Transportation of Heavy Crude Oil: A Review

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Abstract - *There are different types of crude oil based on their composition, constituents and various other factors. Crude oil having API less than 20 and being highly viscous are called the heavy crude oils which has a comparatively higher density/specific gravity when compared to the lighter crude oils. Positive displacement pumps are used for the pumping of heavy crude. The different types of positive displacement pumps are discussed which is followed by the myriad pressure drop calculation correlations. There are methods employed in the transport of heavy crude which includes reducing its viscosity, reducing drag and upgrading the in-situ oil. The various problems encountered during the transport is discussed which is supported by the remedial measures/ solutions to solve/ minimize such problems.*

***Key Words*: Heavy Crude Oil; Pumps; Correlations; Transport Problems and Solutions**

1. INTRODUCTION

Heavy crude oil is the liquid petroleum which has an API gravity less than 20 degrees its specific gravity is greater than compared to lighter crude oil. It has high viscosity. Due to presence of high viscosity the flow of this heavy crude oil is difficult. It is the compounds of higher molecular weight which gives heavy oil this characteristic of having higher specific gravity. There is also a great amount of asphaltene content present in the heavy oil. The presence of asphaltenes and heavy molecular weight compounds, absence of low molecular weight compounds results in the high viscosity of about 10^3 to 10^6 cP and low API gravity (less than 20API). A Positive Displacement (PD) rotary pump is always an easy choice. There are four common types of PD pumps available: internal gear, external gear, timed lobe, and vane. Inlet-conditions required flow rate, differential pressure, temperature, particle size in the liquid, abrasive characteristics, and corrosiveness of the liquid must be determined before a pump selection is made. A pump needs proper suction conditions to work well. PD pumps are self-priming, and it is often assumed that suction conditions are not important, but they are. Each PD pump has a minimum inlet pressure requirement to fill individual pump cavities. If these cavities are not completely filled, total pump flow is diminished.

1.1 Internal Gear Pumps

Fig -1: Internal Gear Pump

Internal gear pumps are ideal for high-viscosity liquids, but they are damaged when pumping large solids.

Because of their ability to operate at low speeds, internal gear pumps are well suited for high-viscosity applications and where suction conditions call for a pump with minimal inlet pressure requirements.

Internal gear pumps have successfully pumped liquids with viscosities above 1,320,000 cSt / 6,000,000 SSU and very low viscosity liquids, such as liquid propane and ammonia.

1.2 External Gear Pumps

Fig -2: External gear pumps (shown is a double pump)

External gear pumps are typically used for high-pressure applications such as hydraulics. External gear pumps are similar in pumping action to internal gear pumps in that two gears come into and out of mesh to produce flow (Figure 2).

External gear pumps handle viscous and watery-type liquids, but speed must be properly set for thick liquids. Gear teeth come out of mesh in a short time, and viscous liquids need time to fill the spaces between gear teeth. As a result, pump speed must be slowed down considerably when pumping viscous liquids.

The pump does not perform well under critical suction conditions. Volatile liquids tend to vaporize locally as gear teeth spaces expand rapidly. When the viscosity of pumped liquids rises, torque requirements also rise, and pump shaft strength may not be adequate. Pump manufacturers supply torque limit information when it is a factor.

1.3 Lobe Pumps

Fig -3: Lobe Pump

Lobes in lobe pumps do not make contact, because they are driven by external timing gears. This design handles low-viscosity liquids.

Lobe pumps (Figure 3) are similar to external gear pumps in operation, except the pumping elements or lobes do not make contact. Since the lobes do not make contact, and clearances are not as close as in other PD pumps, this design handles low viscosity liquids with diminished performance. High-viscosity liquids require considerably reduced speeds to achieve satisfactory performance. Reductions of 25% of rated speed and lower are common with high-viscosity liquids.

