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ARTICLE

Enhancing Heavy Crude Oil Flow in Pipelines through Heating-Induced Viscosity Reduction in the Petroleum Industry

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ABSTRACT

The process of transporting crude oil across pipelines is one of the most critical aspects of the midstream petroleum industry. In the present experimental work, the effect of temperature, pressure drop, and pipe diameter on the flow rate of heavy crude oil have been assessed. Moreover, the total discharge and energy losses have been evaluated in order to demonstrate the improvements potentially achievable by using solar heating method replacing pipe, and adjusting the value of the initial pressure difference. Crude oil of API = 20 has been used for the experiments, with the studied pipelines sections connecting the separator unit to the storage tank operating at a temperature of 25°C–100°C, pressure drop of 3, 4, 5, and 6 kg/cm^2, and with pipe diameter of 4, 6, and 8 in. The results show that on increasing the temperature and/or the pressure drop, the flow rate through the pipeline becomes higher, thus raising the total pumping energy (as the pipe diameter increase), while energy losses increase from the last separator to the storage tank in the field. A pipe diameter increase can also produce a growth of the total pumping energy (i.e., energy losses increase). The results of the present analysis suggest that employing an optimal temperature (50°C) is needed to ensure good performance.

KEYWORDS

Petroleum industry; heavy crude oil; horizontal flow; viscosity reduction

Nomenclature

API	American Petroleum Institute (-)
D	Pipe diameter (m)
dp	Pressure deference (kg/cm^2)
f	Friction factor of pipe (-)
g	Gravitational acceleration (m/s^2)
HC	Hydrocarbon (-)
hf	Head of loss (m)
L	Length of pipe (m)
P	Pressure (Pa)
Q	Flow rate (bbl/day)
Re	Reynolds number (-)
Sp.gr	Specific gravity (-)

V	Fluid velocity (m^2/s)
ε/D	Relative roughness (-)
μ	Dynamic viscosity (Cp)
ν	Kinematic viscosity (cSt)

1 Introduction

In the last few decades, the continuous growth in world energy needs driven by economic growth and the enormous population expansion have caused a decrease in the availability of petroleum resources with characteristics that are amenable to refining and effective production [1,2]. Heavy crude oil transportation through pipelines is a problem because of the oil's inability to flow freely [3,4]. Heavy oil transportation through pipelines is much more complicated without reducing the viscosity because a massive energy demand is needed to offset the higher drop in pressure through the pipeline due to high viscosity [5]. Heavy crude oil contains a higher molecular weight of hydrocarbon (HC), with much more than 50 atoms of carbon, which makes the process of refining complicated and expensive [6–8].

Lowering the consumption of power is one of the keys to remedying the existing concern. Transportation fluids in pipelines and other similar transportation channels tend to consume much power because in a moving fluid, energy is squandered due to fundamental drag friction. About 70% of the total worldwide resources of petroleum have an API grade lower than 20 for heavy oil. Heavy crude oil transportation using pipelines may cause many drops in pressure because of higher viscosity values, which raises the energy needed to pump and also impedes the capability to flow through pipelines [9–11].

From an engineering point of view, numerical models have been widely applied to predict the flow behavior of heavy crude oil [12–15]. Newly proposed technologies in heavy crude oil transport must decrease the impedance to lower the values of the pump requests, and this process should be made more economical [16,17]. Crude oil liquid or product pipelines are handled similarly, with stations of pumps and stations of block valves along the length of the pipelines. Models of the entire pipeline can help to calculate the flow, temperature, and pressure at the main checkpoints. Then, an administrative system can be implemented based on these models [18,19].

To reduce transportation costs and the higher pressure drop, various technologies have been suggested to improve the flow of heavy crude oil and extra heavy oil through pipelines, thus meeting the projected volume production. These technologies include reducing viscosity emulsification during the formation of an oil-in-water emulsion and reducing the oil's pour point by using pour point depressants (PPDs), blending and dilution with light oils or organic solvents, preheating the heavy crude oil, and adding bitumen and later heating the pipeline [20–22]. Crude oil preheating is the most attractive method due to a rapid reduction in the oil viscosity [23,24]. Therefore, the objective of this work is to investigate the influence of the temperature, pressure drop, and pipe diameter of heavy crude oil flow rate to estimate the improvement in the total discharge and energy (pump and energy loss) of crude oil in horizontal pipelines in order to demonstrate the feasibility of using solar heating methods, replacing pipes, and adjusting the value of the initial pressure difference, employed in the petroleum industry.

