Pumping Heavy Oil with Water Lubrication

An Online Continuing Education Course for Engineers

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Pumping Heavy Oil with Water Lubrication

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Introduction

This course provides an overview of the concepts of pumping heavy oil with a focus on the use of water lubrication. Adequate amounts of water are injected into the heavy oil flow to create an annulus or ring that forms around the heavy oil. The annulus delivers a small amount of water at high pressure into the oil stream. This creates a water ring that contacts the pipe or hose wall, thereby reducing friction compared to pumping oil only. The reduction in friction causes less of a pressure drop or loss. This type of oil pumping application is called core annular flow (CAF) since the lubrication water forms an annulus or ring around the oil core.

This course will provide an overview of the governing equations of core annular flow's behavior. Pressure drop and stability of the core annular flow stability will be addressed. Because of its complexity, core annular flow systems are designed typically using both quantitative and experimental methods. Core annual flow systems represent an extraordinarily complex field dependent on advanced numerical methods, computer-aided design, and results from field experiments. A synopsis is provided of core annual flow research such as numerical analysis and experimentation results on oil flow velocity and Reynolds number.

This is not an advanced fluid mechanics course. This course will not present advanced research results but provide an overview of pumping heavy oil via core annular flow. It is presented so that an engineer with a limited fluid mechanics background can understand it. There will be some quantitative explanations and a larger amount of qualitative description. However, there will be more practical emphasis on the design and operation of a heavy oil pumping system. The primary focus will be on the United States Navy's viscous oil pumping system (VOPS) as a real-world example or application. The author was a project manager for the VOPS design and manufacturing. This includes a discussion of the configuration and performance of the viscous oil pumping system's positive displacement screw pump.

Objectives

The student will learn about the following:

- The concepts of pumping heavy oil and application of core annular flow (CAF) such as water holdup and Reynolds number for multi-fluid flow
- The fundamental equations of pumping heavy oil such as the Fluid Energy Equation
- The equipment such as a screw pump for pumping heavy oil

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- The performance of the equipment which includes calculating the pump brake horsepower (BHP) requirements
- Oil flow concepts like grade lines, pressure drop, API, viscosity, shear rate, and pseudo-plasticity
- Research conducted on CAF for the last 40 years
- Preliminary methods with designing a CAF system such as calculating volumetric flow rates for oil and lubrication water

Overview

More and more oil reserves are being discovered. For example, Brazil has an oil reserve of at least eleven billion barrels, and about three billion of that is heavy oil. Heavy oil is characterized by high viscosity, which is why it is also called viscous oil. Viscosity is a fluid's resistance to flow. Another example of heavy oil is bitumen, a dense and very viscous hydrocarbon that is naturally extracted from such locations as the tar sands reserves of Canada. It also can be found as a residue of petroleum processing, such as distillation. Bitumen is mixed with a diluent to reduce density so that it is easier to pump. This mixture is called by the trade name Canadian Western Select. Without using diluents, very viscous oil is difficult to pump from a reservoir or tank through a pipeline to its destination. Core annular flow allows pumping heavy oil with less of a pressure drop and less of pump power requirements and without the use of a diluent.

Additionally, there is the risk of an accident involving rail cars or cargo ship containing heavy oil. In such an emergency case, the oil would have to be offloaded from them. In some cases, the offloading may be over a distance of at least 1000 feet. The emergency pumping equipment would need to do this in a safe and expeditious manner. This course will focus on the configuration for an emergency pumping system for heavy oil using core annular flow. The same core annular flow concepts apply to the transport of heavy oil in commercial, non-emergency applications.

Viscosity

Viscosity is defined as a fluid's (liquid or gas) resistance to flow when an external force is applied. The viscosity can be measured using a sliding plate viscometer (see Figure 1 below). Two horizontal plates at a distance of (d) are separated between each other, and the fluid is between them. An external force (F) is applied to the top plate, which moves at velocity (v). The bottom plate is stationary. The fluid is exposed to the bottom of the top plate, with a surface area denoted as A.