1.4 Vane Pumps

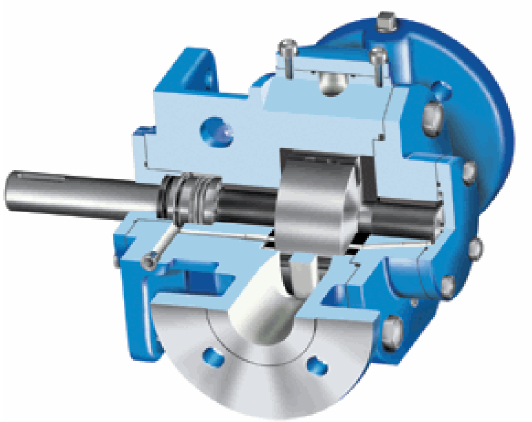

Fig -4: Vane Pump

Vane pumps have better dry priming capability than other positive displacement pumps.

Sliding vane pumps (Figure 4) operate quite differently from gear and lobe types. A rotor with radial slots, is positioned off-center in a housing bore. Vanes that fit closely in rotor slots slide in and out as the rotor turns. Vane action is aided by centrifugal force, hydraulic pressure, or pushrods. Pumping action is caused by the expanding and contracting volumes contained by the rotor, vanes, and housing.

Vane pumps usually operate at 1,000 rpm, but also run at 1,750 rpm. The pumps work well with low-viscosity liquids that easily fill the cavities and provide good suction characteristics. Speeds must be reduced dramatically for high-viscosity applications to load the area underneath the vanes. These applications require stronger-than-normal vane material.

2. PRESSURE DROP CORRELATIONS

There are several fluid correlations, derived empirically, that account for the hydrostatic and frictional fluid losses in a wellbore under a variety of flow conditions. The correlations that are considered are as follows:

Single Phase - Wellbores and pipelines:

- Fanning Gas
- Panhandle
- Modified Panhandle
- Weymouth

Multi-phase - Pipeline:

- Modified Beggs & Brill
- Petalas and Aziz
- Flanigan
- Modified Flanigan

Multi-phase - Wellbore:

- Modified Beggs & Brill
- Gray
- Hagedorn & Brown

The majorly used correlations are the Fanning Correlation, Panhandle Correlation, Modified Panhandle Correlation, Weymouth Correlation and the Fanning Gas Correlation.

2.1 Fanning Correlation

The Fanning correlation is divided into two subcategories Fanning Liquid and Fanning Gas. The Fanning Gas correlation is also known as the Multi-step Cullender and Smith when applied for vertical wellbores.

The Fanning correlation can be written as follows:

$$\Delta P_f = \frac{2 f \rho V^2 L}{g_c D}$$

Where,
ΔP_f = pressure loss due to friction effects (psia)
f = Fanning friction factor (function of Reynolds number)
ρ = density (lbm/ft^3)
v = average velocity (ft/s)
L = length of pipe section (ft)
g_c = gravitational constant (32.174 lbmft/lbfs2)
D = inside diameter of pipe (ft)

This correlation can be used either for single-phase gas (Fanning Gas) or for single-phase liquid (Fanning Liquid).

2.2 Panhandle Correlation

The Panhandle correlation was developed originally for single-phase flow of gas through horizontal pipes. In other words, the hydrostatic pressure difference is not taken into account. We have applied the standard hydrostatic head equation to the vertical elevation of the pipe to account for the vertical component of pressure drop. Thus our implementation of the Panhandle equation includes both, horizontal and vertical flow components, and this equation can be used for horizontal, uphill and downhill flow.

The Panhandle correlation can be written as follows:

$$P_1^2 - P_2^2 = T_a L z_a \,\kappa\, \frac{G^{0.8539}}{D^{4.8539}} \left[\frac{Q_G^\circ}{E}\right]^{1.8539} \left[\frac{P^\circ}{T^\circ}\right]^2$$

Where, κ = 1.279 x 10-5

Hydrostatic Pressure Difference

The original Panhandle equation only accounted for. However, by applying the hydrostatic head calculations the Panhandle correlation has been adapted for vertical and inclined pipes. The hydrostatic head is calculated by:

$$\Delta P_{HH} = \frac{\rho_G g \Delta z}{144 g_c}$$

Nomenclature,
D = pipe inside diameter (in)
E = Panhandle/Weymouth efficiency factor
G = gas gravity
g = gravitational acceleration (32.2 ft/ s^2)
g_c = conversion factor (32.2 (lbm ft) / (lbf s^2))
L = length (mile)
P° = reference pressure for standard conditions
P_1 = upstream pressure
P_2 = downstream pressure
ΔP_{HH} = pressure change due to hydrostatic head (psi)
$Q°_G$ = gas flow rate at standard conditions, T°, P°, (ft^3/d)
T° = reference temperature for standard conditions (°R)
T_a = average temperature (°R)
z_a = average compressibility factor
Δz = elevation change (ft)
ρ_G = gas density (lb/ft^3)