2 Materials and Methods

2.1 Properties of Heavy Crude Oil

Crude oil is classified as light, medium, heavy, and extra heavy according to its measured API gravity, whereas oil viscosity is a measure of the resistance to the flow of the fluid. This study used Iraqi heavy crude oil from the East Baghdad Oil Field. Heavy oil characteristics (i.e., relative density, API grade, water content, sulfur content, sediment content, viscosity, and density) were evaluated in the Department of Petroleum Technology Laboratory at the University of Technology-Iraq, with the data listed in Table 1.

Table 1: Physical properties of Iraqi heavy crude oil

Location	API	Viscosity	Sp.gr	Density	Sulfur (%)	Sediment	Shear stress	Shear rate	Water content
East baghdad oil field	20	4.18 cp (28.9°C)	0.935	0.935 g/cm^3	0.72%	2%	3.79 D/cm	122.3 1/s	2.1%

2.2 Measuring the Heavy Crude Oil Viscosity

All the experiments were tested in the Petroleum Researcher Unit of the Petroleum Technology Department at the University of Technology-Iraq. We studied the effect of temperature variations on the viscosity of Iraqi heavy crude oil at various temperatures (i.e., 25°C, 40°C, 55°C, 70°C, and 100°C) and pressure drop (dp) values (i.e., 3, 4, 5, and 6 kg/cm^2) for three pipe diameters (i.e., 4, 6 and 8 in.).

2.3 Experiment Procedure

The liquid flow rate is generally studied through viscosity measurements using a computerized viscometer (HB-Brookfield Viscometer, Model DV-11+ Pro, USA). The procedure for testing the viscosity of heavy crude oils entailed placing it in a 250-ml container (cylindrical glass) with the temperature controlled using a magnetic stirrer with a thermometer until the computerized viscometer was read for each temperature and pipe diameter, as shown in Fig. 1.

Figure 1: Computerized viscosity measuring device

3 Programming Method (Fortran 90)

Fortran 90 is a newer software program that can identify the characteristics significant to oil flow through a pipeline. The East Baghdad Oil Field was used as a case study for pipelines starting from the last separator to the storage tank in the field by evaluating the total length and pressure drop from the pumps to storage and the pipe diameter for horizontal flow.

3.1 Estimation of Pipe Flow

In modeling pipe flow problems, the known properties of the crude oil that flows through the pipeline and the equations governing the flow were used to determine the crude oil flow characteristics [25]. Kinematic viscosity measurements based on Eq. (1) were calculated, which depend on the dynamic viscosity and density. Additionally, the Reynolds number can be estimated using Eq. (2). The volumetric flow rate (synonymous with the flow rate of the mass) can be estimated using Eq. (3):

$$\mathrm{v}p = \mu \tag{1}$$

$$R_e = \frac{pud}{\mu} = \mathrm{ud/v} \tag{2}$$

where

$$Q = \frac{u\pi D^2}{4} \tag{3}$$

The velocity of crude oil can be calculated with Eq. (4), using the value as the average velocity along the pipe since all parameters exist.

$$v = \sqrt{(H_1 - H_2)\frac{2g.D}{f.L}} = \sqrt{h_f\frac{2g.D}{f.L}} \tag{4}$$

The friction factor in the above equation can be calculated by the iteration method, as shown in Table 2, using the following procedure:

1. Calculate the relative roughness (ε/D).
2. Choose f and suppose that the flow is turbulent with perfect roughness: f(i) = f(0).
3. Calculate the velocity using Eq. (4).
4. Calculate the Reynolds number from Eq. (2).
5. Calculate f from Steps 1 and 4 [f(i + 1)] using Eq. (5) or a Moody chart.
6. Check to see if f(i + 1) = f(i).
7. If no, return to Step 3.
8. If yes, continue.
9. Calculate V.

