NON-NEWTONIAN FLOWS IN PIPELINES

Abstract

There are many analytical methods that can be employed by Flow Assurance engineers to great benefit and saving. One such example is for the analysis of Non-Newtonian fluids, such as gelled oils. A method has been developed and successfully employed on such diverse systems as a deepwater flowline containing a gelled oil and the effluent stream from a pharmaceutical reactor. Gelled oils in pipelines present a particularly difficult problem as their rheological behaviour can be a function of temperature and the history of how the gel was formed. This leads to considerable uncertainty associated with the fluid properties. Given these uncertainties, a fit-for-purpose model is described which predicts the flows of gels in pipes. This model provides a cost-effective and inexpensive alternative to expensive add-ons to transient simulators.

Non-Newtonian Fluid Mechanics

Non-Newtonian fluids (i.e. fluids which do not obey Newton's law of viscosity and have an effective viscosity which is a function of the shear rate) appear in many different industries including the food, sewage and pharmaceutical industries. Waxy crudes in the oil industry can also form non-Newtonian gels if allowed to cool below their gel-points. This can present a particular problem as the pressure drop required to move the gel may be many times that required when the fluid is above its gel-point.

The behaviour of gels under flowing conditions can typically be described by the Herschel-Bulkley model:

$$\tau_{rz} = -\mu_0 \left(-\frac{du_z}{dr} \right)^n - \tau_y \qquad (1)$$

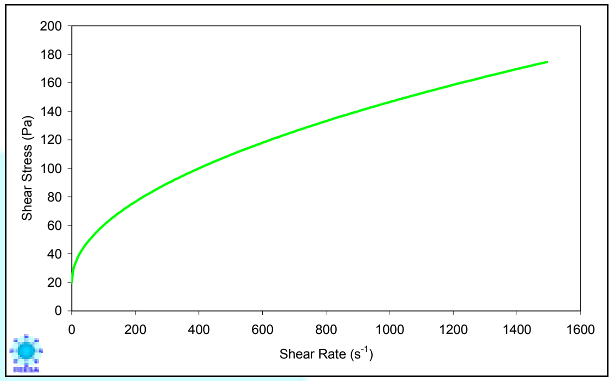
Where τ_{rz} is the shear stress in the z direction (i.e. is negative if in the opposite direction to flow), τ_y is the yield stress of the material, μ_0 and n are parameters specific to that particular fluid. The effect of temperature is often captured with an exponential decay function for μ_0:

$$\mu_0 = \mu_I e^{-\varsigma T} \qquad (2)$$

Where μ_I and ζ are constants and T is the temperature in Kelvin. Parameters μ_I, ζ (or μ_0 if the system is isothermal) n and τ_y can be obtained from rheometer tests on the fluid.

Typical output from a rheometer, in the form of a shear stress versus shear rate plot is shown in Figure 1.

Figure 1 Shear Stress – Rate Plot for a Typical Gel



It should be noted that some of the more common fluid types (e.g. Newtonian, power law fluids or Bingham plastics) are also represented by the Herschel-Bulkley model. Newtonian fluids are when τ_y is zero and n is unity, power law fluids are when τ_y is zero but n is some value other than unity and Bingham plastics have n as unity but τ_y as some finite number. Hence the Herschel-Bulkley model applies equally well to these other types of fluids.

The first analysis a process engineer would carry out on a gelled pipeline is probably a simple force balance. This is to calculate the pressure drop required across the pipeline to exactly match the yield stress acting at the wall-gel interface. In other words this is the minimum pressure drop that must be applied to make the gel begin to flow. For a horizontal pipe the expression is:

$$\Delta p_{yield} = \frac{2L\tau_y}{R} \qquad (3)$$

Where R and L are the pipeline radius and length, respectively.

This equation is correct, however it only tells us the pressure drop required to overcome the yield stress of the fluid, not the pressure drop required to achieve a given non-zero flow rate.

To move the fluid at any appreciable rate may take a significantly higher pressure drop than the yield stress pressure drop.

