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Core Annular Flow (CAF) Modelling as a Breakthrough to Improve the Transport of Heavy Oils Using Water as Lubricant and Saving Energy

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Abstract. Transportation of heavy oil by pipeline faces several problems, such as asphaltene clogging, wax deposition, and large pumping power. The objective of this research is to develop Core Annular Flow (CAF) as an effective method solution to reduce operational costs, which technology has not been widely applied to the oil and gas industry in the world. The method used is a simulation of Computational Fluid Dynamics (CFD). CAF modeling shows the oil flow using water as a lubricant and the oil is not in contact with the inner wall of the pipe, so the friction force is proportional to the force that occurs when only water flows in the pipe. The results show pressure drops and pumping power can be reduced by up to 50%. Sensitivity analysis has been carried out to see the absolute pressure, velocity, and volume fraction. The analysis was also carried out to compare the required pump power between the CAF and the single-phase oil flow.

Keyword: core annular flow (CAF), Heavy Oil Transportation, Horizontal Pipe, Computational Fluid Dynamics (CFD)

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1 Introduction

Oil is still one of the biggest sources of energy used to support the world's energy needs. Heavy Oil is defined as liquid oil that has an API degree of less than 20 or has a viscosity of more than 200 cP at reservoir conditions [1]. Heavy Oil is formed from the results of hydrocarbon deposits that are degraded by algae, which eat a light fraction of hydrocarbons, leaving only the heavy fraction. Heavy oil in particular is projected to have a large role to meet energy demand, and soon replacing light oil. For the past decade, research about heavy oil is increasing and encouraging to find an effective and economic solutions to improve its production and transportation.

The heavy oil transportation using pipeline encountered several flow assurance challenges such as asphaltene blockage, wax deposition and large pumping power. Deposition of asphaltene, heavy metals, sulfur, and brine or salt content that makes heavy oil difficult to transport and process in a refinery by conventional methods without upgrading it to suit the properties of conventional light crude oil [2].

High brine content can make the pipes corrode faster. Several methods that can be a solution to this problem are the following methods, namely viscosity reduction, friction reduction, and in-situ upgrading [3].

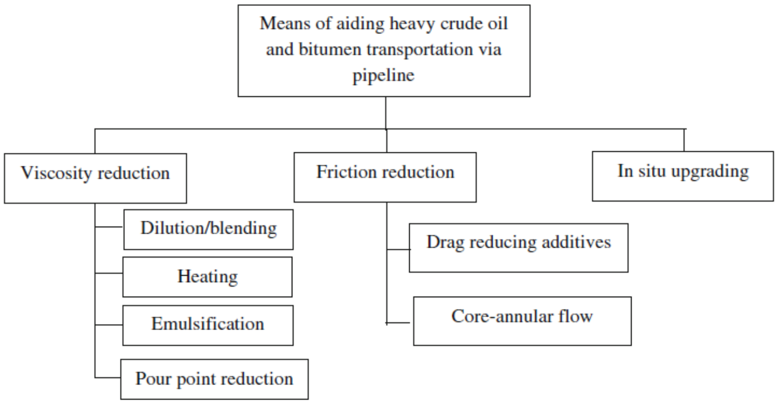


Figure 1**Error! No text of specified style in document.**.1 Heavy Oil Transportation Method by Pipeline (Hart, 2014)

The first method is to reduce the viscosity of the oil so that it is easier to transport. Some of the methods that can reduce viscosity are as follows:

• Dilution / Mixing

This method works by mixing heavy oil with a diluent or blending fluid which has a much smaller viscosity. This method will produce a mixture of heavy oil and diluent that has a low viscosity, making it easier to transport. According to Gateau *et al.* [5], examples of diluents that are often used are natural gas, naphtha, kerosene, crude oil matches, and others. Meanwhile, the organic solvents that are often used are alcohol and methyl tert-butyl ether.

• Heating

Another method according to Hart [4] is to install a heater on the pipe so that it can reduce the viscosity of the heavy oil transported and increase flowability. However, this method is considered less effective and efficient. This is because increasing the temperature of the fluid in the pipe requires high energy and costs. Another problem is the corrosion of the pipe due to continuous heating and the pipe can expand and contract. This method is also not suitable for underwater pipelines, because the low temperature below sea level makes using this method considered wasteful.