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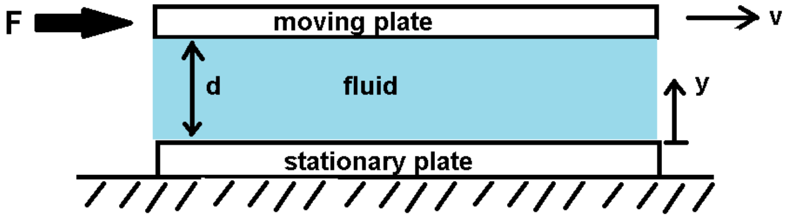

Figure 1: Sliding Plate Viscometer

The further away the fluid is from the stationary plate, the greater the velocity of the fluid. The fluid's greatest velocity is at the distance where y equals d. This is where the fluid contacts the top plate. The lowest velocity of the fluid is at the stationary plate, where the fluid velocity is zero.

The fluid's viscosity is expressed as symbol μ. F/A is the external force divided by the surface area of the moving plate. F/A also represents the shearing stress on the fluid (τ). Shearing or shear stress is from the force (F) acting in parallel or tangential to the material cross-section.

$$\frac{F}{A} = \tau$$

$$\tau = \mu\left(\frac{\Delta \mathrm{v}}{\Delta y}\right) = \mu\left(\frac{d\mathrm{v}}{dy}\right)$$

The above formula applies only to Newtonian fluids, which have constant viscosity (μ). For a Newtonian fluid, a plot of shear stress (τ) versus shear rate or velocity gradient ($d\mathrm{v}/dy$) would be linear with the slope equal to viscosity (μ). The shear rate is the change in velocity that corresponds to the change in distance from the bottom stationary plate.

Later, there will be discussion on heavy oil exhibiting some tendency to exhibit non-Newtonian fluid characteristics. The heavy oil's viscosity decreases to some extent, with an increase in shear rate. This is advantageous for pumping heavy oil as a reduction in viscosity results in lower friction and, ultimately, less pump power.

Viscosity expressed as the symbol μ is known as absolute or dynamic viscosity. Its units of measurement include poise (P), centipoise (cP), N-s/m^2 and lb_f-s/ft^2.

$$1 \text{ poise} = 2.089 \times 10^{-3} \frac{\mathrm{lb_f - s}}{\mathrm{ft^2}} = 0.1 \frac{\mathrm{N - s}}{\mathrm{m^2}}$$

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$$1 \text{ centipoise} = 0.01 \text{ poise} = 2.089 \times 10^{-5} \frac{\text{lb}_\text{f} - \text{s}}{\text{ft}^2} = 0.001 \ \frac{\text{N} - \text{s}}{\text{m}^2}$$

Heavy oil generally has at least a dynamic (or absolute) viscosity of 100 cP at 20 ^{o}C or 68 ^{o}F.

Viscosity also is measured in units of kinematic viscosity, which is denoted as ν .
Kinematic viscosity is equal to absolute viscosity (μ) divided by the density of the fluid (ρ).

$$\nu = \frac{\mu}{\rho}$$

Kinematic viscosity is traditionally measured by noting the time taken for a fluid sample to travel through an orifice in a capillary under the force of gravity. The units for kinematic viscosity are stoke, centistokes (cSt), m^2/s, and ft^2/s.

$$1 \text{ stoke} = 1.076 \times 10^{-3} \frac{\text{ft}^2}{\text{s}} = 1 \times 10^{-4} \ \frac{\text{m}^2}{\text{s}}$$

$$1 \text{ centistoke} = 1.076 \times 10^{-5} \frac{\text{ft}^2}{\text{s}} = 1 \times 10^{-6} \ \frac{\text{m}^2}{\text{s}}$$

The more viscous the fluid, the more time required for the fluid to leak out of a tube through an orifice opening. Saybolt Seconds Universal (SSU) applies for a scale of kinematic viscosity based on a small orifice opening. The time required for gravity flow of the fluid through 60 cm^3 of a metal tube and through its small opening is called an SSU.