A flow equation can be derived analytically from first principles with a Herschel-Bulkley fluid assuming laminar flow. First one must check that the form of

Reynolds number applicable for Herschel-Bulkley fluids (known as the Metzner Reed Reynolds number) is in the laminar flow region. This is defined thus:

$$Re = \frac{\rho \bar{u} D}{\mu_W \left(\frac{3n+1}{4n}\right)\left(\frac{1}{1 - aX - bX^2 - cX^3}\right)} \qquad (4)$$

Where $\bar{u}$ is the average velocity and D the pipe diameter and:

$$\mu_W = \tau_W^{\left(\frac{n-1}{n}\right)}\left(\frac{\mu_0}{1-X}\right)^{\left(\frac{1}{n}\right)} \qquad (5)$$

$$X = \frac{\tau_y}{\tau_W} \qquad (6)$$

$$a = \frac{1}{(2n+1)} \qquad (7)$$

$$b = \frac{2n}{(n+1)(2n+1)} \qquad (8)$$

$$c = \frac{2n^2}{(n+1)(2n+1)} \qquad (9)$$

$$\tau_W = \frac{R\Delta p_f}{2L} \qquad (10)$$

The system is deemed to be in laminar flow if this Metzner Reed Reynolds number is less than 2200.

If the flowing gel is in the laminar region, one can now derive the flow equation for Herschel-Bulkley fluids.

In vector form, the conservation of linear momentum may be written as:

$$\rho \frac{\partial \underline{u}}{\partial t} + \rho \underline{u} \bullet \nabla \underline{u} = \rho \underline{g} - \nabla p + \nabla \bullet \underline{\underline{\tau}} \qquad (11)$$

Where:

ρ is the fluid density

$\underline{u}$ the velocity vector

$\underline{g}$ the gravity body force vector

p the pressure

$\underline{\underline{\tau}}$ the stress tensor

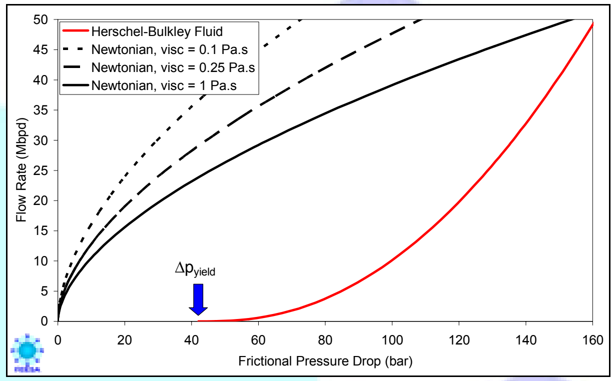
In cylindrical polar coordinates with velocity components u_r, u_θ and u_z in the r, θ and z directions, respectively, this equation becomes:

$$\frac{1}{r}\frac{\partial}{\partial r}(r u_r) + \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{\partial u_z}{\partial z} = 0 \qquad (12)$$

Using the continuity equation, Equation 1 and Equation 11 and integrating across the diameter of the pipe the following expression relating the volumetric flow rate to the applied pressure drop is obtained:

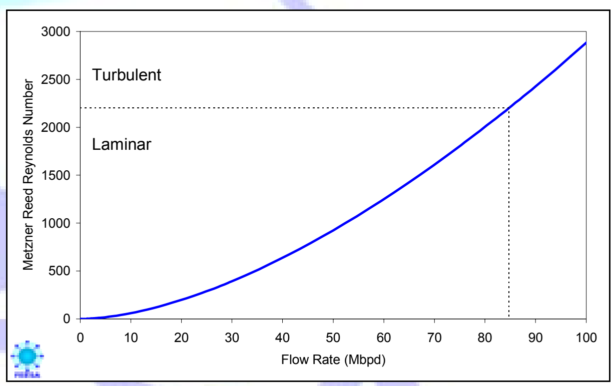
$$Q = \frac{\pi}{\mu_0^{\frac{1}{n}}}\left(\frac{2L}{\Delta p_f}\right)^3 \left[\frac{\tau_w^2(\tau_w - \tau_y)^{\frac{1}{n}+1}}{\frac{1}{n}+1} - \frac{2\tau_w(\tau_w - \tau_y)^{\frac{1}{n}+2}}{(\frac{1}{n}+1)(\frac{1}{n}+2)} + \frac{2(\tau_w - \tau_y)^{\frac{1}{n}+3}}{(\frac{1}{n}+1)(\frac{1}{n}+2)(\frac{1}{n}+3)}\right] \qquad (13)$$

Figure 2 Typical Flow Equations



This equation has been plotted in Figure 2 for a 10 km 8-inch pipe with a Herschel-Bulkley gel and with μ_0, n and τ_y of 4, 0.5 and 20 Pa, respectively. The Metzner Reed Reynolds number (Equation 4) has been plotted in Figure 3 as a function of flow rate in this system. As can be seen, the 2200 transition between laminar and turbulent flow is at 85,000 bpd, hence equation 13 is only valid at flow rates less than about 85,000 bpd.

