Flow Characteristics of Waxy Crude Oils: Application to Pipeline Design

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Waxy crude oils are highly non-Newtonian materials known to cause handling and pipelining difficulties and whose flow properties are time- and history-dependent. Experimental techniques are described that enable reproducible steady-state flow property data to be obtained from rotational viscometers. The flow properties are shown to depend strongly on the shear rate applied during cooling (shear history effect). This leads to a definable minimum operating point below which flow in a waxy crude oil pipeline would cease. Modified pipeline design techniques are presented for both laminar and turbulent flow at temperatures below the pour point, and it is shown that existing techniques overestimate the flow rate in laminar flow by the order of 100%. The modified design techniques can be used to quantitatively assess the performance of flow improver (pour point depressant) additives under steady-state conditions.

Introduction

The presence of crystallized wax in crude oil and petroleum products converts a simple Newtonian fluid, whose viscosity is readily measured using such devices as glass capillary viscometers, into a very complex non-Newtonian fluid whose flow properties are very difficult to measure in a reliable and repeatable manner even in the most sophisticated viscometers. Many crude oils throughout the world contain significant quantities of wax, which will readily crystallize during the production, transportation and storage of the oil, resulting in an increase in viscosity by several orders of magnitude, oil gelation (the formation of a yield stress) and deposition on pipeline walls.

In the past, research has been carried out primarily to solve the pipelining difficulties of specific crude oils using a range of laboratory viscometers (Perkins and Turner, 1971; Sifferman, 1979; Withers and Mowll, 1982). In some instances, complex and costly pilot-scale pipelines have been utilized (Ford et al., 1965, Wyllie and Jones, 1960; Thomson and Farrant, 1984). However, poor reproducibility of the flow property measurements of different laboratory viscometers and of laboratory and pilot plant data (Davenport and Somper, 1971) has left considerable uncertainty in the scale-up of viscometric data to operating pipelines at temperatures below the pour point of the oil even in the simplest case of steady-state flow.

Many pipelines are maintained at temperatures well above the pour point to avoid the problem of handling a waxy crude oil, for example, by using reheating stations (Yan and Luo, 1987). Maintaining an elevated temperature, however is, not an economic alternative for many pipelines, such as the 0.3-m-dia., 1,100-km Jackson to Brisbane pipeline in southern Queensland, where a combination of blending and the use of flow improver (pour point depressant) additives has been applied successfully to maintain production through the winter months when ground temperatures can fall to 10°C—some 12°C below the pour point of the oil (Thomson and Farrant, 1984).

Originating from consulting work carried out for the Australian oil industry, research has been carried out at the University of Melbourne to determine appropriate measurement techniques for waxy crude oils and to study the parameters affecting the rheology. The most significant parameter has been found to be the effect of the shear rate(s) applied during the cooling of the oil (termed the shear history). Although it has long been recognized that the shear and thermal history must be controlled to measure the flow properties of waxy crude oils (Ford et al., (1965), the role of the shear history in determining the flow properties and the consequent effect on pipeline design has not been fully appreciated.

This article summarizes the measurement techniques needed

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to obtain reproducible results in two commonly used rotational viscometer geometries: the concentric cylinder viscometer and the cone and plate viscometer. Discussed also are the modified design techniques in laminar and turbulent flow for the case of steady-state flow at temperatures below the pour point. It is shown that a single viscosity measurement does not provide enough information for design and overestimates the flow rate by a considerable margin. Flow improver additives act to reduce the effect of the shear history. A quantitative method of assessing flow improver additives is described based on the measurements carried out using a series of shear histories. The complexity of waxy crude oils makes the capillary viscometer and a pilot-scale pipeline largely unsuitable for flow property measurement.

For waxy crude oils, the equilibrium flow curves of samples, cooled under shear, take on the character of yield—pseudoplastic fluids with a small yield stress. Statically cooled (no applied shear) samples possess viscosities and yield stresses several orders of magnitude higher than the equilibrium (sheared) value at the same temperature. The yielding behavior of statically cooled waxy oils is very complex and the application of yield point data to pipeline design is not straightforward. This is discussed elsewhere (Wardhaugh, 1990). It should be emphasized that both the steady-state and the unscheduled shutdown (leading to static cooling) situations must be taken into account in the overall design of a pipeline for waxy crude oils.

