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Research Article

Using injected additive materials to improve pipeline transportation in real-world experiments and computational fluid dynamics

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ABSTRACT

In this paper, an experiment has been conducted where additive materials have been added to heavy crude oil to improve transportation. This is done on a pipeline length of 186 km. During the experiment, materials will be added to the inner pipeline to lubricate the heavy crude oil fiber and reduce the pressure drop. The additive materials, which are Drag-Reducing Agents (DRAs) (These are polymers that reduce the friction between the crude oil and the pipeline walls) are injected into heavy crude oil at different doses (two materials); the doses are 4, 6, 8, 10, and 12. A comparison between the cases before and after this additive has been obtained in the pipeline for velocity magnitude, vorticity magnitude, pressure drop, and wall shear stress. It can be observed that doses (8, 10, and 12) obtained a wide range of flow rates with fewer pressure drops than other dose points. The pressure at the city of Al-Faw has been found, and the maximum values are 1.482, 1.413, and 1.399 MPa for doses 12, 8, and 6, respectively. The simulation was done with COMSOL 5.4 Multiphasic software. Flow ranges increase as the dose increases. Shear stress increases with mass injection rate. Transporting heavy crude oil long distances is easier with additive materials. After the additive materials are added, crude oil will be transported for a long time without pressure drops, increasing the flow rate. The two turbines pump heavy crude oil through a 48 inches wide and 186 km long pipeline. These pipelines transfer heavy crude oil from the refinery to Al-Faw City.

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INTRODUCTION

In the present energy scenario, oil companies are persuaded to exploit crude oil resources with high viscosity and extreme chemical composition. This makes production and transportation complex. The most efficient, safest, and cheapest way to transport crude oil is via pipelines. Long-term returns on their investment come from decades of use after a high initial investment. The purpose of pipeline networks is to transport crude oil from nearby oil wells to oil

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tankers over long distances. The South oil company needs to transport crude oil from the production area south of Basra city to the export port, 186 km: these days, crude oil demand increases occasionally. Water lubrication is one method to decrease the difficulty of transporting heavy crude oil and high shear stress at the wall. The water will pump along the pipeline sufficiently to suppress shear stress and decrease crude oil viscosity.

A few studies focused on crude oil transport, Al-Wahaibi et al. [1] studied heavy crude oil transportation by pipeline over long distances, resulting in pressure loss and increased pumping energy requirements. Also, it consumes more energy due to frictional pressure loss over wall surfaces. They added additives to heavy crude oil in the pipeline to reduce frictional pressure drop. Flowing heavy crude oil in pipelines is easy when additives are added. Pump efficiency increases, and pumping power is reduced. This reduces the cost of transportation and, therefore, the cost of the oil. Adding additives also benefits the environment, reducing the energy needed for pumping. Ahmed et al. [2] studied the factors that affect the viscosity of surfactant viscous crude oil in pipeline transportation—increased emulsion stability due to increasing oil mixing speed and content. Due to surfactant injection into synthetic formation water, emulsification affects pump systems and tubing for heavy crude oil production. By emulsifying Egyptian crude oil with water, its viscosity decreased. As a result, the viscosity of crude oil in water emulsion is low and will make pipeline transportation easy. Asante B. [3] used the steady-state hydraulic behavior of gas pipeline parameters as input to flow equations, such as flow, operating temperature, and operating pressure with inner pipe roughness. His process involves reviewing flows and pressure drops to determine pumping capacities, pipeline diameter, and station pump power. The facility selection process begins with creating a demand and supply forecast. These forecasts usually involve examining all existing data. Mohitpour and McManus [4] created the hydraulic computer model of the pipeline system to which the forecast for supply and demand is added. Steady-state simulations are then run to determine where flow is restricted.

On the other hand, pressure surge describes a relatively rapid process with incompressible fluids. Gateau et al. [5] showed that transporting crude oil in the pipeline is complicated without reducing crude oil viscosity. That happens when oil mixes with light hydrocarbons. The viscosity of that mixture depends on oil density, viscosity, and dilution rate. Adding a polar solvent to the asphaltene solution in toluene affects the colloidal structure. Solvent parameters' polarity and hydrogen bonding are higher at a constant dilution rate. This is due to the reduction of diluted crude oil due to the increased relative viscosity. The polar solvents have little hydrogen bonding, reducing the viscosity of crude oil. Hart [6] studied different technologies for transporting crude oil and bitumen through the pipeline. He analyzed the advantages and disadvantages of these technologies. Also, he reviewed the improvement and development of each technology for crude oil and bitumen transportation through pipelines. Several strategies have been examined to prevent fouling at core-annular flow pipeline walls by Arney et al. [7]. performed lubricate or curb wall fouling by using water. They showed from the experiments that oil is fouled in some places. They also showed the highest pressure value near the pump station and the wave structure in the pipe core. The stratified flow is formed of water and oil; this will stick oil to the pipeline wall. Tripathi et al. [8] experimentally studied heavy oil transport in a horizontal pipe as a core-annular flow. They recorded the pressure drop and images using a high-speed camera of a fully-developed core-annular flow. Calculate the average oil holdup, interface speed, and interface profile power. They also showed that wall shear stress is proportional to the square of the value of core velocity.