Approximate conversion of SSU to stokes is

$\upsilon = 0.00226(SSU) - 1.95/SSU$ (if SSU is between 32 and 100 seconds)

$\upsilon = 0.00220(SSU) - 1.35/SSU$ (if SSU is 100 seconds or greater)

Saybolt Seconds Furol (SSF) applies for a scale of kinematic viscosity for more viscous oils, which require a large orifice opening such as heavy oil. The time required for gravity flow of the fluid through 60 cubic centimeters of a metal tube and through its large opening is called an SSF.

Approximate conversion of SSF to stokes is

$\upsilon = 0.00226(SSF) - 1.84/SSF$ (if SSF is between 25 and 40 seconds)

$\upsilon = 0.00216(SSF) - 0.60/SSF$ (if SSF is 40 seconds or greater)

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For water, converting between centistokes and centipoise is relatively easy because water has a specific gravity of one. Specific gravity is equal to the density of the liquid, such as oil, divided by the density of water at 70 ^{o}F. The kinematic viscosity (ν) of water at 70^{o} Fahrenheit or 21^{o} Celsius is 1 centistoke (cSt), and the absolute or dynamic viscosity (μ) is 1 centipoise (cP). The conversion is shown below based on 1 N equal to 1 kg-m/s^2 and a water density of 1,000 kg/m^3.

$$\mu = \upsilon\rho$$

$$\mu = (1\ \mathrm{cSt})\left(1{,}000\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)$$

$$\mu = \left(1\ \times 10^{-6}\frac{\mathrm{m}^2}{\mathrm{s}}\right)\left(1{,}000\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)$$

$$\mu = 0.001\ \frac{\mathrm{kg}}{\mathrm{m}-\mathrm{s}}$$

$$\mu = 0.001\ \frac{\mathrm{kg}-\mathrm{m}-\mathrm{s}}{\mathrm{m}^2-\mathrm{s}^2}$$

$$\mu = 0.001\ \frac{\mathrm{N}-\mathrm{s}}{\mathrm{m}^2} = 1\ \mathrm{cP}$$

Heavy oil has a specific gravity less than but nearly equal to one. Specific gravity for liquid such as heavy oil is equal to the density of the liquid at 20 ^{o}C divided by 1,000 kg/m^3. The density of water is assumed to be nearly 1,000 kg/m^3 at 20 ^{o}C. Since heavy oil's specific gravity is nearly equal to one, then its density is nearly equal to that of water. Therefore, the numerical value of its kinematic viscosity is the same as that of its dynamic viscosity. For example, if the heavy oil's kinematic viscosity is 60,000 cSt and specific gravity is 0.98, then its dynamic viscosity is nearly 60,000 cP.

Table 1 below shows the absolute viscosities at 20 ^{o}C (68 ^{o}F) for different fluids.

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Fluid	Absolute or Dynamic Viscosity (centipose)
Acetone	0.3 cP
Water	1 cP
Blood	10 cP
Motor oil sae 10	88 cP
Motor oil sae 30	420 cP
Motor oil sae 40	650 cP
Honey	2,000 cP
Venezuela’s orinoco belt heavy crude oil	10,000 cP
Ketchup	50,000 cP
Toothpaste	90,000 cP
Canadian bitumen (max viscosity)	1,000,000 cP

Table 1: Dynamic Viscosities of Different L ids

Another way to identify hea stitute (API) gravity.
This number is referred is denoted as °API. The
lower the API, the grea g/m^3). An API of 10°
has a specific weight an he below formula. For
simplicity, the notation ‘ ty.

To view the remainder of the course material and to take the quiz for PDH credit, you must purchase the course.

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Extra-heavy oil with an A less heavy oil with
an API greater than 10 wei nge of bitumen,
each with an API less than 1.01. Number 2
diesel fuel has an API of ab itumen has an API
of about 8 and weighs sligh s more to crude
oil, which is a mixture cons the liquid phase in
below ground reservoirs and ressure and temperature. Table 2
below shows the categories y density and API.

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