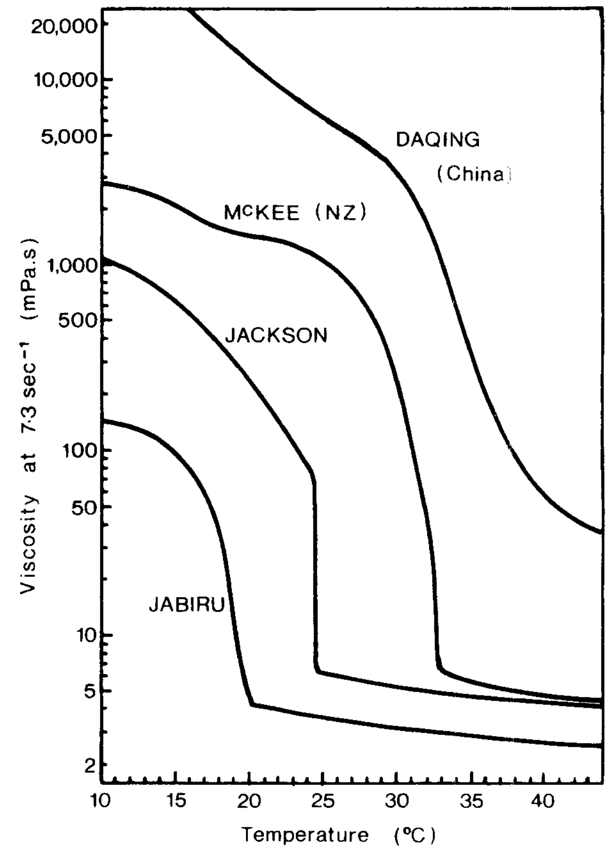

Figure 1. Waxy vs. heavy crude oils.

R19 Weissenberg Rheogoniometer in cone and plate configuration; shear history = 7.3 s^{-1} (constant)
Cooling program (programmer set-points): 54°C to 34°C at 0.49 C/min; 34°C to 20°C at 0.08 C/min; 20°C to 4°C at 0.05 C/min (Wardhaugh and Boger, 1987)

Development of Experimental Techniques

The measurement of the viscosity of waxy crude oil is not simply a matter of placing an oil sample in a viscometer and proceeding to collect data as is the case with many simple fluids. For a waxy oil sample placed in a viscometer, without concern for its prior treatment, the measured viscosity changes with shear and with time, while repeat samples do not give the same results. This is particularly the case for the measurement of the breakdown of a gelled oil. Davenport and Somper (1971) noted that repeatable results could not be obtained even with the same apparatus.

In an earlier publication, Wardhaugh and Boger (1987) showed that only by the removal of fluid memory and the control of the shear and thermal history, can repeatable equilibrium results be obtained in a single viscometer. This is achieved by heating the (well mixed) sample to sufficient temperature to fully dissolve the wax crystals and colloidal asphaltene species, loading into a preheated viscometer and then cooling the sample and the instrument to the test temperature with careful control of the shear rate (usually a constant value during the entire experiment) and cooling rates while monitoring the shear stress. Typical results are shown in Figure 1 for three waxy crude oils (each with a negligible asphaltene content) and for the heavy Daqing crude oil (China) which contains a high proportion of both wax and asphaltene.

A distinction must be made between the flow behavior of waxy crude oils and of heavy crudes that may also contain wax. For the waxy crude oils at high temperatures, Newtonian behavior is exhibited and the oil shows an expected viscosity temperature dependence. However, at a lower temperature termed the "wax crystallization point" (approximating the cloud point), a very rapid increase in viscosity and the onset of non-Newtonian flow behavior occurs. As cooling continues, the viscosity increases by a further order of magnitude. For heavy crude oils, such as Daqing crude, the increase in viscosity occurs more gradually and non-Newtonian behavior may appear at relatively high temperatures due to the associating action of asphaltenic colloidal micelles (Reerink, 1973). For Daqing oil, the transition from Newtonian to pseudoplastic behavior occurs at temperatures between 46°C and 50°C. A plot of shear stress vs. temperature (as in Figure 1) will be referred to as a "comparative test" and its scope is limited to a comparison between (say) treated and untreated samples or a comparison between the dosage rates used. It is possible to make such a comparison on a single graph only if the test conditions are identical for each oil sample. For reasons discussed below, it is not possible to use comparative data (such as Figure 1) directly in design. Similar plots of viscosity vs. temperature have been published by Sifferman (1979) for a range of crude oils and by Withers and Mowll (1982) who used the data directly in Newtonian design equations.

As the test temperature (final temperature) is approached in a testing program like that illustrated in Figure 1, the measured shear stress (or viscosity) reaches a peak value and then steadily decreases exponentially with time. After several hours of continued shear at the final temperature, an equilibrium shear stress is finally established. Figure 2 illustrates the peak