Figure 3 The Laminar – Turbulent Transition



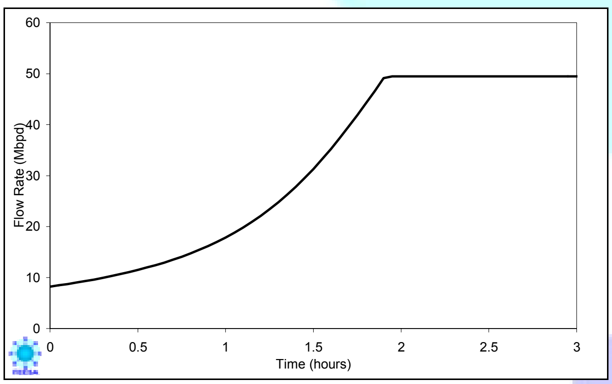
Using Equation 3 the pressure drop to create the yield stress at the wall is 42 bar, this is shown in Figure 2. However, the Herschel-Bulkley flow curve in Figure 2 also shows that a significantly greater pressure drop is required to flow the gel at any significant flow rate (for example 136 bar for 30Mbpd).

This study highlights the importance of a complete non-Newtonian analysis and that the simple yield stress pressure drop calculation is insufficient when investigating the hydraulics of gels in oil pipelines.

Also shown in Figure 2 are flow curves for Newtonian fluids with different viscosities to show how different Newtonian and non-Newtonian fluids behave with pressure drop.

Using these flow performance curves with a specified pump curve and some simplifying assumptions, it is possible to perform transient calculations for such systems. One example given below is the displacement of a gelled flowline with a Newtonian fluid. Such an operation could be the hot-oiling of a gelled flowline. A detailed accurate transient simulation should take into account the thermal dependence of the Herschel-Bulkley parameters (Equation 2). However, neglecting these complicating factors, it is possible to generate a simplified transient plug flow model which can be implemented conveniently in a spreadsheet. Such a model can predict how the system moves from the initial state being full of gel, to the final state being full of hot flowing oil. Provided the displacement time is not needed to the nearest minute such simple models are sufficient in many cases. Figure 4 presents an example and shows that it takes the pump 2 hours to displace the gel, making the system Newtonian and easier to pump.

Figure 4 Transient Gel Calculation Results



Gels Have Long Memories

The proposed analysis is relatively straightforward to implement, and provides an efficient method for modelling non-Newtonian flows in pipelines. However, caution is required when interpreting the results. It is important to note that the model is only as good as the empirical parameters on which it is based. Therein lies the essential difficulty in predicting the flows of gelled oils, namely that these empirical parameters can varying enormously even for the same oil. In particular, the parameters are a very strong function of the history of how the gelled was formed. For example, the flow rate at which the oil cools, the speed with which it is cooled and the length of time it is left stagnant can all affect the empirical constants.

In order to have confidence in the predictions, care must be taken to ensure that the rheometer tests are carried out on a sample that has been treated in a similar manner to that in which the flowline fluid will be handled. Even then, an exact replication of the *in situ* flowline fluids may not be feasible.

With these difficulties in mind, there would seem little benefit in employing a more elaborate approach, such as a transient flowline software, if the rheological properties of the pipeline fluid cannot be reliably predicted.

Close liaison between the Flow Assurance engineer and the testing laboratory is advisable in order to ensure that a reasonable *worst case* gel treatment is tested.

Conclusion

This case study highlights the importance of a thorough rheological analysis of non-Newtonian fluids such as gelled oils. A method is presented for predicting the flow rate of a non-Newtonian Herschel-Bulkley type fluid through a pipeline under the conditions of an applied pressure drop. The method improves on the simple yield stress / pressure drop calculation which is standard in the industry.

However, it is emphasised that the essential difficulty of predicting non-Newtonian flows of oils in pipelines, is selecting representative rheological parameters to describe the fluid used in the industrial application. In particular, the history of the treatment of the oil can lead to wide variations in its rheological behaviour resulting in markedly different values of the physical properties. Hence, the prediction of non-Newtonian oils reduces to the problem of determining a sound and representative basis for the calculations.

Notwithstanding these remarks, it is suggested that for many gelled flowline applications, the straightforward method proposed here is sufficient to size delivery pumps for the *worst case* gel behaviour. Furthermore, the method when extended to model the transient displacement of the gel, provides an efficient means by which to estimate the displacement time.