• Emulsification

Emulsification is defined as oil which is dispersed in water in the form of droplets with a stable surfactant rock and oil-in-water emulsion so that the viscosity is reduced. The reduced viscosity will make it easier for oil to flow in the pipe

• Pour Point Reduction

This method uses an additional chemical called Pour Point Depressant (PPD). The concept used is to reduce the pour point of oil transported. The pour point of a liquid is the temperature at which a liquid loses its flow characteristics or the lowest temperature at which oil can flow. Paraffinic oil is often associated with a high pour point because it contains wax.

Wax will form when the temperature is low, then settle and build up on the pipe walls. This wax deposition will reduce the cross-sectional area of the inner wall of the pipe which causes the oil flow rate to decrease.

Therefore, Paraffinic Oil is usually added with PPD additives to reduce the pour point, so that wax does not easily form in the pipe due to low temperatures Hart [4].

The second method is In-situ Upgrading. In Situ Upgrading works by reducing the viscosity of heavy oil in the reservoir (in situ) by heating or burning it, then adding a catalyst that speeds up this process. As a result of this heating, the oil that comes out of the reservoir is thinner and has a lower viscosity, making it easier to produce and transport. This method is also called the Thermal Cracking method because it can break down heavy molecules into lighter ones by heating them.

Heavy oil which has a high viscosity generates a greater friction force when transported by pipeline when compared to light oil. This also results in a large amount of pressure loss along the pipe. Therefore a method is needed to reduce this large pressure loss, such as by applying the Drag Reducing Additives and Core Annular Flow (CAF) methods [9].

• Drag Reducing Additives

This method works by adding additives which function to reduce friction between the oil and the inner wall of the pipe. This additive acts as a buffer along the pipe wall. Drag Reducing Additives are divided into three categories, namely polymers, fibers, and surfactants [6].

• Core-Annular Flow

According to Niazi [7], Core Annular Flow is a technique for forming a layer of water in pipes that utilize oil. The presence of a water layer prevents crude oil from making contact with the wall pipe, thereby reducing the pressure drop due to friction.

2 Methodology

2.1 Core Annular Flow

Ghosh *et al.* [8] define the way CAF works as water is injected into oil that flows to form an annular layer along the pipe wall while oil flows in the middle, as shown in Figure 2.1. Since oil is not in contact with the wall, its friction force is proportional to the force that occurs when only water flows in the pipe. This reduces pumping power and costs significantly. This technique saves a lot of energy when compared to other transport processes.

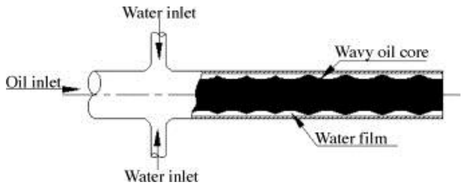


Figure 2.1 Schematic of annular cores in horizontal pipes [8]

According to Bensakhria [10], CAF is a flow regime where the oil phase is in the middle of the pipe and water flows near the surface of the wall. He claims that from his experimental results, the CAF method can reduce pressure drop by as much as 90% compared to the non-lubrication method. He also made an experiment by making a CAF lubrication injector as Figure 2.2.

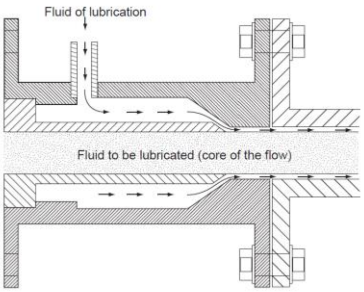
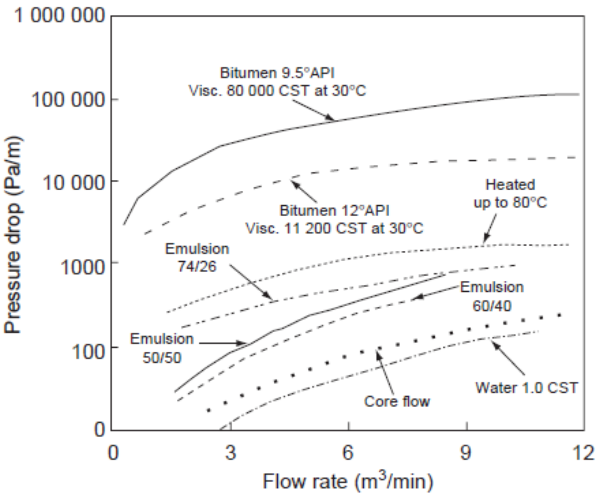


Figure 2. 2 Lubrication Injector Scheme [10]

2.1.1 Pressure Drop Profile

Based on the Guevara [11] experiment, CAF shows very satisfactory results than other heavy oil



transportation methods, such as emulsification, dilution using heaters, and conventional methods in terms of pressure loss. The pressure drop result on the flow rate of the CAF is also close to that when only water is transported in the pipe. However, this can happen if Annular Flow between water and oil persists and is not destroyed along the pipe.