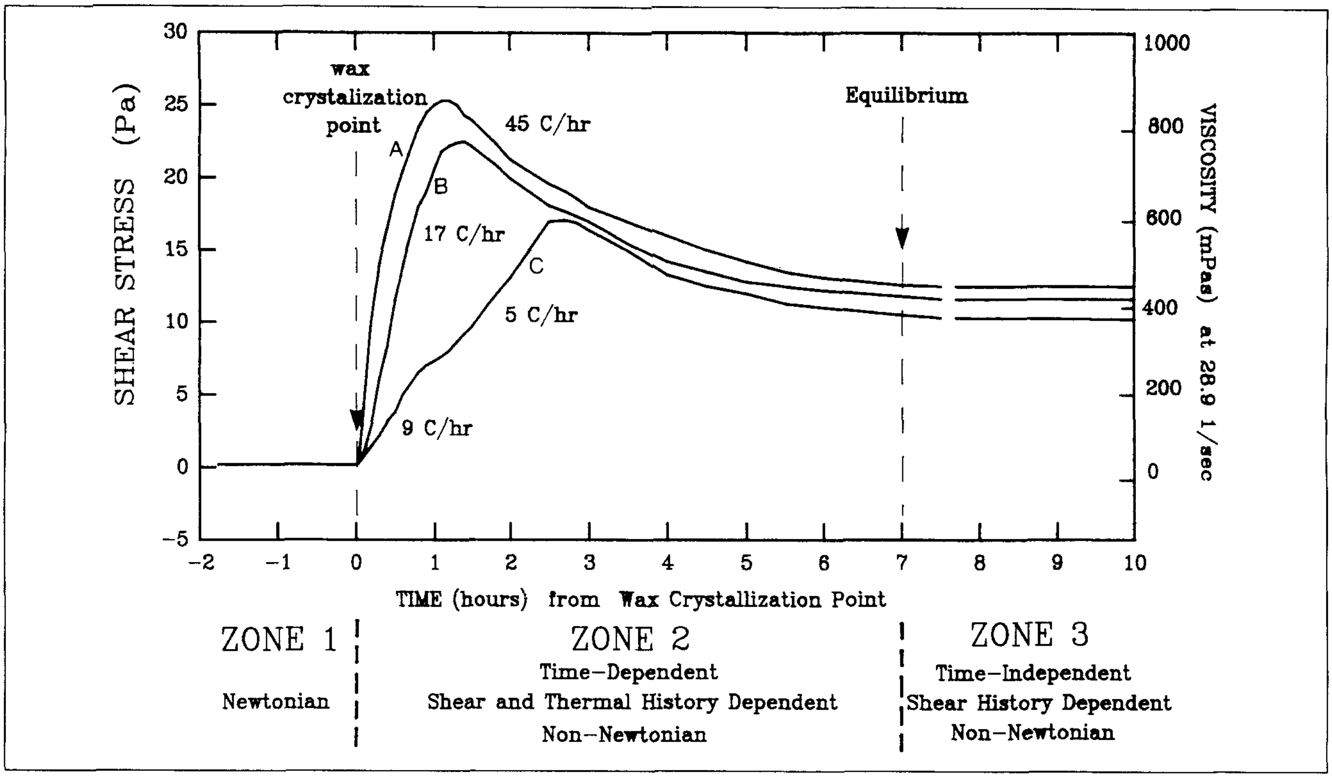

Figure 2. Effect of cooling rate on the transient shear stress response plotted as time from wax crystallization point.

Jackson-Hutton crude oil; R19 Weissenberg Rheogoniometer; shear history = 28.9 s^{-1}
Cooling program: (A) ice bath and (B) medium cooling rate, 50°C to 7°C at 0.37 C/min; (C) slow cooling rate: 54°C to 34°C at 0.49 C/min; 34°C to 20°C at 0.2 C/min; 20°C to 7°C at 0.1 C/min.
Approximate actual cooling rates as marked

shear stress and the exponential decline to an equilibrium value for a sample cooled at 7°C at several cooling rates. The functional form of the shear stress time curve shown in Figure 2 at a fixed shear rate is a result of two opposing mechanisms: an increase in viscosity due to temperature reduction to the final value and viscosity reduction due to structural breakdown in the shear field. The maximum in shear stress corresponds to the time when the final temperature is reached. The viscosity or shear stress decreases from this maximum with time, and the structure of the fluid breaks down in the shear field until no further change in structure occurs. The results fall into three distinct sections: the first section in which the shear history has no effect and the fluid properties remain Newtonian; the second where results depend strongly on the shear and cooling rates as well as the temperature and time of shear; and the third where steady state or equilibrium is reached in which the thermal history (applied cooling rate) does not have a strong effect as seen in Figure 2. The shear history [the constant (test) shear rate applied during cooling], however, has a very strong effect as discussed below.

Once an equilibrium or steady-state shear stress has been established, a time-independent flow curve can be measured (by a stepwise decrease in the shear rate from the test shear rate to a very low value followed by a stepwise increase returning again to the test value), an example of which is given in Figure 3. Such an equilibrium flow curve is readily duplicated on a repeat sample (given the same shear and thermal history in the same instrument). It is also possible to repeat the flow