Table 2: Iteration table

$f^{(i)}$	v	R_e	$f^{(i+1)}$
$f^{(0)}$ assumed	Calculated	Calculated	$f^{(1)}$ determined
$f^{(1)}$	Calculated	Calculated	$f^{(2)}$ determined
$f^{(2)}$	Calculated	Calculated	$f^{(3)}$ determined
Iteration is	Stopped	When	$f^{(2)} = f^{(i+1)}$
$f^{(i)}$			$f^{(i+1)}$

The friction factor can be obtained from a Moody chart or be determined using Eq. (5).

$$\mathrm{F} = \frac{1.325}{\left(\ln\left(\frac{\epsilon}{3.7 * D}\right) + \left(\frac{5.74}{Re^{0.9}}\right)\right) \wedge 2} \tag{5}$$

3.2 Head Loss Determination and Power

Head losses encompass all he numerous losses incurred by flowing liquids, including inlet and outlet losses, friction, etc. The main losses result from the frictional resistance of the pipes, which depends on their internal coarseness. Darcy's law, Eq. (6) is the general form for estimating the head loss based on the friction and power use calculated according to Eq. (7) [26].

$$hf = f\,\frac{L.V^2}{D.2g} \tag{6}$$

$$\text{Power} = \Delta \text{p} * \text{Q} \tag{7}$$

$$\Delta \text{p} = \rho * \text{g} * \text{h} \tag{8}$$

4 Results and Discussion

4.1 Effect of Temperature on the Viscosity of Crude Oil

The effect of temperatures ranging from 25°C–100°C on the viscosity of crude oil in the East Baghdad Oil Field is shown in Fig. 2. Increasing the temperature caused the value of the kinematic viscosity for the crude oil to decrease rapidly [27]. The kinematic viscosity results indicated the importance of the heating process as an efficient method for improving the flow properties of heavy crude oils [28]. Moreover, solar heating methods can be applied successfully to provide the required energy. Such type of energy is considered one of the renewable energy sources with relatively low costs.

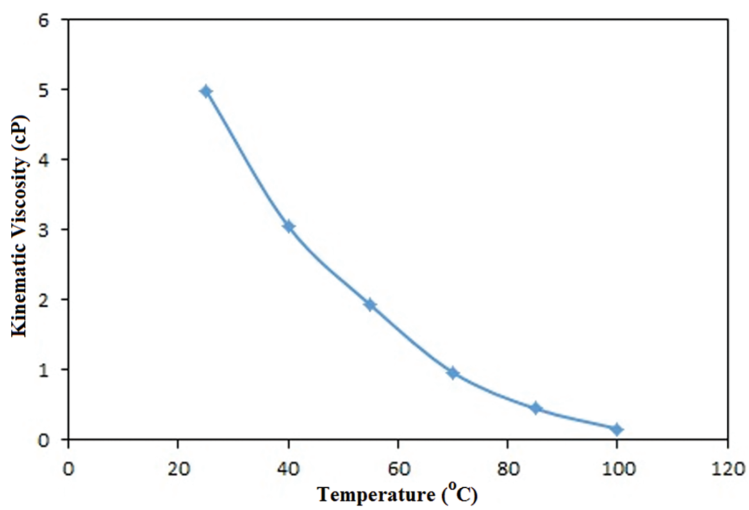

Figure 2: Effect of the temperature on the kinematic viscosity for the heavy oil

The results showed that a temperature of 50°C can be employed because the viscosity decreased to 53.9%. In comparison with other research, there is research using the dilution method (adding 20 wt. % of acetone) and the percentage of viscosity decrease was about 21.98%, as well as the use of changing the electric current, the percentage of viscosity decrease was 35.61%, and the two methods were also used together in combination (Dilution and Electrical Field), achieving an optimum viscosity reduction of about 61.856% [6].

4.2 Effect of Temperature on the Flow Rate and Reynolds No.

The effect of the kinematic viscosity of heavy crude oil on the flow rate for three pipe diameters (i.e., 4, 6, and 8 in.) and the effect of a constant pressure drop are presented in Table 3 and Fig. 3. When the temperature increased (and the viscosity decreased), the flow rate of the crude oil increased and reached 21.60837, 62.69048, and 133.261 L/s for the three pipe diameters (i.e., 4, 6, and 8 in.), respectively. This occurred because high viscosity heavy crude oils cannot be produced, transported, and pumped with conventional pipelines. Instead, heavy crude oils require additional treatments that reduce the viscosity of the crude oil because a more viscous fluid has a lower tendency to flow [28].

