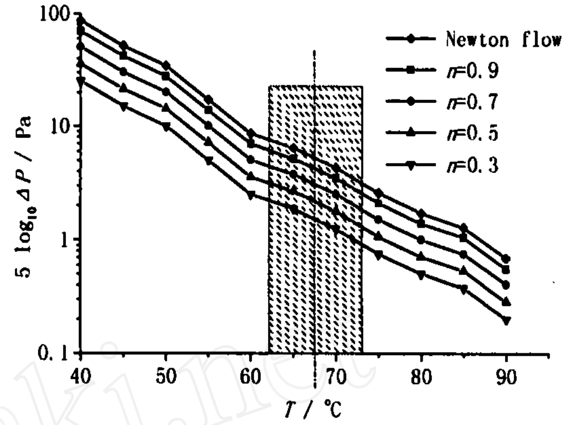


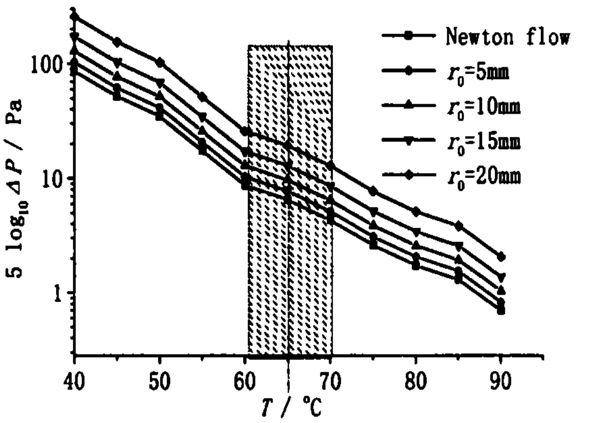
Fig. 5 Results of temperature

3. 2 *Pressure drop*

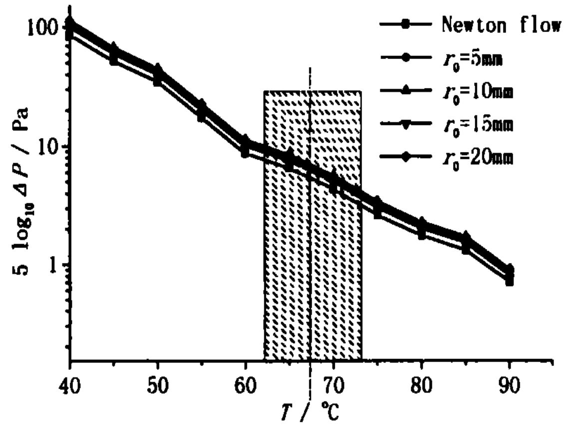
Predicating oil pipe pressure drop is very important in designing pipelins, but it can not be calculated based on Newtonian fluid pressure drop equation due to high oil viscosity. In despite the lots of models were developed for calculating pressure drop of oil, there are no models that can fit all kinds of oils under different conditions. Fig. 6 shows the comparisons of the predicted pressure drop data between Newtonian flow model and three oil models (i. e., the exponential model, Bingham model and Karson model)[8]. It is clear from these results that the differences of predicated data by different models are very large, so it is an open problem to calculate pressure drop of oil pipeline.



6(a) Predicted pressure drop by expontial model



6(b) Predicted pressure drop by Bingham model



6(c) Predicted pressure drop by Karson model

Fig. 6 Predicted pressure drop by three non-Newtonian flow model

When oil is heated, the viscosity decreases from 3×10^4 mPa·s at 75 ℃ to 10^3 mPa·s at 100 ℃. The oil pressure drop can be predicated approximatively by Newton pressure drop equation as given below.

$$Q = \frac{\pi R^4 \Delta P}{8 \mu L} \quad (2)$$

where Q ——flow rate, m^3/s

R ——radius of pipe, m

ΔP ——pressure drop, Pa

μ ——Oil viscosity, PaS

L ——length of pipeline, m

In contrast, Fig. 7 gives three curves of the pressure drops from measured data at different oil temperatures and calculated values by Newtonian model. As expected, measurement data are close to the calculated data. So the pressure drop calculation is also simplified by heating transportation method. The error between the measurement data and calculated values is mainly due to the assumption of the fluid model to be a single-phase fluid, instead of two-phase flow. On the other hand, part of pipeline pressure drop is offset due to transformation of the kinetic energy between steam and oil.