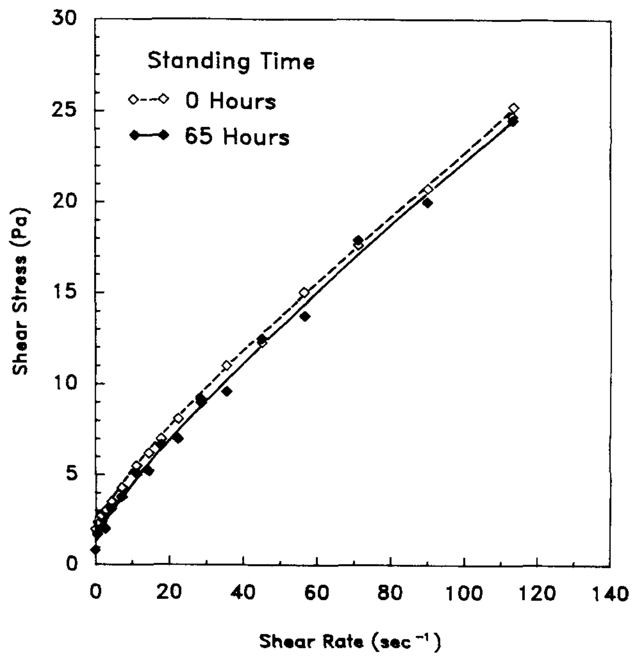

Figure 3. Effect of standing time on the equilibrium flow curve of a waxy crude oil.

Jackson-Hutton crude oil at 11°C; R18 Weissenberg rheogoniometer; shear history = 113.5 s^{-1}
Cooling program: 50°C to 35°C at 0.5 C/min; 35°C to 9°C at 0.2 C/min

curve measurement on a given sample at equilibrium after allowing the sample to stand for some period of time (up to 65 hours tested), Figure 3, provided that no change in the temperature of the sample occurs. The stability of a sample at steady state to a period of standing is contrary to that reported in much of the literature (Sifferman, 1979), in which it is maintained that the yield stress (gel strength) of the oil increases with time of standing. To measure a flow curve prior to equilibrium, a time-dependent result is obtained showing considerable hysteresis and very poor repeatability. In the reported cases of the structure development in a waxy oil on standing, it is most probable that either an equilibrium or steady-state condition was not established or a (very slight) temperature reduction occurred. Only when time-independent viscometric data are obtained, it is possible to compare the results of different instruments for waxy crude oils.

Because of the complexity of the oils and the nature of the experiment in which the temperature has to be cycled, each type of viscometer presents its own unique problems and advantages that would not occur when applied to other non-Newtonian materials. The errors arise from:

- A time lag between the measured and the actual sample temperature. Temperature is usually measured at a point in the cooling jacket or the air space adjacent to the sample. During the cooling program, the actual sample temperature lags behind the measured temperature by a varying amount depending on the instrument and jacket design. A temperature offset may also exist at equilibrium. Prior calibration using very fine thermocouples attached to the torque measurement surface allows correction of the measured temperature to a reasonable estimate of the actual sample temperature. Without such correction, comparative data taken from different instruments, such as those in Figure 1, show a large discrepancy.
- Contraction of the sample, which reduces the contact area with the instrument surface from which the stress is determined. This effect is particularly serious in narrow gap concentric cylinder viscometers in which a large proportion of the sample volume exists in the dead space beneath the bob. If the contraction can be accurately measured, then a correction can be applied to the torque data.
- Expansion and contraction of the instrument that affects both the contact area and the geometric relationship of rotational speed to shear rate.
- Deposition of the sample as a nonsheared layer on the instrument surfaces, together with possible segregation within the sample.
- Bridging effects resulting from the interaction of wax crystals simultaneously with both viscometer surfaces in the concentric cylinder gap and at the truncation of the cone, thereby increasing the torque above the value given by the bulk fluid.
- End effects resulting from the shape of the cup and bob, entrance and exit effects in the capillary viscometer, the truncation of the cone, reservoir and free surface effects.
- A change in composition of the sample during testing due to the loss of light ends, oxidation or polymerization of components in the oil.
- The variation in shear rate across the radius that is an inherent feature in the concentric cylinder and the capillary viscometers, for which standard correction methods are available (but only for time independent flow data) (Krieger and Maron, 1954; Nguyen and Boger, 1987).

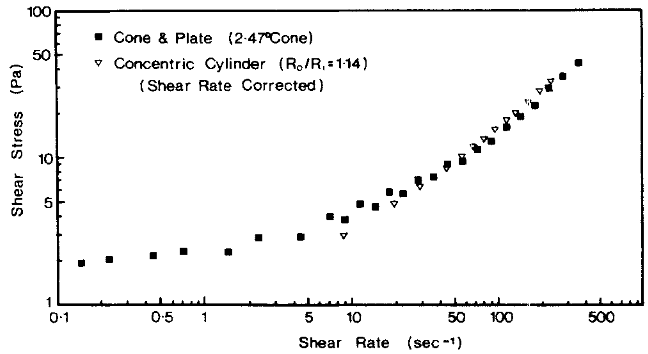

Figure 4. Agreement between the concentric cylinder viscometer (Haake Rotovisco RV3—MVII geometry) and the cone and plate viscometer (R19 Weissenberg Rheogoniometer).