Table 3: Effect of temperature for pipe diameters of 4, 6, and 8 in.

D = 4 in.									
Temperature (°C)	Viscosity (cP)	Kinematic viscosity (cSt)	Velocity (m/s)	Re	Flow rate Q (m^3/s)	Flow rate Q (bbl/day)	Pump power (watt)	dp (Pa)	Power loss (w)
25	4.66	4.989293362	2.46851	50052.89	0.02000283	10870.33093	7849.111	392400.0254	7849.111
40	2.85	3.051391863	2.53302	84340.11	0.02052558	11154.41401	8054.239	382406.295	7649.208109
55	1.8	1.927194861	2.5772	135867.5	0.02088357	11348.95997	8194.713	375851.0159	7518.083976
70	0.9	0.96359743	2.62144	276400.3	0.0212421	11543.79939	8335.401	369507.2992	7391.191689
85	0.42	0.449678801	2.64896	598504.1	0.0214651	11664.98643	8422.906	365668.5038	7314.404917
100	0.15	0.160599572	2.66664	1686996	0.02160837	11742.84503	8479.123	363244.0115	7265.90821
D = 6 in.									
Temperature (°C)	Viscosity (cP)	Kinematic viscosity (cSt)	Velocity (m/s)	Re	Flow rate Q (m^3/s)	Flow rate Q (bbl/day)	Pump power (watt)	dp (Pa)	Power loss (w)
25	4.66	4.989293362	3.23003	98241.08	0.0588907	32003.5414	23108.71	392399.9885	23108.71
40	2.85	3.051391863	3.29917	164775.3	0.06015125	32688.57425	23603.35	384176.7212	22624.43603
55	1.8	1.927194861	3.34584	264584.9	0.06100217	33150.99791	23937.26	378817.8355	22308.8475
70	0.9	0.96359743	3.39198	536466.4	0.06184332	33608.11218	24267.32	373665.4177	22005.41801
85	0.42	0.449678801	3.42034	1159184	0.06236047	33889.15199	24470.25	370566.6426	21822.92898
100	0.15	0.160599572	3.43844	3262891	0.06269048	34068.49251	24599.75	368615.9366	21708.05054
D = 8 in.									
Temperature (°C)	Viscosity (cP)	Kinematic viscosity (cSt)	Velocity (m/s)	Re	Flow rate Q (m^3/s)	Flow rate Q (bbl/day)	Pump power (watt)	dp (Pa)	Power loss (w)
25	4.66	4.989293362	3.89559	157978.4	0.1262671	68618.54863	49547.2	392399.9205	49547.2
40	2.85	3.051391863	3.96805	264242.9	0.1286159	69894.97968	50468.88	385233.863	48642.3627
55	1.8	1.927194861	4.01649	423491.8	0.1301859	70748.17993	51084.96	380588.0668	48055.75148
70	0.9	0.96359743	4.06397	856996	0.1317249	71584.53355	51688.84	376141.4888	47494.29498
85	0.42	0.449678801	4.09276	1849429	0.132658	72091.61709	52055	373495.756	47160.22597
100	0.15	0.160599572	4.11137	5201941	0.133261	72419.3112	52291.63	371805.7046	46946.82808

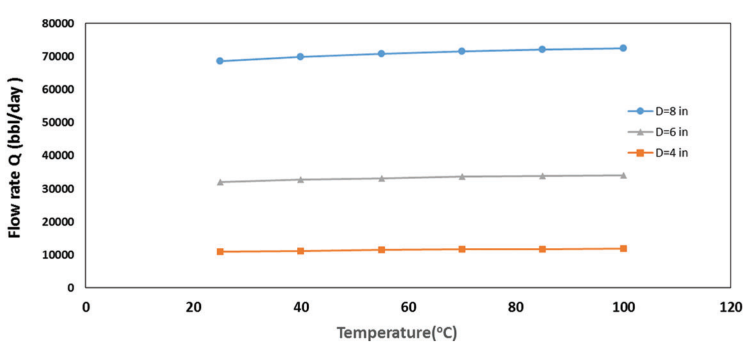

Figure 3: Effect of the temperature of the crude oil on the flow rate for pipe diameters of 4, 6, and 8 in.