Heavy oil transportation in pipelines produces high-pressure drops that require higher energy. Heating or mixing oil with light oil is inexpensive [9, 10]. Abdurahman et al. [11] observed that with Malaysian heavy crude oil, stable concentrated oil-in-water (O/W) emulsions were prepared and investigated for pipeline transportation of heavy oil. Heavy crude oil emulsions were produced from two Malaysian samples, Tapis and a blend of Tapis and Masilla. Emulsion properties and stability were investigated based on a variety of factors. The crude oil content of the emulsions had a limit of 68 vol% and 72 vol%. Above that limit, phase inversion occurred. Oil-in-water emulsions stabilized with Triton X-100 exhibit increased stability with increasing surfactant concentrations, with a consequent decrease in crude oil–water interfacial tension. The emulsion's stability improved as the oil content, mixing speed, salt concentration, and pH of the emulsion's aqueous phase increased.

In contrast, the viscosity of emulsions prepared by homogenization was reduced substantially by increasing the heat. The stability and viscosity of an emulsion were studied using fresh water and synthetic formation water. Based on the results, stable emulsions can be formed with synthetic formation water with low dynamic shear viscosity.

Bitumen transportation through a pipeline is difficult due to the high viscosity of crude oil. The addition of C4 and paraffinic liquid hydrocarbons has solved this problem. This diluent has several obstacles. The alternate use of MTBE (methyl tert-butyl ether), a gasoline additive, as an alternative solvent has been investigated to overcome these difficulties. A liquid viscosity model has been used to calculate component viscosities as a function of temperature. It uses a mixing rule to determine blend viscosity as a function of composition. A simple distillation was performed on a 35% MTBE (mass basis) blend to study the ease of separation of the liquid diluent from the heavy oil phase under atmospheric conditions [12]. It was found that adding 25-30% MTBE (mass basis) was sufficient to reduce the viscosity of Cold Lake bitumen to meet pipeline specifications. The viscosity model was found to be accurate over the entire range of compositions and temperatures examined.

Heavier oil is one of the kinds of crude oil. Meyer and Dietzman 1979 reported that heavy crude oil production was about 5% of the rest of the oil produced. They predicted that heavy crude oil production would increase. 1979 they reported Canadian heavy oil production cumulatively at 197 million barrels. The system's capacity decreased without expanding pumps and pipes due to heavy crude in the system. Various techniques are available to keep the capacity at constant values [13]. Arney et al. [14] studied the experiment with emulsified waxy crude oil and fuel oil No. 6 to lubricate the pipeline and compared the results with other researchers. A correlation formula estimates a holdup fraction. They are based on theory and depend on the concentric core-annular flow model. They obtained the most effective results of the high Reynolds number flow regime. Abdulwahid et al. [15] studied analytically of five different profiles for a uniform radial influx through a perforated wellbore. Despite frictional acceleration, gravitational pressures also affect the pressure drop caused by the inflow through the perforations. The inflow through the wellbore model affects shear stress due to wall friction. The shear stress increased with the increase in radial flow and decreased with the decrease in radial flow. Due to the high viscosity value at average field temperatures, special facilities are required in the pipeline to transport heavy crude oil. When heavy crude oil transfers from one place, the oil is heated along the pipeline, while at other times, the oil is diluted by 30 percent with kerosene. They showed that the effective viscosity in heavy oils pipeline flow decreased by 3-4. The pressure drop associated with heavy crude oil pipeline flow can be reduced significantly by adding butanol or pentanol [16]. Recently, Saleh et al. [17] studied the Iraqi heavy oil transportation in convoying pipeline presented concerning the CFD model. An artificial lift method in heavy oil wells uses the core-annular flow pattern. It is considered a non-Newtonian fluid with laminar flow. Inherit the CFD model is set up with the help of ANSYS FLUENT 15. The pipe's geometrical domain is (a 3/4-inch inner diameter with a 1m length in a horizontally flowing direction).

Using Omani heavy crude oil [18] investigated the effects of water content, shear rate, temperature, and solid particle concentration on viscosity reduction (VR). The viscosity of the crude oil was initially measured concerning shear rates at different temperatures from 20 to 70 C. The crude oil exhibited shear thinning behavior at all temperatures. The strongest shear thinning was observed at 20 C. The results indicated that VR was inversely proportional to the temperature and concentration of silica nanoparticles. VR increased with the shear rate for water-in-oil emulsions and eventually reached a plateau at 350 s^{-1}. This was attributed to the continuous phase's thinning behavior. The VR of oil-in-water emulsions remained almost constant as the shear rate increased due to the water's Newtonian behavior. Martínez-Palou et al. [19] studied an overview of the current and innovative technological solutions for reducing viscosity and friction to move crude oils from the production site to the processing facilities.

After adding the additive materials, the crude oil will be transported for a long time without causing pressure drops, thereby increasing the flow rate. Also, the test pipe is simulated from the experimental worksite with an inner tube diameter of (1.219 m) and a length of (5 m) in the horizontal direction. The model is solved with non-Newtonian fluid, laminar flow, and power-law type. Multi-Dos of additive chemical materials were used to verify the optimum reduction in pressure drop. The CFD analysis of 2D contour plotted with helpful COMSOL 5.4 Multiphysics free demo [20].

METHODOLOGY

To transport heavy crude oils long-distance, especially from the production zone to the storage zone or export zone, it is necessary to have a lower pressure drop value in the pipelines to decrease the pump power. Therefore, to facilitate pipeline transportation, a reduction in viscosity. The methods used to transport crude oil consist of three main categories:

- Viscosity reduction can be achieved by heating the oil and pipeline, diluting with lighter hydrocarbons or solvents, emulsifying the oil, and pouring point reduction.
- Friction reduction: This can be achieved by lubricating the pipeline wall with drag-reducing additives and core-annular flow.
- In-situ/partial upgrades.