Jackson-Hutton crude oil at 10°C; shear history = 115 s^{-1} (nominal)

Cooling program (R19 Weissenberg rheogoniometer): as for Figure 2C; (Haake RV3): 46°C to 34°C at 0.49 C/min; 34°C to 20°C at 0.2 C/min; 20°C to 10°C at 0.1 C/min.

Note that these different programs result in identical measured temperature profiles (Wardhaugh and Boger, 1987)

The above are all systematic errors that are manifested to different degrees in each instrument and contribute to the lack of agreement between different viscometers. To scale up any viscometric data to an operating pipeline, it is essential to confirm that the data represent the oil (that is, material data) and are not limited by instrument errors or inappropriate measurement techniques. An effective method of confirming material data is to obtain agreement between different viscometer geometries. It must be of concern that in the vast bulk of the literature on waxy crude oils, only a single instrument is used, or a large discrepancy between instruments is reported without further discussion. Figure 4 is an example of agreement of equilibrium data between a Haake Rotovisco RV3 with concentric cylinder (MVII) geometry and a Weissenberg R19 Rheogoniometer (2.5° 7.5-cm-dia. cone) for Jackson-Hutton crude oil at 10°C. The limit of sensitivity of the Haake instrument is approximately 5 Pa preventing reliable data at low shear rates to be collected. The sources of error listed above also contribute random errors to the measurements which reduce the repeatability in a single instrument. More details of the experimental errors, their assessment and correction are provided elsewhere (Wardhaugh and Boger, 1987; Wardhaugh, 1990).

Effect of Shear History

Figure 5 shows the results, plotted as viscosity vs. temperature, for a series of experiments in which identical samples of Jackson-Hutton oil were given the same thermal history, but different shear histories varying in each case by a factor of 10. Figure 5 shows that, as expected, a constant viscosity occurs in the sample above the wax crystallization point regardless of the shear rate, but that the viscosity increases substantially with the reduction in shear history for temperatures below this point, consistent with the non-Newtonian character of the oil at these temperatures. Such curves have been previously reported by Withers and Mowll (1982).

The plot of viscosity vs. temperature, however, belies a very

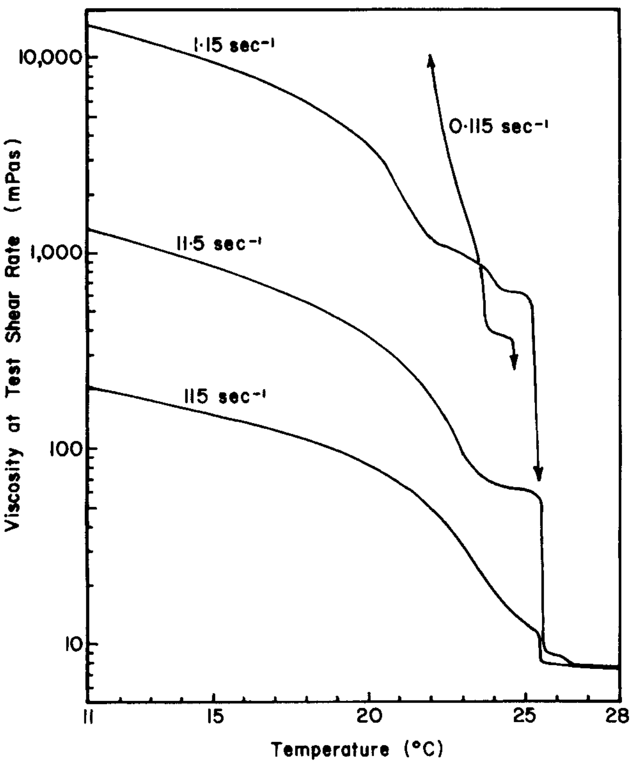

Figure 5. Effect of the shear history on the comparative test result.

Jackson-Hutton crude oil; R19 Weissenberg rheogoniometer
Cooling program: as for Figure 2C

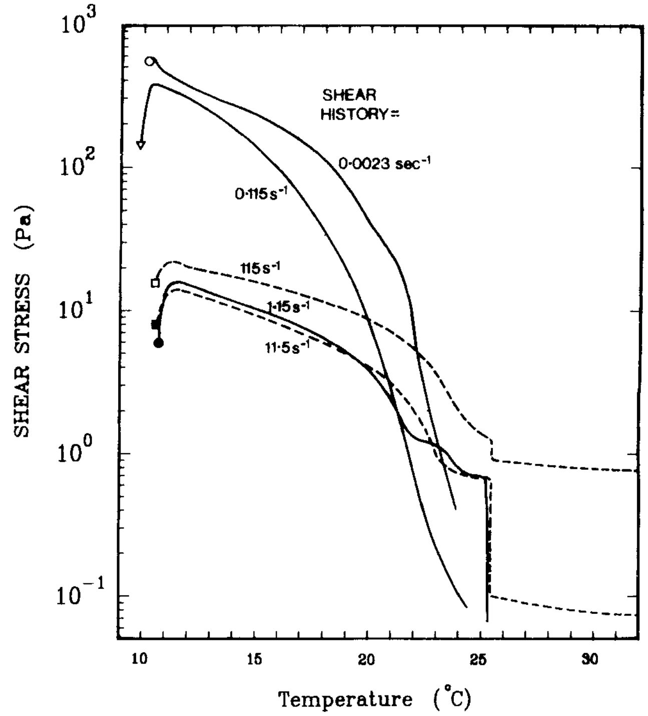

Figure 6. Effect of shear history plotted as shear stress vs. temperature.