Moreover, the results in Fig. 4 and Table 3 show that the Reynolds number (Re) is integrally related to the temperature of the crude oil. As the viscous forces are proportional to the viscosity of the fluid, the Reynolds number is inversely proportional to the viscosity. Therefore, the Reynolds number increased as the viscosity of the heavy crude oil decreased. The flow arrangement with minimum resistance to crude oil flow makes the transport of crude oil more rapid. Additionally, it can be concluded that when the pipe diameter increased from 4 to 6 to 8 in., the flow rate and Reynolds number of the crude oil increased in direct proportion, as shown in Eq. (2) [6,25].

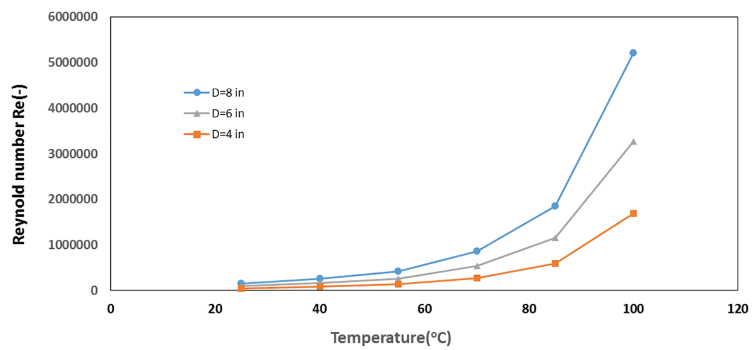

Figure 4: Effect of the temperature of the crude oil on the Reynolds number for pipe diameters of 4, 6, and 8 in.

4.3 Effect of the Temperature on the Power Losses and Pressure Losses

Power consumption is a major problem for energy in pipeline conveyances [29]. The relationship between the pumping power (w), power losses, and pressure losses with temperature for three (i.e., 4, 6, and 8 in.) pipe diameters of heavy crude oil are illustrated in Table 4 and Figs. 5 and 6. Fig. 5 shows that the pumping power rose with increasing temperature because the flow rate of the crude oil increased. This also occurs in Eq. (7) for the constant pressure drop because the kinematic viscosity decreases as the temperature rises. While the amount of energy (power losses) displayed in Fig. 6 demonstrates an increase in power losses with increasing viscosity and pipe diameter because of increasing friction loss between the crude oil and the pipe. Since heavy oil becomes more viscous, the pressure head suffers, and the pump consumes more power [30,31].

Fig. 7 presents the relationship between the pressure losses and the temperature for various pipe diameters (i.e., 4, 6, and 8 in.) transporting heavy crude oil. The pressure losses increased with decreasing temperature because the kinematic viscosity increased. There is an inverse relationship between the crude oil viscosity and the pressure drop because a higher viscosity causes power to disperse as the fluid flows. Also, Fig. 7 illustrates that the pressure losses rose as the pipe diameter increased from 4 to 6 to 8 in. Eq. (6) shows the effect of increasing the velocity more than decreasing the friction factor, which is inversely affected by increasing the diameter.

Table 4: Result of changing the pressure difference for a pipe diameter of 4 in.