The biggest problem encountered in transporting crude oil via pipeline for a long distance is pressure drop. When crude oil is transported via pipeline, the turbulent flow added to the high viscosity of crude oil causes frictional losses. Due to these, the energy required for crude oil transportation is high and wasted.

Materials

The two turbines pump heavy crude oil through a 48 inches and 186 km long pipeline. The operation conditions before additive materials were added(which is Drag-Reducing Agents (DRAs) these are polymers that reduce the friction between the crude oil and the pipeline walls); the average pumping of the two turbines ranged from 6800 to 7000 m^3/h. The discharge pressure is 34 -35 kg/cm^3. The speed of the turbine was 87%. The temperature of the crude oil was 28 - 33° C, and the minimum and maximum temperatures of the surrounding area were 4° C and 22° C, respectively.

The continuity equation is modeled as follows:

$$\nabla \cdot V = 0 \tag{1}$$

While the equation of momentum [21, 22]:

density*acceleration
=pressureforceperunitvolume*viscousforceperunitvolume*
gravityforceperunitvolume

$$\rho(V \cdot \nabla V) = -\nabla p - [\nabla \cdot \tau] + \rho g \tag{2}$$

In the pipeline with real fluid flows, at the wall, there is shearing stress retarding the flow. As the fluid overcomes the shear stress, energy is lost. The retarding force caused by the shear stress by the walls is equal to the shear stress multiplied by the effective area;

$$retarding\ force = \tau_w x \pi d L \tag{3}$$

When the flow is in equilibrium, the forces are equally so

Driving force = retarding force

$$\Delta p \frac{\pi d^2}{4} = \tau_w . \pi d L \tag{4}$$

$$\Delta p = \frac{\tau_w .4L}{d} \tag{5}$$

From Eq. (4) notes that the pressure drop in a pipeline is proportional to the shear stress at the wall and the length of the pipeline but inversely to the diameter (*d*). Shear stress varies with flow velocity and Reynolds number. The friction pressure drop ($\Delta p/L$) in the equation

$$\tau_w = \frac{d}{4} \cdot \frac{\Delta p}{L} \tag{6}$$

The friction factor is:

$$f = \frac{d \cdot \Delta p}{\left(2L\rho_m \cdot u_m^2\right)} \tag{7}$$

Several parameters are related to crude oil transportation in pipelines:

1- Velocity, 2- viscosity, 3- temperature, 4- density, 5- pour point.

The crude oil flow rate in the pipeline depends on the pressure drop value between the pump station and the storage tank. This is the last points of supply of crude oil. Pressure drop is a function of diameter, length, pipe roughness, fluid velocity, and friction factor, but the last two are variables. The Darcy-Weisbach equation determines pipe head loss:

$$\Delta h = f \cdot \frac{L}{d} \cdot \frac{v^2}{2g} \tag{8}$$

Physical Model Simulation

One heavy liquid flow is considered a Non-Newtonian fluid with a power-law model type to simulate crude oil flowing inside pipelines. Figure 1 illustrates a physical flow domain of 2D uniform velocity with fully developed laminar flow conveyed inner tube diameter (1.219 m) and the test section length (5 m). The boundary condition at the pipe is inlet velocity, and at the outlet of the pipe is outlet pressure (0 gauge pressure). The flow enters the pipe from the left side and the outlet from the right side. The fully developed laminar flow and isothermal flow. The red lines have plotted the result of the most critical effective parameters by COMSOL Multiphysics 5.4 software used to simulate the effects of the doses added with the crude oil to decrease the viscous forces during the flow inside the pipeline. The optimisation was solved at the mesh number elements of 18978 with average element quality of 0.8689.

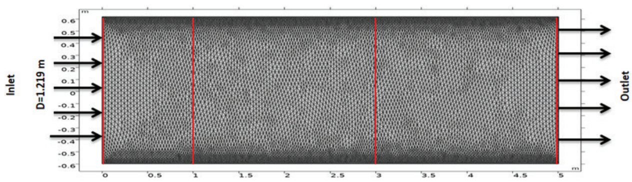

Figure 1. Test section of crude oil domains.

RESULTS AND DISCUSSION

Figure 2 illustrates the pressure drop in Al-Faw with flow rate for different doses of additive materials. Figure 2 clearly illustrates that when the flow rate of a liquid increases, the pressure drop will increase too. This is because the friction force generated between the liquid and in contact with the pipe inside the wall will suffer from shear stresses. Now, the additive materials work as a damping medium for friction forces. This minimises the shear stresses between the liquid and the inside pipe wall. The variety of these doses gives different ranges of liquid flow rates and corresponds to pressure drop inside the pipe. Again, Figure 2 represents the optimum dose that acts for less pressure drop with a wide range of flow rates; thus, doses (6 and 8) give a wide range of flow rates with moderated pressure drop values. This result can be attributed to the additive's ability to reduce the liquid's viscosity, thus reducing the friction between the liquid and the pipe wall. This, in turn, helps reduce the pressure drop and improve the process's efficiency. The doses (4, 6, 8, 10, and 12) were selected depending on the concentrations of the two additive materials. The dose of 4 was chosen as the lowest concentration, while the dose of 12 was the