The Panhandle equation incorporates a simplified representation of the friction factor, which is built into the equation. To account for real life situations, the flow efficiency factor, E, was included in the equation. This flow efficiency generally ranges from 0.8 to 0.95. Although we recognize that a common default for the flow efficiency is 0.92, our software defaults to E = 0.85, as our experience has shown this to be more appropriate [1].

2.3 Modified Panhandle Correlation

The Modified Panhandle correlation is a modified version of the original Panhandle equation (Gas Processors Suppliers Association, 1980) and is sometimes referred to as the Panhandle Eastern Correlation or the Panhandle B correlation. [2] As such, the Modified Panhandle is also a single- phase correlation for horizontal flow. As with the original Panhandle equation, we have applied the standard hydrostatic head equation to the vertical component of the pipe, and thus, our Modified Panhandle correlation accounts for horizontal, inclined and vertical flow. The Modified Panhandle correlation can only be used for single-phase gas flow.

The pressure drop due to friction is given by:

$$P_1^2 - P_2^2 = T_a L z_a \,\kappa\, \frac{G^{0.9608}}{D^{4.9608}} \left[\frac{Q_G^\circ}{E}\right]^{1.9608} \left[\frac{P^\circ}{T^\circ}\right]^2$$

Where: κ = 2.385 x 10-6

Hydrostatic Pressure Difference

We have accounted for the vertical component of flow in pipes by using the standard equation for hydrostatic head.

$$\Delta P_{HH} = \frac{\rho_G g \Delta z}{144 g_c}$$

Nomenclature,
D = pipe inside diameter (in)
E = Panhandle/Weymouth efficiency factor
G = gas gravity
g = gravitational acceleration (32.2 ft/ s^2)
g_c = conversion factor (32.2 (lbm ft) / (lbf s^2))
L = length (mile)
P° = reference pressure for standard conditions
P_1 = upstream pressure
P_2 = downstream pressure
ΔP_{HH} = pressure change due to hydrostatic head (psi)
$Q°_G$ = gas flow rate at standard conditions, T°, P°, (ft^3/d)
T° = reference temperature for standard conditions (°R)
T_a = average temperature (°R)
z_a = average compressibility factor
Δz = elevation change (ft)
ρ_G = gas density (lb/ft^3)

Like the original Panhandle equation, the Modified Panhandle equation used a simplified representation of the friction factor, which was built into the equation. To account for real life situations, a flow efficiency, E, was included in the equation. Although this efficiency factor is generally thought to range from 0.88 to 0.94, our software defaults to E = 0.80, as this is more appropriate. [1]

2.4 Weymouth Correlation

This correlation is similar in its form to the Panhandle and the Modified Panhandle correlations. It was designed for single- phase gas flow in pipelines. As such, it calculates only the pressure drop due to friction. However, we have applied the standard equation for calculating hydrostatic head to the vertical component of the pipe, and thus our Weymouth correlation accounts for Horizontal, Inclined and, Vertical pipes. The Weymouth equation can only be used for single-phase gas flow.

Friction Pressure Loss

The pressure drop due to friction is given by:

$$P_1^2 - P_2^2 = T_a L z_a \, \boldsymbol{\kappa} \, \frac{G}{D^{5.334}} \left[\frac{Q_G^\circ}{E}\right] \left[\frac{P^\circ}{T^\circ}\right]^2$$

Where: κ = 5.3213 x 10-6

The Weymouth equation incorporates a simplified representation of the friction factor, which is built into the equation. To account for real life situations, the flow efficiency factor, E, was included in the equation. The flow efficiency generally used is 115%.[1] [3]