Temperature (°C)	Viscosity (cP)	Kinematic viscosity (cSt)	Velocity (m/s)	Re	Flow rate Q (m^3/s)	Flow rate Q (bbl/day)	Pump power (watt)	dp (Pa)	Power loss (w)
dp = 3 kg/cm^2									
25	4.66	4.989293362	2.11821	42904.21	0.0171643	9327.761184	5051.453	294299.9715	5051.453
40	2.85	3.051391863	2.17922	72559.9	0.01765867	9596.421444	5196.946	286060.7849	4910.03313
55	1.8	1.927194861	2.22121	117100.3	0.01799895	9781.343088	5297.089	280652.6492	4817.206266
70	0.9	0.96359743	2.26385	238696.8	0.01834449	9969.123225	5398.784	275366.2271	4726.468532
85	0.42	0.449678801	2.29064	517544.2	0.01856151	10087.0605	5462.651	272146.6626	4671.206961
100	0.15	0.160599572	2.30795	1460074	0.01870177	10163.28334	5503.93	270105.6103	4636.173727
dp = 4 kg/cm^2									
25	4.66	4.989293362	2.46851	50052.89	0.02000283	10870.33093	7849.111	392400.0254	7849.111
40	2.85	3.051391863	2.53302	84340.11	0.02052558	11154.41401	8054.239	382406.295	7649.208109
55	1.8	1.927194861	2.5772	135867.5	0.02088357	11348.95997	8194.713	375851.0159	7518.083976
70	0.9	0.96359743	2.62144	276400.3	0.0212421	11543.79939	8335.401	369507.2992	7391.191689
85	0.42	0.449678801	2.64896	598504.1	0.0214651	11664.98643	8422.906	365668.5038	7314.404917
100	0.15	0.160599572	2.66664	1686996	0.02160837	11742.84503	8479.123	363244.0115	7265.90821
dp = 5 kg/cm^2									
25	4.66	4.989293362	2.77784	56265.07	0.02250945	12232.52763	11040.89	490500.2121	11040.89
40	2.85	3.051391863	2.84544	94742.41	0.02305716	12530.17496	11309.54	478848.6527	10778.6198
55	1.8	1.927194861	2.89118	152420.5	0.02342784	12731.61717	11491.36	471272.2129	10608.07831
70	0.9	0.96359743	2.93664	309633.9	0.02379619	12931.79316	11672.03	463977.2165	10443.87196
85	0.42	0.449678801	2.96472	669845.3	0.02402372	13055.44199	11783.64	459582.8623	10344.95746
100	0.15	0.160599572	2.98268	1886931	0.02416929	13134.5505	11855.04	456814.8258	10282.65048
dp = 6 kg/cm^2									
25	4.66	4.989293362	3.0583	61945.76	0.02478208	13467.56488	14586.73	588599.9077	14586.73
40	2.85	3.051391863	3.12826	104159.5	0.02534896	13775.62995	14920.39	575437.0199	14260.52626
55	1.8	1.927194861	3.17526	167397.1	0.02572984	13982.61524	15144.58	566918.7993	14049.42704
70	0.9	0.96359743	3.22169	339689.5	0.02610605	14187.06267	15366.02	558749.0256	13846.96305
85	0.42	0.449678801	3.25022	734351.4	0.02633721	14312.68418	15502.08	553844.9213	13725.42915
100	0.15	0.160599572	3.26841	2067694	0.02648463	14392.79806	15588.86	550762.0835	13649.03001

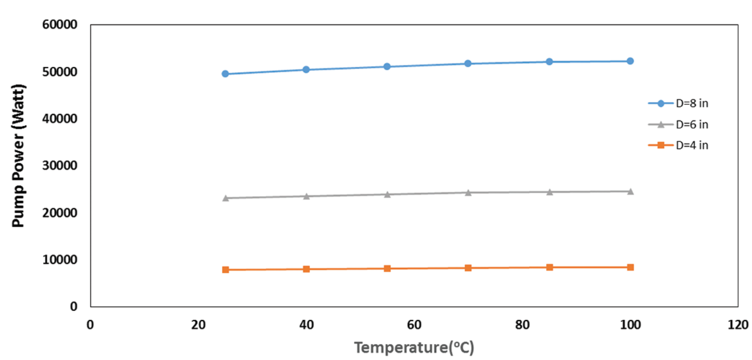

Figure 5: Effect of the temperature of the crude oil on the pump power for pipe diameters of 4, 6, and 8 in.