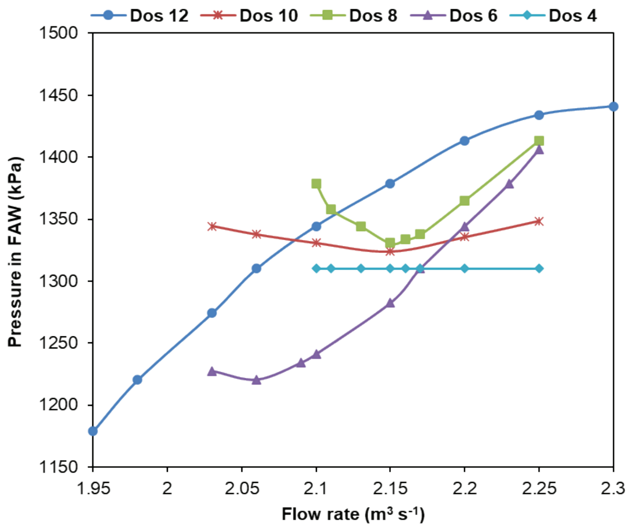

Figure 2. Pressure versus flow rate for different doses of additive materials.

highest. The other doses were selected to create a range of concentrations between the two.

For liquids to flow quickly, the pump's capacity must be sufficient to overcome the pressure drop generated inside the pipe and (the pump's head pressure). As shown in Figure 3, there is a pressure drop in pumping stations with different flow rate ranges at different doses. It can be observed that doses (8, 10, and 12) obtained a wide range of flow rates with fewer pressure drops than other dose points. This indicates that the pressure drop is inversely proportional to the flow rate. Moreover, the higher the flow rate, the lower the pressure drop. This allows the pump's capacity to be increased significantly.

Figure 3 shows the total pressure drops of liquid with flow rates at different doses. When an increase in dose leads to more flow rate ranges, the dose increase will decrease the shear stress forces between the liquid and the pipe's inside wall, reducing the pressure drop in the pump station. Now, Figure 4 illustrates the doses of (4, 8, 10, and 12) for optimum pumping. This will result in a decrease of energy consumption and will also reduce the amount of water wasted. Such a decrease in pressure drop can significantly lower operational costs and help to save energy. This will also help reduce the risk of pipe leakage and maintenance costs. These cost savings can be reinvested in other business areas, such as research and development, to improve the system's efficiency further. As the flow rate increases, the pressure drop decreases. This is because the fluid can flow more efficiently with a higher flow rate. The pressure drop is the difference in pressure between two points in a system and is an indication of the resistance the fluid is experiencing. The higher the flow rate, the less resistance the fluid experiences, resulting in a lower pressure drop. This is because the velocity of the fluid increases, allowing it to flow more freely and reduce the frictional forces between the fluid and the pipe walls.

Figure 5 illustrates the wall shear stresses in the pipe with strain at different doses of additive materials. The doses of (6, 8, 10, and 12) produced moderate values of wall shear stresses, leading to moderate friction forces and pressure drop inside the pump station with a wide range of flow rates. Shear stress increases with an increasing mass injection rate, which causes a higher pressure gradient. The wall shear stress is highest at a mass injection rate of 12 due to the significant increase in pressure gradient. The strain at this rate is also relatively high, which can result in pipe damage. Therefore, using the right amount of additive materials

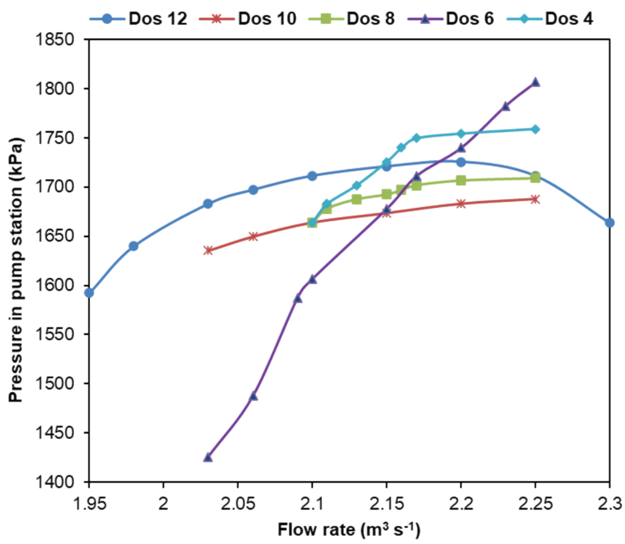

Figure 3. Pressure in pump station versus flow rate of different doses of additive materials.

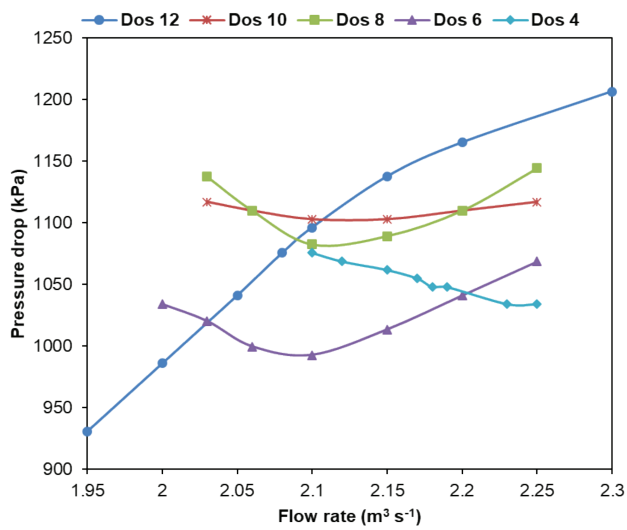

Figure 4. Pressure drop versus flow rates for different doses of additive materials.

to maintain a safe level of strain and wall shear stress is important. It is essential to monitor the strain and wall shear stress levels to ensure optimal efficiency and safety. Regular maintenance and inspections should be carried out to identify any damage caused by high levels of shear stress. It is also essential to use the correct materials to reduce the risk of damage. Viscosity is typically measured by the shear rate of a fluid, which is the rate at which the fluid changes its shape when a force is applied. It is also affected by the temperature and pressure of the fluid, as well as the chemical composition of the fluid. The higher the viscosity, the slower a fluid will flow.