This pressure drop on the CAF has a relationship with the pump power (pumping power) to pump oil from the inlet to the outlet pipe. The greater the pressure drop that occurs, the greater the pumping power that must be given. Then the greater the pumping power, the greater the costs.

2.2 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is one of the calculation methods in a control of dimensions, area, and volume using the help of a computer to perform calculations on each of the dividing elements. CFD is also defined as an analysis process of a particular system that involves problems of heat transfer, fluid flow, velocity distribution, and phenomena related to fluid dynamics where the calculation and analysis process is carried out using a computer [11]. CFD was nominated as the most effective method of

Figure 2. 3 Pressure Drop vs Flow Rate in Heavy Oil Transport Using Pipeline [11]

investigating complex flows. Partial Differential Equation (PDE) numerical solution used by CFD to estimate fluid movement. The process of making simulations in this research using ANSYS Fluent R20.1 Student Version software is divided into three stages that must be done, namely: Preprocessing, Solver, and Post Processing.

2.2.1 Preprocessing

This stage is the stage where the geometry and domain of solid and fluid geometries are made. Then, after making geometry, meshing, and naming the boundary conditions. In this study, a horizontal pipe without elevation was used with an oil inlet diameter of 80 mm, an inlet with a water diameter of 100 mm, and a pipe length of 1000 mm as in Figure 2.4.

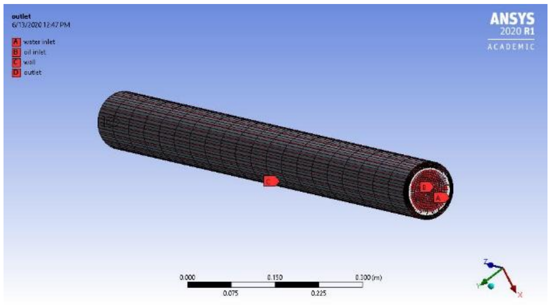


Figure 2. 4 Geometry and Mesh of the pipe

2.2.2 Solver

This stage is a crucial step in making a CFD simulation. At this stage, data input, selection of equations, and the model used as the basis for calculations are carried out iteratively. The objective of this calculation is to achieve the smallest error or to reach a convergent value. At this solver stage, physical data are used, as well as the velocity of oil and water used as in Table 2.1.

Table 2. 1 Fluids Data

	Water	Crude Oil
Density	998 kg/m3	976.2 kg/m3
Viscosity	0.001 Pa.s	0.19 Pa.s
Inlet Velocity	2 m/s	2 m/s

2.2.3 Post Processing

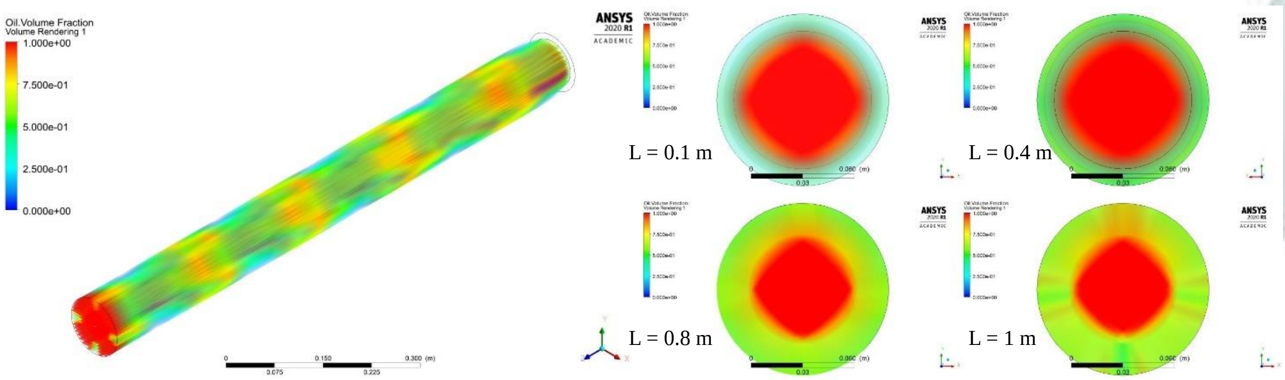
This stage is used to visualize and present the calculation results from the previous Solver Stage. Calculation results can be interpreted as images, graphics, contours, and animation with color patterns. The multiphase Volume of Fluid (VOF) model is selected to visualize the CAF. This method models two immiscible fluids by completing the momentum equation and tracking the volume fraction of each phase. The finite element method is used to discretize the differential equations. Finally, the coupled algorithm is applied to couple the pressure and velocity equations for both phases. Meanwhile, the second-order upwind scheme for calculating volume control is selected and the convergence criteria are set at 10^{-3}.