Jackson-Hutton crude oil; test conditions as for Figure 5

important feature of the shear history. If the data are replotted as shear stress vs. temperature (as in Figure 6) a different picture emerges. A tenfold reduction in shear history from 115 s^{-1} to 11.5 s^{-1} results in a tenfold reduction in the shear stress above 25.4°C (the wax crystallization point) and a less than tenfold reduction as non-Newtonian flow properties develop below this temperature. Such a result is shown in Figure 6. A further tenfold reduction in the shear history (to 1.15 s^{-1}), however, leads to higher shear stresses between 19°C and 11°C than those at a shear history of 11.5 s^{-1}. Further reduction in the shear history by a factor of ten to 0.115 s^{-1} leads to dramatic increases in shear stress. However, a further decrease by a factor of fifty to 0.0023 s^{-1} results in only a small increase relative to the 0.115 s^{-1} results. Perhaps a limiting state is being achieved at low shear rate. Such a reversal in shear stress with the reduction in shear rate is, of course, thermodynamically impossible, unless the character of the fluid (particle size, interaction, etc.) has changed as a result of each shear history.

A crude oil that is statically cooled possesses a very high resistance to flow and solid-like characteristics. In the literature, the static and dynamic (sheared) test situations have always been considered quite separately. These results show, however, that a gradual transition in flow behavior occurs as the shear history is reduced to zero.

Equilibrium results

Once the equilibrium position or steady state (the points indicated by the symbols on the left in Figure 6) has been reached as a result of continued shear, time-independent flow curves can be determined as described above. Figure 7 shows the equilibrium flow curves for three of the shear histories in Figure 6. In each case, the test shear rate (shear history) is not exceeded when determining the flow curve. If the shear history were not important, all of these curves should coincide. The fact that the flow curves do not coincide is further evidence that each shear history gives rise to a unique material, each

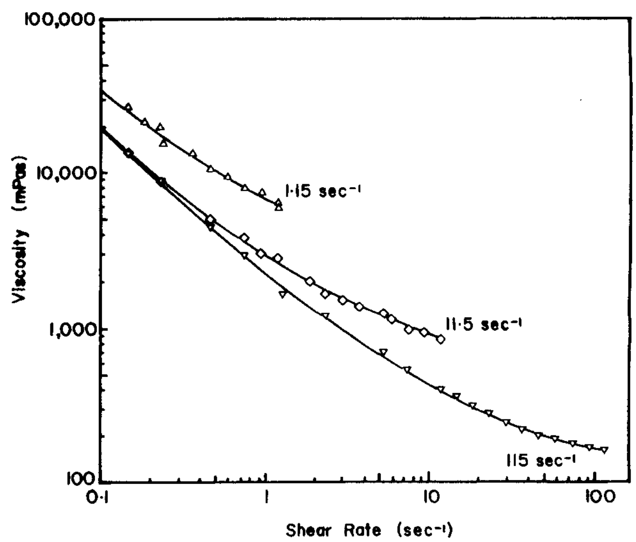

Figure 7. Effect of shear history on the equilibrium flow curves.

Jackson-Hutton crude oil at 10°C, test conditions as for Figure 5

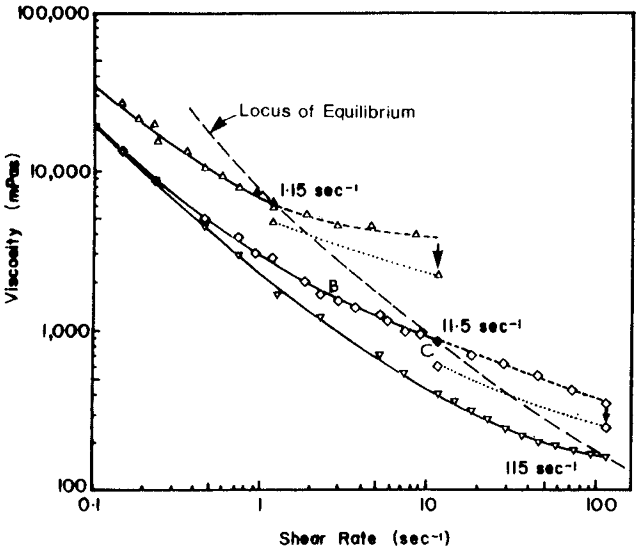

Figure 8. Test of time-dependent character of equilibrium data by increasing the shear rate above shear history value.