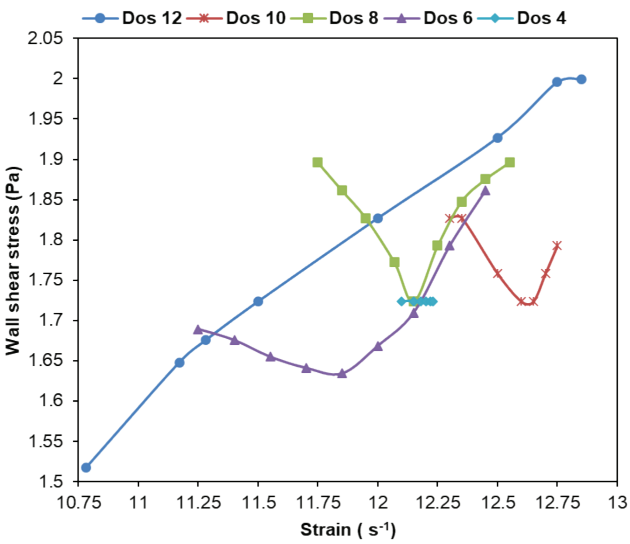

Figure 5. Wall shear stress versus strain for different doses of additive materials.

Optimum Dos Simulation

Simulation is done for experimental measurements without doses. Figure 6 and Figure 7 showed variations in 2D plane uniform velocity magnitude at a volume flow rate of (6800 to 7000 m³/h), respectively. A smooth streamline indicated crude oil's laminar flow because of the Non-Newton fluid flow across the test section. The uniform distribution of velocity magnitude at the inlet, outlet, center lines, and layers near the walls. The overall flow pattern was observed to be symmetric. Streamline contour further confirmed the uniform flow of oil across the test section. The pressure drop across the test section was found to be negligible. The experiment results showed that the oil flow patterns conformed to the expected flow model. The oil's laminar flow was uniform and symmetric, with a negligible pressure drop.

Figure 8 and Figure 9 illustrate that the flow near the walls approximates zero values and then gradually increases into the maximum value at the pipe diameter center-line, thus for the inlet, at x=1 and 3 m, and the outlet. This

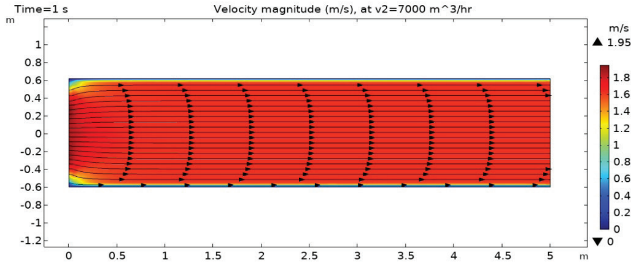

Figure 6. 2D uniform velocity magnitude at V_1=6800 m³/h.

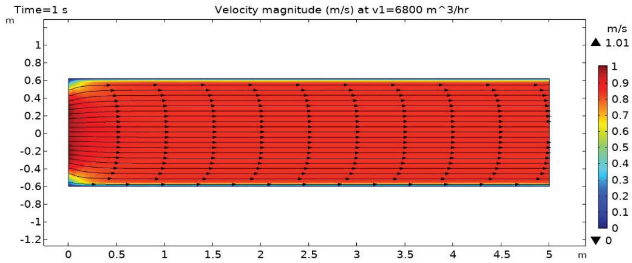

Figure 7. 2D uniform velocity magnitude at V_2=7000 m³/h.

indicates that the flow is laminar and follows a parabolic profile, as expected for a fully developed flow. The Figures also show that the flow is symmetrical about the pipe center-line, which implies that the flow is not affected by any external forces. The clear, varied values indicate viscous forces' influence.

The fluid's viscosity and velocity are applied as a pressure gradient in isothermal flow. This combination leads to a change in flow strain, particularly in dense or viscous fluids. Here the heavy crude oil flow inside the pipeline is simulated to analyze the variations in shear rate (*SR*) with a

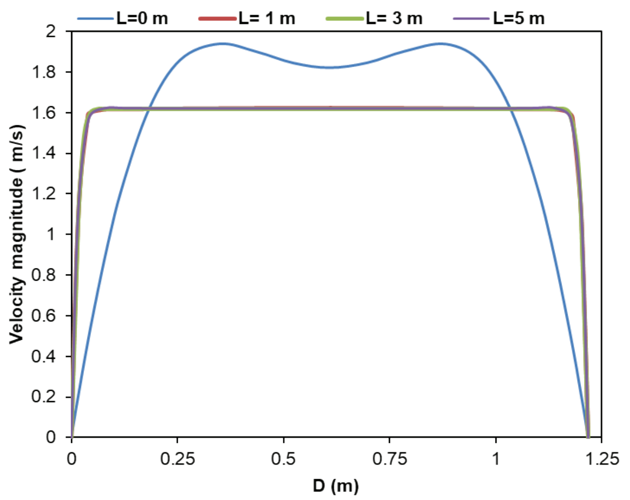

Figure 8. Velocity distribution through the inner pipe diameter at V_1=6800 m³/h.