3 Result and Discussion

There are several aspects that are reviewed from the simulation results that have been carried out with the previous CFD simulation, namely volume fraction, velocity profile, absolute pressure, pressure drop, and pumping power. Then a comparison between CAF and single-oil phase flow is also carried out from these aspects.

3.1 Volume Fraction

In Figure 3.3, very high oil content is indicated in red, and blue is indicated as very little oil content or indicates the presence of water. In the axial section (a), it can be seen that oil flows in the middle of the pipe and is covered by water. In the radial section (b), it is shown that there are four observation points along the pipe, namely at 0.1 m, 0.4 m, 0.8 m, and 1 m. Oil flowing in the middle of the pipe is marked with red color, and green indicates the presence of water flowing in the annular part of the pipe. In this study, CAF flow was formed and could flow well from the inlet to the outlet



(a) (b)

Figure 3. 1 (a) Axial CAF Oil Volume Fraction Contour (b) Radial CAF Oil Volume Fraction Contour

3.2 Velocity Profile

velocity is a vector quantity that shows how fast an object is moving, in the context of this research the object in question is oil and water fluids. The velocity recorded in this sensitivity is the velocity of the mixture between oil and water as shown in Figure 3.1. At the axial velocity section, CAF and single-phase oil flow starts at a speed of 2 m / s, then increases as it approaches the outlet pipe. Single-Phase Oil Flow Velocity is higher because it is laminar flow, while CAF is more turbulent. The maximum velocity of CAF is 2.49 m / s, while for single-phase oil flow it is 3.14 m / s.

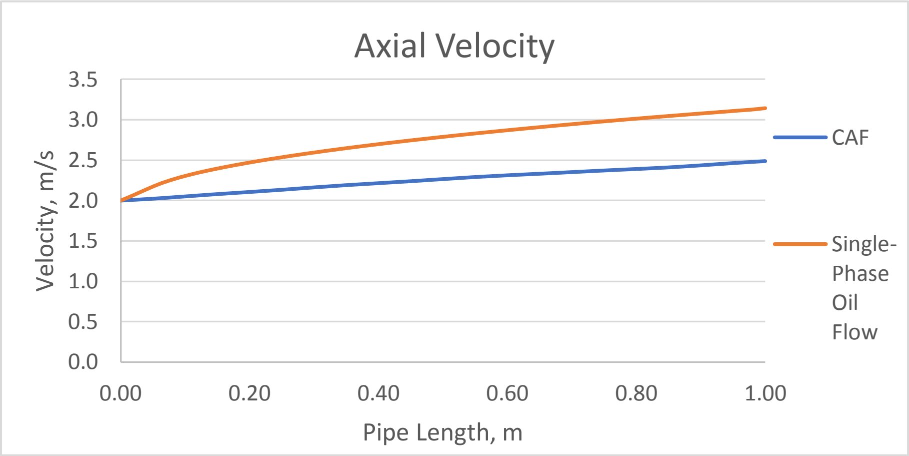


Figure 3. 2 Velocity Profile

3.3 Absolute Pressure Profile

Absolute pressure is the pressure that is influenced by the amount of outside air pressure. In this simulation, the operating pressure acts as an atmospheric pressure which has a value of 1 atm or 101325 Pascal. At the start of the fluid flow at the inlet, CAF and single-phase oil flow have high absolute pressure. The maximum pressure from CAF is 101263 Pa, while the maximum pressure for single-phase oil flow is 101369 Pa, then the pressure drops as in Figure 3.2, it is seen that CAF can maintain pressure so that the absolute pressure curve is more linear. The lowest pressure is at the outlet end of the pipe, at CAF around 99946 Pa and single-phase oil flow of 98566 Pa.