— — — —, shear rate; ————, flow curve at each shear history replotted from Figure 7; · · · ·, lowest viscosity achieved by applying the highest shear rate; — — —, locus of equilibrium viscosities (A)
Jackson-Hutton crude oil at 10°C, test conditions as for Figure 5

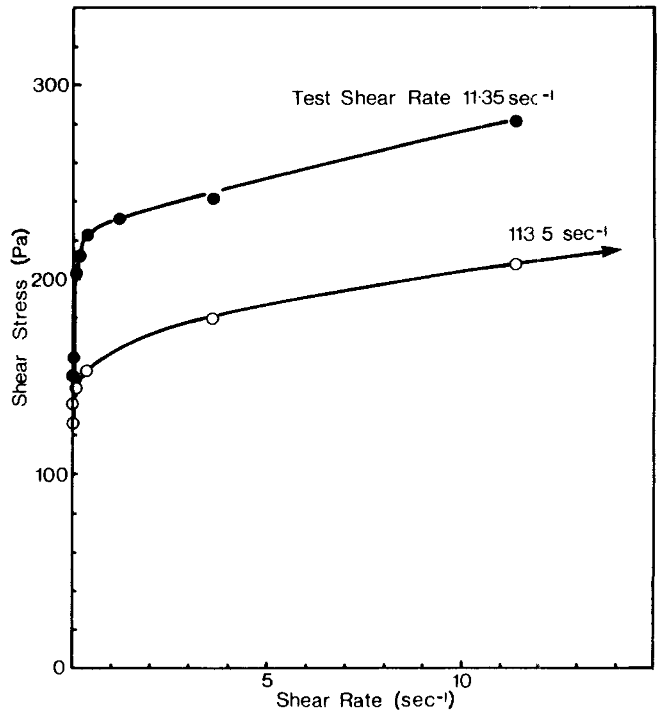

Figure 9. Effect of shear history equilibrium flow curves of the heavy Daqing (Chinese) crude oil at 20.6°C.

R18 Weissenberg rheogoniometer
Cooling program: 65°C to 50°C at 0.5 C/min; 50°C to 20°C at 0.2 C/min

represented by a separate flow curve. Repeat experiments over a wide range of shear histories would result in a locus of individual equilibrium points shown as curve A in Figure 8.

For a fluid that was simply time-dependent (but not shear-history-dependent) it should be possible to step from one equilibrium flow curve (such as, the one arrived at after a shear history of 11.5 s^{-1} in Figure 7) to another flow curve (such as, the one for a shear history of 115 s^{-1}) by simply increasing the shear rate to the higher level thereby inducing sufficient structural breakdown for the two results to coincide. This is tested in Figure 8 (on which the flow data of Figure 7 are reproduced) by increasing the shear rate (short dashed lines) to levels above the shear history value. The increase in shear rate does produce some structural breakdown, but the new data still do not coincide with the flow curve generated by applying the higher test shear rate throughout the cooling program. The dotted line in Figure 8 represents the lowest viscosity achieved after continued shear at the highest shear rate (a stable value is reached within 20 minutes).

The flow properties of a waxy oil at a given temperature therefore depend strongly on the shear rate applied to the sample during the approach to that temperature: the flow properties are shear-history-dependent. This is termed the shear history effect. At equilibrium at a given temperature, the oil is therefore described by not one flow curve, but by a family of flow curves, each determined by the shear history. The oil could be said to be represented by the locus of the equilibrium viscosities (Figure 8), but this is not the flow curve of the oil. For geometries in which the shear rate varies spatially, such as in the capillary viscometer or in an operating pipeline, the oil, as it cools, is subjected to a range of shear histories that depend on the radial position of each fluid element in the pipe. Effects due to prior shear in waxy crude oils have been commented on by a number of researchers as early as 1971 (Davenport and Somper, 1971), as well as by Grodde (1973), Smith and Ramsen 1978), and Withers and Mowll (1982). No mention, however, has been made of the consequences of these effects on pipeline design procedures beyond the original approach of Ford, Ells and Russell (1965) discussed below. In fact, the shear history effect has a major impact on the design and operation of oil pipelines as will be shown below.

All of the waxy and heavy crude oils tested in this study displayed, to varying extents, an effect of the shear history. Daqing crude, which has both a high wax and asphaltene content, is also described by a series of flow curves, each defined by the shear history at a given temperature (20.6°C) in Figure 9. The most severe case of the shear history effect was seen in the McKee crude from New Zealand, which is solid at room temperature if statically cooled. Whereas most crudes displayed an increase in the shear stress at relatively low shear histories, McKee crude displayed higher shear stresses at 11.5 s^{-1} than at 115 s^{-1}. Below a shear history of 11.5 s^{-1}, the sample become solid before reaching the test temperature preventing a result from being obtained.