Hydrostatic Pressure Difference

The original Weymouth equation only accounted for ΔPf. However, by applying the hydrostatic head calculations, the Weymouth equation has been adapted for vertical and inclined pipes. The hydrostatic head is calculated by:

$$\Delta P_{HH} = \frac{\rho_G g \Delta z}{144 g_c}$$

Nomenclature,
D = pipe inside diameter (in)
E = Panhandle/Weymouth efficiency factor
G = gas gravity
g = gravitational acceleration (32.2 ft/ s^2)
g_c = conversion factor (32.2 (lbm ft) / (lbf s^2))
L = length (mile)
P° = reference pressure for standard conditions
P_1 = upstream pressure
P_2 = downstream pressure
ΔP_{HH} = pressure change due to hydrostatic head (psi)
$Q°_G$ = gas flow rate at standard conditions, T°, P°, (ft^3/d)
T° = reference temperature for standard conditions (°R)
T_a = average temperature (°R)
z_a = average compressibility factor
Δz = elevation change (ft)
ρ_G = gas density (lb/ft^3)

The Weymouth correlation is of the same form as the Panhandle and the Modified Panhandle equations. It was originally developed for short pipelines and gathering systems. As a result, it only accounts for horizontal flow and not for hydrostatic pressure drop. We have applied the standard hydrostatic head equation to account for the vertical component of pressure drop. Thus, our implementation of the Weymouth equation includes both horizontal and vertical flow components, and this equation can be used for horizontal, uphill and downhill flow.

2.5 Fanning Gas Correlation

This correlation is also known as Multi-step Cullender and Smith. The Fanning friction factor pressure loss (ΔP_f) can be combined with the hydrostatic pressure difference (ΔP_{HH}) to give the total pressure loss. The Fanning Gas Correlation is the name used in this document to refer to the calculation of the hydrostatic pressure difference (ΔP_{HH}) and the friction pressure loss (ΔP_f) for single-phase gas flow, using the following standard equations.

This formulation for pressure drop is applicable to pipes of all inclinations. When applied to a vertical wellbore it is equivalent to the Cullender and Smith method. However, it is implemented as a multi-segment procedure instead of a two-segment calculation.

Friction Pressure Loss

The Fanning equation is widely thought to be the most generally applicable single-phase equation for calculating friction pressure loss. It utilizes friction factor charts (Knudsen and Katz, 1958), which are functions of Reynold's number and relative pipe roughness. These charts are also often referred to as the Moody charts. We use the equation form of the Fanning friction factor as published by Chen, 1979.

$$\frac{1}{\sqrt{f}} = -4.0 log \left[0.2698\left({}^{k}/_{D}\right) - \frac{5.0452}{Re} log\left\{0.3539\left({}^{k}/_{D}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}}\right\}\right]$$

The method for calculating the Fanning Friction factor is the same for single-phase gas or single-phase liquid.

Hydrostatic Pressure Difference

The calculation of hydrostatic head is different for a gas than for a liquid, because gas is compressible and its density varies with pressure and temperature, whereas for a liquid a constant density can be safely assumed. Either way the hydrostatic pressure difference is given by:

$$\Delta P_{HH} = \frac{g}{144 g_c} \rho_G \Delta z$$

Since varies with pressure, the calculation must be done sequentially in small steps to allow the density to vary with pressure.

Nomenclature,
D = pipe inside diameter (in)
f = Fanning friction factor
g = gravitational acceleration (32.2 ft/ s^2)
g_c = conversion factor (32.2 (lbm ft) / (lbf s^2))
k/D = relative roughness (unitless)
L = length (ft)
ΔP_{HH} = pressure change due to hydrostatic head (psi)
ΔP_f = pressure change due to friction (psi)
Re = Reynold's number
V = velocity (ft/s)
Δz = elevation change (ft)
ρ_G = gas density (lb/ft^3)

3. PROBLEMS IN TRANSPORT AND SOLUTIONS

Transportation of heavy crude oil to pipeline is difficult because of low mobility and less flow of the crude.

There are several other factors that affect the flow of heavy oil in pipelines such as the wax and asphaltene deposition on the pipeline internal wall surfaces.

An example of the composition of heavy crude oil containing different amounts of asphaltene and molecular weights has been illustrated in Table 1.