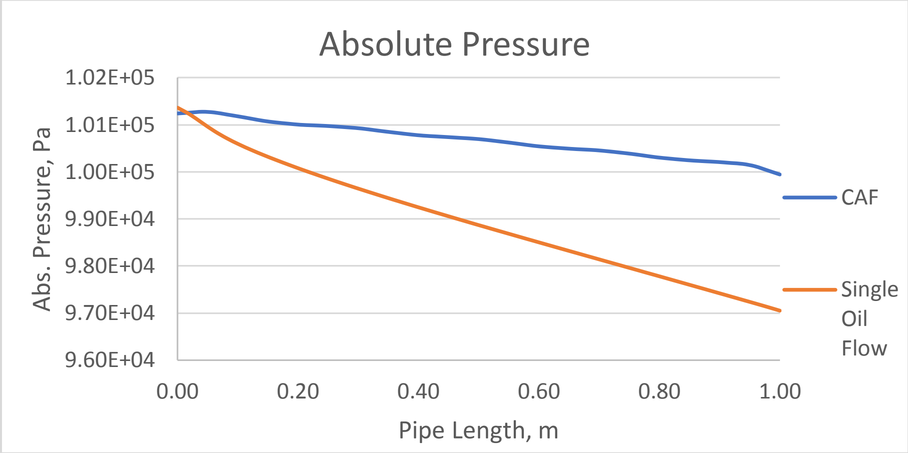


Figure 3. 3 Absolute Pressure Profile

3.4 Pressure Drop Profile

Pressure drop along the pipe as in Figure 3.4. CAF has a lower pressure drop than single-phase oil flow from the inlet to almost the outlet end. The waveform CAF pressure drop curve may be influenced by turbulent flow. THE total CAF Pressure Drop along the pipe is 0.013 Bar, while for single-phase oil flow it is 0.028 Bar. There is a difference of about 0.015 Bar which makes CAF

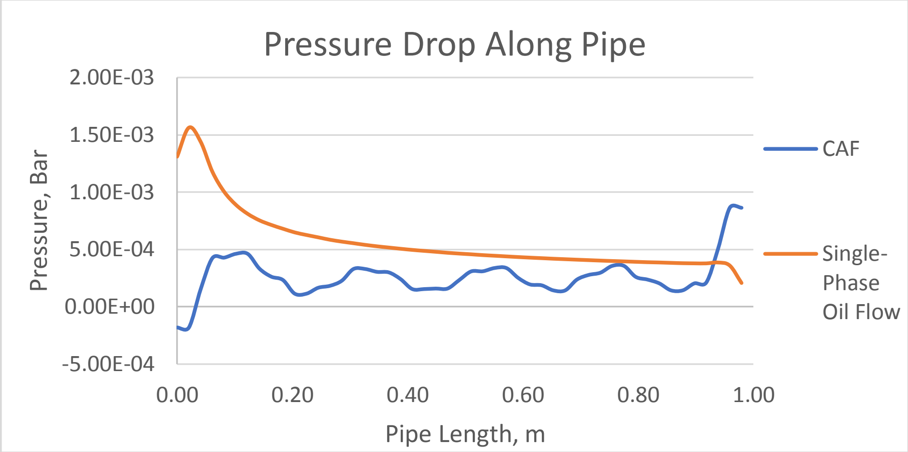


Figure 3. 4 Pressure Drop Profile

more efficient from this pressure drop analysis.

3.5 Pumping Power

The main objective of developing the CAF method is to reduce the frictional force that occurs in the pipe, thereby reducing the required pump pressure. Equation used in this study is based on the Engineering Data Book FPS Version Volumes I & II Sections 1-26, so it is used as in Equation (1)

$$P = \frac{\Delta P \; x \; Q}{36 \; X \; Mechanical \; Efficiency \; X \; Elcetrical \; Efficiency} \tag{1}$$

where:

P	: Pump Power, kW
ΔP	: Pressure Drop, Bar
Q	: Flow rate, m^3/h
Mechanical Efficiency	: Rule of thumb = 0.5
Electrical Efficiency	: Rule of thumb = 0.9

In the simulation results, the single-phase oil flow requires a power of 0.0977 kW. Meanwhile, CAF requires a pump power of about 50% of the single-phase oil flow, which is 0.0454 kW as shown in Table 3.1

	Pumping Power Calculation	
Flow Type	*Single-Phase Oil Flow*	*CAF*
Pressure Drop	0,028 bar	0,013 bar
Pumping Power	0,0977 kW	0,0454 kW

Table 3. 1 Pumping Power Data

4 Conclusion

It is known that an important factor affecting the stability of CAF is the difference in density and viscosity between oil and water, as well as the geometry of the pipes used. The simulation in this study uses well-proven Computational Fluid Dynamics which shows the behavior of two immiscible fluids accurately through volume fraction analysis. Based on the simulation results, the method of pipeline transportation using the CAF method is proven to reduce pressure drop by 50% and also reduce pump power by up to 50% compared to single-phase oil flow. CAF has good projections in the future that can be developed and applied on an industrial scale.

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