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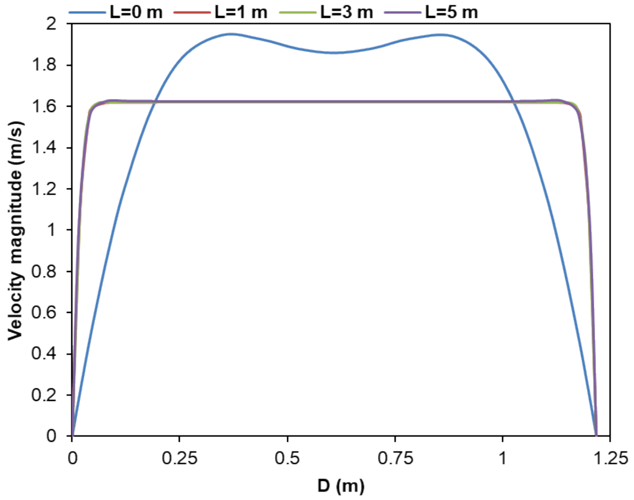

Figure 9. Velocity distribution through the inner pipe diameter at V_2=7000 m³/h.

pressure gradient equal to the circulation of vorticity. This analysis helps to determine the turbulent flow patterns, which provides insight into the energy requirements for transporting heavy crude oil in the pipeline. It also helps to identify the points of maximum friction and wear in the pipeline. Finally, it helps to plan the pipeline route and optimize the design. For flow in the x-direction of Figure 5, the shear rate is given as follows:

$$S_R = \left(\frac{\partial v}{\partial y} - \frac{\partial u}{\partial x}\right)\partial y \partial x \tag{9}$$

In Figures 10 and 11, we can see the 2D element contour of the vorticity magnitude across the inlet, and outlet, at x =1 and 3 m at V_1 and V_2. From the contour, Figures indicate the flow strain is more significant near inner pipe walls. That is because of the viscous forces and friction the fluid flows through the boundary layer generates. This results in a higher velocity in the boundary layer and higher vorticity levels. The higher vorticity magnitude near the inner wall suggests the flow is more turbulent in this region.

To explore the vorticity forces by plotting the graph lines at the inlet-outlet at x =1 and 3m at V_1 and V_2. Figures 12 and 13 show the variations in vorticity across the pipe

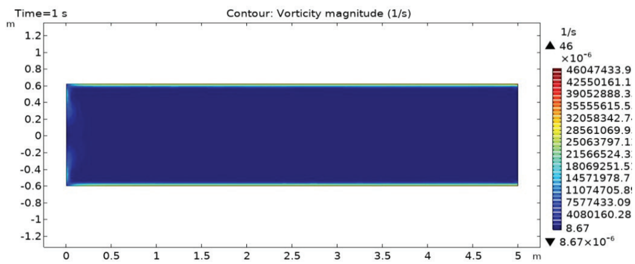

Figure 10. 2D vorticity magnitude at V_1=6800 m³/h.

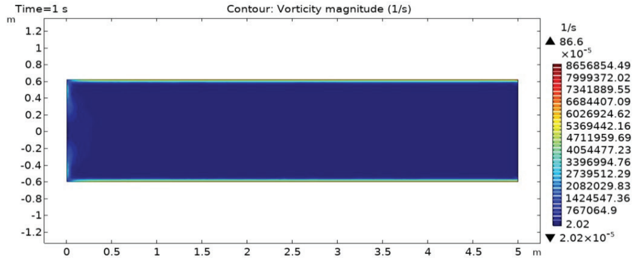

Figure 11. 2D vorticity magnitude at V_2=7000 m³/h.

diameter at different positions along the test length. This is to analyse the behavior of strain rate and shear rate combined released. At increases in volume flow rate, vorticity increases too, ranging from the inlet to the outlet. This is because of the strain generated in the near layer of the inner pipe walls. While at the entrance region, the flow was uniform, and the strain forces started to recognize due to the molecules of crude oil being more cohesive between them. This created high strain and shear rates, propagating toward the outlet. The strain and shear rate then increased exponentially as the flow rate increased. Eventually, the vorticity reached a steady state until the volume flow rate was increased again.

New chemical materials have been injected along with heavy crude oil in industrial plants To minimize the influence of viscous forces forced through convoyed pipelines. From the presented results, the optimum value of chemical materials injected with crude oil is Dos 12. In here, the complete simulation with Dos 12 for graph line velocity, vorticity, and the total pressure drop per pipe length at a crude oil volume flow demonstrates the results (As shown in Figure 14, the same proportion of uniform velocity magnitude is plotted for the inner pipe diameter at the inlet and at x=1 and 3 m, as well as the length of the test pipe at

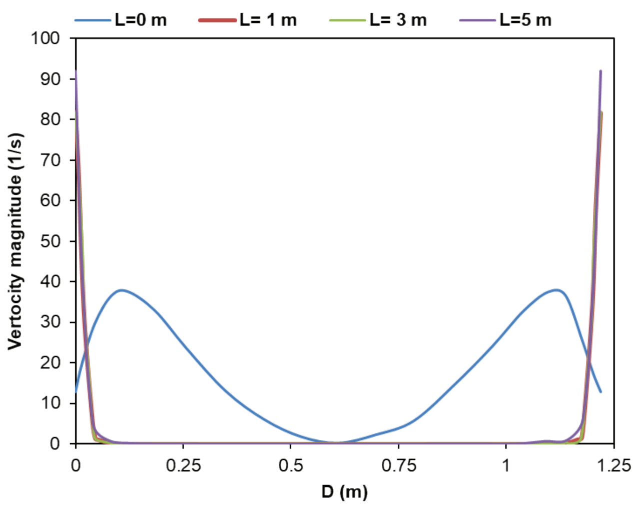

Figure 12. Vorticity magnitude cross pipe diameter at V_1=6800 m³/h.