Table -1: Properties and composition of medium, heavy and extra-heavy Mexican crude oil. [4] [5]

Parameter	Mexican Crude Oils		
	Medium	Heavy	Extra-Heavy
API gravity	21.27	11.90	9.17
Molecular weight (g/mol)	314.8	486	507.8
Sulfur content (%)	3.40	5.0	4.80
Water content (%)	1.80	0.05	0.05
SARA analysis			
Saturates	26.53	7.94	15.00
Aromatics	14.74	5.28	19.11
Resins	47.60	70.93	46.78
Asphaltenes (from n- C7)	11.13	15.85	19.11

With this we can observe the variation in the API gravity of the oil taking under consideration, the different amounts of substances present in it.

This distinguishes it from it being medium, heavy or extra- heavy.

Now the question of how we transport this heavy crude oil through pipes arises. This can be accomplished by:

1. Viscosity Reduction
2. Drag Minimization
3. Upgrading in-situ oil

We can reduce the viscosity of the oil by diluting it with other substances by-

- Formation of oil-in-water emulsions.
- Increasing or trying to save/conserve the oil's temperature
- Lowering down the pour point

Well, dilution does have a few problems that has to be taken care of.

During dilution any change in oil composition can affect the required oil solvent ratio.

Special attention must be given to the asphaltene and parafins stability, since condensate or light oil addition can cause precipitation and clogging of the pipeline [6]

Formation of oil in water in emulsions can reduce the viscosity of heavy crudes and help in transport.

An effective way to reduce the viscosity of heavy oil is the formation of oil in water emulsions with the help of surfactant agents. This will reduce the interfacial tension.

Effect of heat on viscosity is very significant. Increase in heat/temperature of oil reduced its viscosity.

There is a requirement for heating and pump stations at regular intervals throughout the length of the pipeline. Many polymer compounds have been described as pour point depressants, the most extensively used for waxy heavy oils are highly branched poly-α-olefin [7], alkyl esters of unsaturated carboxylic acid-α-olefin copolymers [8], ethylene-vinyl fatty acid ester [9] [10] [11], vinyl acetate-α-olefin styrene maleic anhydride copolymers [12], long-chain fatty acid amides and poly-n-alkyl acrylates.[13].

There is a lot of losses in flow energy due to drag. This causes the pressure to drop. We should use drag reducing additives These additives prevent the formation of turbulent eddies by absorption of energy released by breakdown of lamellar layers. Drag reducing agents such as:

- Surfactants
- Fibers
- Polymers

Surfactants can reduce the surface tension of a liquid while fibers and polymers orient themselves in the main direction of the flow, limiting eddies appearance which results in drag reduction. A study suggests the formation of polymer films inside the crude oil's matrix that lubricates it and allows an effective drag reduction.[14]

There are various problems such as pipeline clogging which would be a result of not monitoring the viscosity and temperature.

4. CONCLUSION

In this study of heavy crude oil, we see the pumps which are required for the transport, the various correlations to calculate the pressure drop, the problems faced during the transport and the requisite solutions for the same. We notice that there are a lot of solutions which deals with altering the properties of crude, let it be, with the dilution of crude to accommodate lighter crude as solvent, increasing the temperature, reducing the viscosity, and adding chemical additives which would lower the pour point and for emulsification. The various problems and the solutions for the same were discussed. The needs for improved and new chemicals should boost the research and development on surfactants, flow improvers, drag reducing agents, catalysts and other valuable additives. Besides the need for fundamental research, future developments on crude oil transportation should be based on results from pilot plant and semi-industrial facilities, like instrumented loop pipelines and reactors, in order to offer to the end-users a reliable and tailor-made technology. Soon, the technological advancements are likely to be aligned with the anticipated requirements to transport the increasing production of heavy and extra-heavy crude oils. This might require the convergence of several technologies in order to satisfy the local and specific requirements of the petroleum industry. Then, we expect that new developments will migrate from out-of-well to inside-the reservoir technologies where, i.e. the O/W emulsion could be formed, or the crude oil might be upgraded inside the reservoir itself.

5. AUTHOR AFFILIATION

With the help of this paper we are trying to throw some light on and get some insights on heavy crude oil. This would give us an idea of what are the challenges being faced currently. The focus on addressing the issues and giving radical solutions for the same instills the positive movement towards the development of the pre-existing approaches. Not only are these problems limited to this type of oil. There are myriad solutions which are applicable for various types of oil. We should have the audacity to interpret the importance that has to be given to every intricate problem with the implementation of the right direction supported by different correlations and experimentation.

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