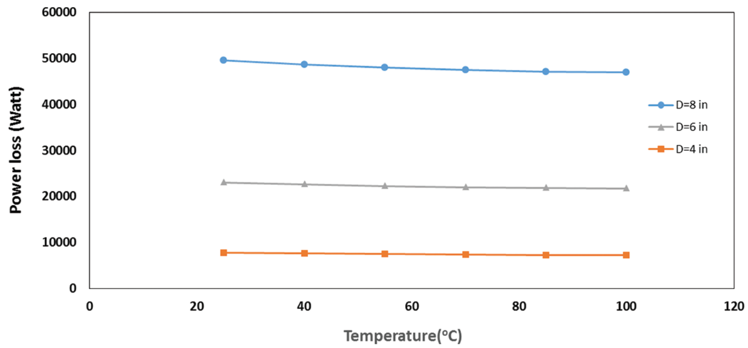

Figure 6: Effect of the temperature of the crude oil on the power losses for pipe diameters of 4, 6, and 8 in.

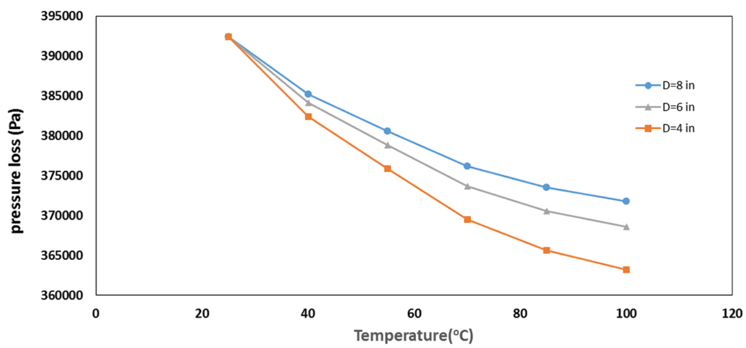

Figure 7: Effect of the temperature for crude oil on the pressure losses in the pipe diameter (4, 6, and 8 in.)

4.4 Effect of the Pressure Drop on the Flow Rate and Reynolds No. of Heavy Crude Oil

Table 4 and Figs. 8–11 illustrate the effect of the pressure drop on the flow rate, Reynolds number, pump power, power losses, and difference in pressure in relation to heavy crude oil in a 4-in. diameter pipe. The flow rate and Reynolds number rose as the pressure drop increased, as shown in Figs. 8 and 9. When the pressure drop increased (meaning there was an increase in the differential pressure), there was more flow, reaching 14392.7980 bbl/day at a pressure drop of 6 kg/cm^2, while for 10163.2833 bbl/day, it was 3 kg/cm^2. The flow rate is directly proportional to the pressure differential. Higher pressure differences will drive greater flow rates [32].

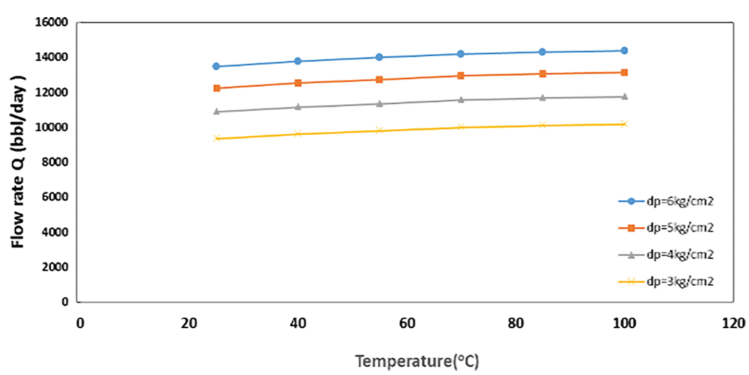

Figure 8: Effect of the pressure difference of the crude oil on the flow rate for a pipe diameter of 4 in.

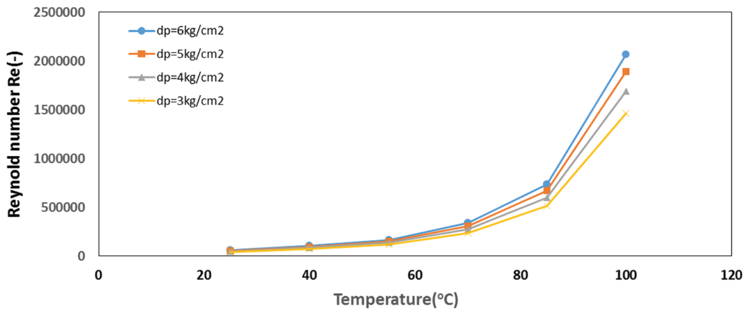

Figure 9: Effect of the pressure difference of the crude oil on the Reynolds number for a pipe diameter of 4 in.