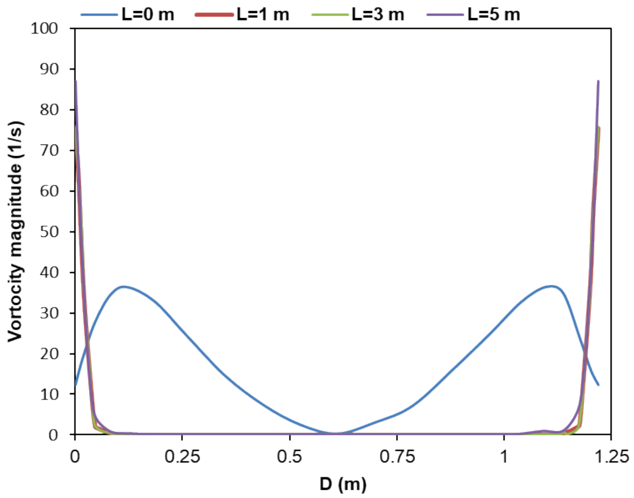

Figure 13. Vorticity magnitude cross pipe diameter at V_2=7000 m^3/h.

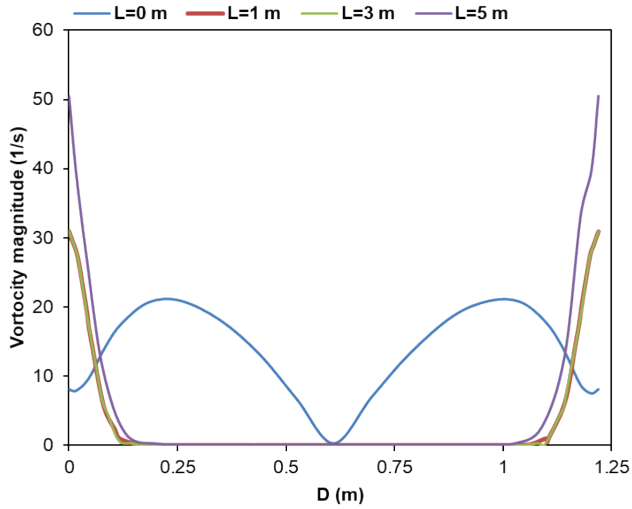

Figure 15. Vorticity magnitude cross pipe diameter at V_2=7000 m^3/h at Dos (12).

the outlet alone =7000 m^3/hr). When comparing the present result at Dos (12) with the result in Figure 9, additive chemical materials have been successfully applied to crude oil. A higher velocity profile was obtained, which resulted in a reduction of the viscous forced action. This result demonstrates that adding chemical materials can be used to modify the properties of crude oil, resulting in increased efficiency. The improved velocity profile also reduces the overall friction, leading to further gains in efficiency.

To test the additive chemical material, when injected with crude oil flow, works to slide the liquid surfaces and the inner pipe wall surfaces. Fluid strain force is minimized due to molecules. It can quickly determine the deviation of the strain minimized. As a compression, Figure 15 plotted the vorticity magnitude vs. the inner pipe diameter with Dos (12) in Figure 13. The results showed that the Dos (12) had the highest vorticity magnitude. The same results were found for the other additives. These results indicate that the additive chemical material effectively reduces friction and minimizes strain force in crude oil flows.

Figure 16 shows the pressure drop per unit length of pipe at the variation of volume flow rate and Dos (12). Due to the dense formation near the inner walls and slightly in the center of the pipe, pressure drops increase with increasing volume flow rate. When the Dos (12) is added to the crude oil flowing, that reduces the shearing forces between crude oil and the pipe's inner surface. The pressure drop decreases gradually at the outlet. This suggests that adding Dos (12) to crude oil helps reduce the shear forces and increase the flow rate. As a result, the pressure drop is reduced, and the flow

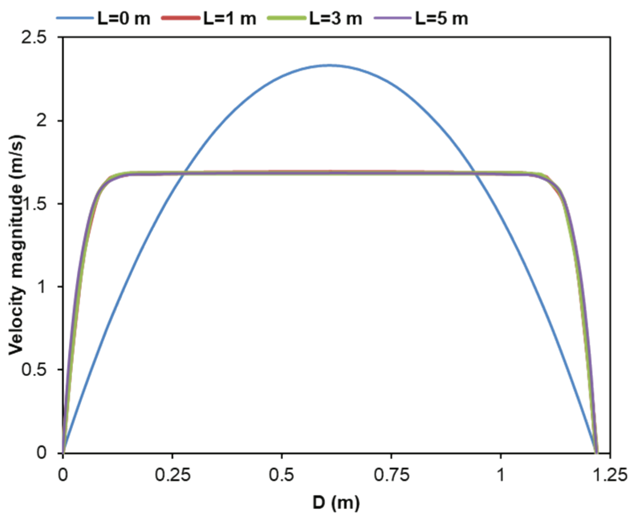

Figure 14. Velocity distribution through the inner pipe diameter at V_2=7000 m^3/h at Dos (12).