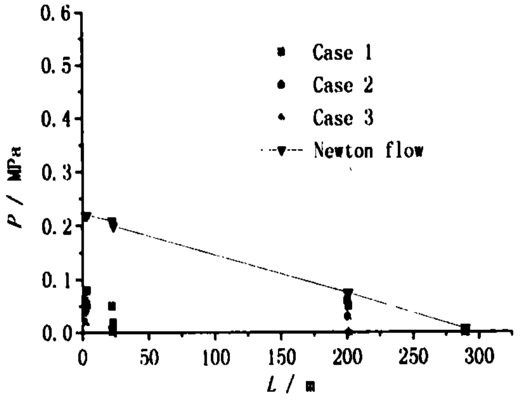


Fig. 7 Results of pressure

3.3 *Water fraction*

From the economic viewpoint, it is more profitable and cost-effective to increase oil temperature using a minimum amount of steam. Simpson and Chan[9] experimentally examined the heat transfer of steam jet condensation at an intermediate steam flow rate (subsonic jets). They observed that the dynamics of subsonic jets were quite different from those of sonic jets and found that the average heat transfer for subsonic jets was about one-fifth to one-tenth of the sonic jet values.

With these results, the sonic steam jet is the preferred choice, which can be obtained at the nozzle exit by adjusting the steam pressure. The relation between nozzle pressure and jet velocity is given as

$$m = A_2 \sqrt{\frac{2k}{k-1} p_0 \rho_0 \left[\left(\frac{p_2}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_0}\right)^{\frac{k+1}{k}} \right]} \quad (3)$$

m ——steam mass flow rate, kg/s

A_2 ——nozzle exit area, m^2

p_0 ——nozzle pressure, Pa

p_2 ——back pressure of nozzle, Pa

ρ_0 ——steam density, kg/m^3

k ——coefficient, 1.13

Water fraction in crude oil can be calculated not only from Eq. (3) (Method 1), but also from the heat equilibrium equation that gives the latent heat of condensed steam to be equal to the absorption heat needed for increasing oil temperature (Method 2). In fact, measured data is larger than calculated data by Method 2, while close to the calculated data by Method 1. So Method 2 overestimates the heat exchange ratio. It should be noted that measurement data also has errors, which are caused by the incomplete separation of the water in oil specimen. Whatever the differences might be, water content in crude oil was found to increase less than 8 % when a temperature increases about 30 ℃.

3.4 *Restart-up after emergent shutdown*

For efficient operation of a pipeline system, it is desirable to maintain a steady and continuous steam flow rate without any interruption. However, transportation shutdown may occur regularly for operational reasons and occasionally for emergency reasons. When the steam pipeline is shut down, oil may flow through the nozzle to the heating section of the jet pump due to pressure at inner pipe being higher than that at the heating section. Checking valves prevent crude oil from its flowing to the steam pipeline. In winter, or in subsea areas, the warm crude oil may be cooled below its freezing point, forming a gel. To restart the pipeline, a steam pressure higher than the usual operating pressure is required to overcome the gel strength of the solidified oil. The first step requires opening the valves to connect the steam to the keeping temperature section of jet pumps. The high temperature steam will melt the solidified oil in the heating section. The second step is opening the valves connected with the heating section of jet pumps, then oil flows with steam jet through nozzles to the oil pipeline. The pipeline can be restarted after the steam clears the gelled oil in the jet pump and pipeline.

4. CONCLUSION

(1) Crude oil temperature is increased greatly by a small quantity of steam due to the high steam latent heat and direct contact heat transfer coefficient.

(2) A jet pump has been designed based on the free injection principle, provided with no rotation parts and no converging mixing chamber, so that it may hardly be blocked by crude oil.

(3) The oil transportation temperature could be altered in a certain range by adjusting the steam pressure and flow rate.

(4) Since oil obtains energy from high velocity of steam jet in heatig, a part of pipeline pressure drops could be offset and the pipeline transortation ability has been enhanced.

(5) The jet pump not only could heat crude oil by injecting steam, but also could be used for clearing off oil remnants in pipeline.

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