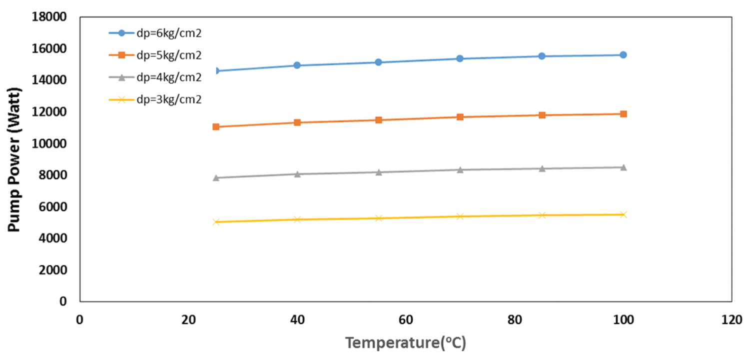

Figure 10: Effect of the pressure difference of the crude oil on the power pump for a pipe diameter of 4 in.

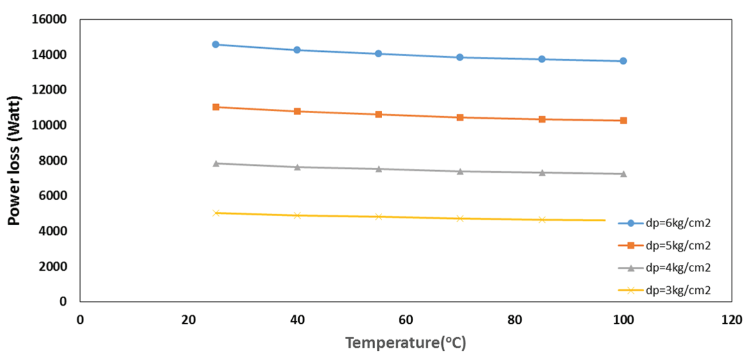

Figure 11: Effect of the pressure difference of the crude oil on the power loss for a pipe diameter of 4 in.

Results related to the pump power and power losses with pressure drop are described in Figs. 9 and 10. When the pressure drop in the line is high, the rate of energy consumption to maintain the desirable flow process must also be large, which requires a higher motor horsepower. Inversely, by lowering the drop in pressure at the pipeline, less energy is consumed, which provides the potential to using a lower value motor horsepower [33].

5 Conclusions

The heating method was successfully applied to reduce the viscosity of heavy crude oil to enhance their flow rate and consumed pumping energy through horizontal pipelines in the petroleum industry. This was achieved using a heating method to demonstrate the feasibility of using solar heating methods, replacing pipes, and adjusting the value of the initial pressure difference. It was found that the operating temperature plays a major role in determining the viscosity of heavy crude oil. The effect of temperature (25°C–100°C) on the viscosity of heavy crude oil indicated a clear reduction in viscosity in the range of 4.9892 to 0.16059 cSt. The results showed that a temperature of 50°C can be employed because the viscosity decreased to 53.9%, the flow rate increased to 3.8%, the power losses decreased to 3.7%, and the pressure drop decreased to 3.7%. Additionally, this temperature retained the light components in heavy crude oil. Also, when increasing the pressure drop from 4 to 6 kg/cm^2 for a pipe diameter of 4 in. and reaching a temperature of 50°C, the results show that the viscosity decreased by 53.9% and enhanced the flow rate by 3.31%, the Reynolds number was 136.2%, and the power losses decreased to 3.2%. Therefore, the effect of temperature decreases when the pressure drop increases. Also, when increasing the pipe diameter from 4 to 8 in. for a pressure drop of 4 kg/cm^2 and a temperature of 50°C, the viscosity decreased by 53.9% and enhanced the flow rate by 2.69%, and the Reynolds number by 134.5%, while the power losses decreased by 2.62% and the pressure drop decreased by 2.62%. Therefore, the effect of temperature decreases when the pipe diameter increases.

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