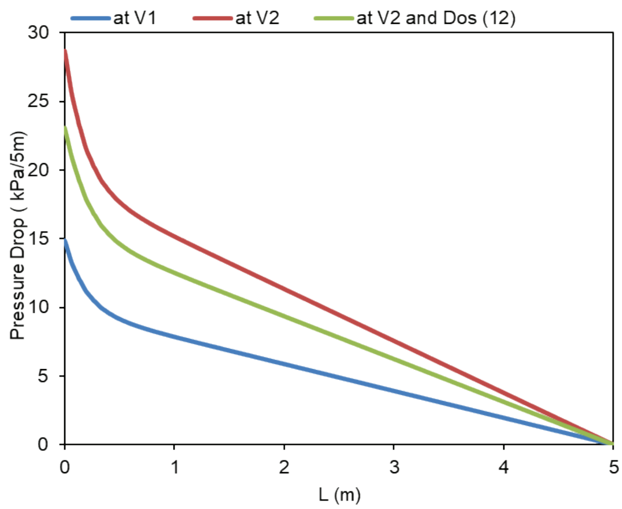

Figure 16. Pressure drop per unit length of test pipe at the variation of volume flow rates.

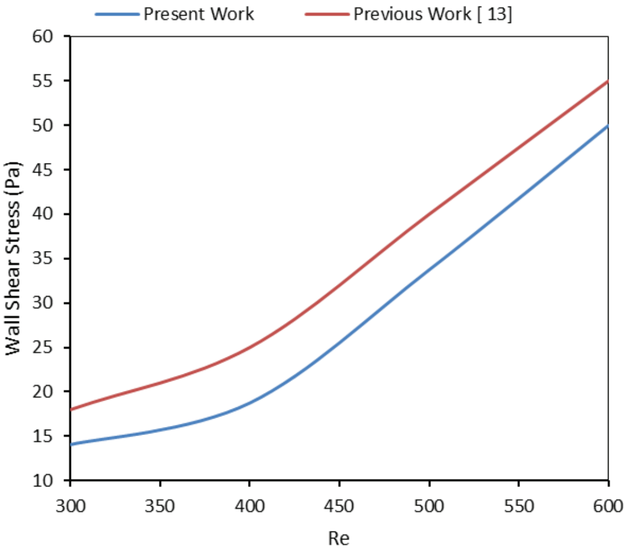

Figure 17. Compression results of the present work within the previous work for wall shear stress.

rate increases. This indicates that adding Dos (12) to crude oil improves the flow rate without dramatically increasing the pressure drop. Thus, it is an effective way to improve the efficiency of crude oil transportation.

Figure 17 shows the compression results of the present work within the previous work for wall shear stress. Crude oil flowing through the pipeline produced action forces of fluid motion that were higher in the inner pipeline wall and decreased towards zero in the center line. With an increase in Reynolds number, the velocity profile of crude oil in the pipeline increases. This results in a higher pipeline wall shear stress. With no additive materials used in previous studies, the deviation between the present and previous studies ranged from (3% to 6%). This is because the friction between the crude oil and the inner wall of the pipeline increases as the Reynolds number increases. This increased friction causes the crude oil to move faster, thus increasing the wall shear stress. The presence of additives can also further increase the wall shear stress by reducing the friction between the crude oil and the inner wall of the pipeline.

CONCLUSION

A non-Newtonian fluid with laminar flow was successfully tested on Iraqi crude oil using a power-law model. COMSOL Multiphysics 5.4 software simulates crude oil flowing into the pipeline. The model is built as a non-Newtonian fluid of laminar flow and power-law type. Two crude oil volume flow rates were used to determine the optimum doses of additive chemical material injected into the flow stream. Experimental validation and simulation presented the influence of additive chemical material injected into crude oil transported through a horizontal pipe. The following conclusions are listed.

- Due to added additive materials at pump stations to transfer crude oil to Al-Faw city, the pressure drop decreased. Adding additive materials, such as surfactants, reduces the surface tension between the oil and water, which in turn reduces the amount of energy needed to move the oil through the pipeline. This results in a lower pressure drop, allowing for more efficient transfer of the oil.
- A crude oil viscosity force forms a shear force near the layer of inner pipe walls due to friction and strain generated during flow. This shear force leads to increased pressure drop in the pipe, which then affects the flow rate of the crude oil. It can also cause the formation of solid deposits on the inner walls of the pipe, leading to decreased flow efficiency.
- As a result of the simulation, various crude oil volume flow rates were analyzed without and with additives.
- The optimum Dos is simulated to analyze the velocity distribution, vorticity, and pressure drop along the pipe length. It is found that the Dos (12) gives the optimum flow performance.
- The maximum pressure drop was observed at Dos 12. The pressure drop decreased with an increase in the Dos. The flow in the pipe was found to be more uniform at Dos 12.

NOMENCLATURES

d	Pipe diameter (m)
Δh	Head loss (m)
g	Gravity acceleration (m sec^{-2})
L	Pipeline length (m)
ΔP	Pressure drop (kPa)
V	Absolute fluid velocity (m s^{-1})
u	Average velocity (m s^{-1})
S_R	Shear rate (s^{-1})

Greeks

ρ	Fluid density (kg m^{-3})
f	Friction factor
τ	Shear stress (N m^{-2})

Subscribed

m	Mixture, mean
w	Wall

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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