Minimum operating condition

Figure 6 shows that the shear stress decreases steadily and then increases abruptly at a fixed temperature as the shear history is reduced to low levels. This suggests that a minimum equilibrium shear stress exists at intermediate values of shear history. This minimum is illustrated in Figure 10 in which the end-points of Figure 6 are plotted as a function of the shear

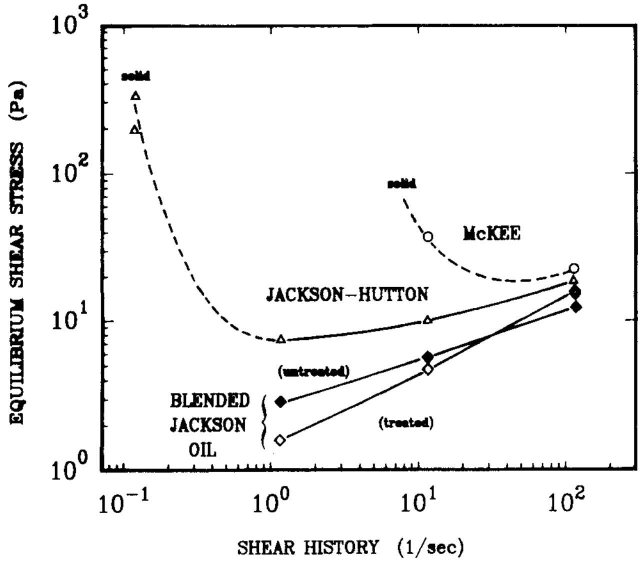

Figure 10. Equilibrium shear stress resulting from various shear histories showing the minimum operating condition.

McKee crude (NZ) at 10°C; Jackson-Hutton at 10°C, blended Jackson oil at 11°C, untreated and treated with 1,000 ppm additive no. 2

history. For waxy crude oils at a steady-state condition of temperature and viscosity, a "minimum operating condition" could therefore exist at temperatures below the pour point due to the shear history effect. This minimum is determined by the rheology of the oil and is quite distinct from the well-known phenomena, occurring in both Newtonian and non-Newtonian oils, where an optimum flow rate exists in a cooling pipeline due to the higher viscosities (higher pumping pressures) that can be generated at lower flow rates simply due to the lower average temperatures over the length of the pipeline (Szilas, 1985).

Figure 10 identifies a minimum operating condition for Jackson-Hutton at 10°C occurring at a shear history of approximately 1 s^{-1} and equilibrium shear stress of about 8 Pa. For any element of fluid in the pipeline, a minimum shear stress (available pressure drop) of 8 Pa must be available to maintain flow if the oil cools to 10°C. The minimum shear stress is not equivalent to the yield stress of the fluid; however, if the available shear stress in the pipeline were to fall below 8 Pa (at an oil temperature of 10°C), then flow of oil in the pipeline would cease. Smith and Ramsden (1987) documented a pipeline trial using an 80/20 mixture of North African waxy crude and Middle East diluent, in which the pipeline shut itself down following a reduction in flow rate (possibly explained as a fall below the minimum shear history). The Jackson pipeline normally runs at wall shear rates in excess of 7 s^{-1}, well above the minimum operating point for this oil. However, as production declines in the Jackson and surrounding oil fields, it can be anticipated that difficulties in maintaining flow will increase.

It is common for an oil pipeline to be designed only for the maximum flow rate (since for normal fluids, lower flow rates require lower pumping pressures). The minimum operating condition, which is a result of the shear history effect, substantially alters this philosophy. This is particularly important in declining oil fields where lower production rates lead to much higher viscosities than those predicted from laboratory data originally determined to correspond to maximum flow rates. It is therefore necessary to design a waxy crude oil pipeline not only for the maximum expected flow rate, but also for the minimum flow rate occurring at the end of the life of the field or at times of curtailed production.

The minimum operating point is unique to each crude oil (compare Jackson to Hutton and McKee crude oils in Figure 10), but its location is shifted to lower values of shear history and equilibrium shear stress by blending with diluent oils and by using effective flow improver additives (as for the blended Jackson crude in Figure 10, which consists of over 90% Jackson-Hutton oil). The effect of flow improver additives is discussed below.

Steady-State Flow of Waxy Crude Oil in a Pipeline

Three Zones in an Operating Pipeline

Consider the situation in which a waxy crude oil leaves the well-head (or reheating station) at an elevated temperature (with the wax in solution) and then cools to a constant ambient temperature (below the point of wax crystallization) as it flows through a pipeline. Data such as those in Figures 1 and 2 can be considered to represent the properties of elements of fluid both along the length and (if appropriate) across the radius of the pipeline. Clearly the flow properties change dramatically along the length of the pipeline in both value and form. Our earlier publication (1987) identified the existence of three quite distinct zones in a pipeline handling waxy crude oils, each of which would require quite different design techniques and information inputs. These three zones and their fluid characteristics are identified in Figure 2.

In the first zone, immediately downstream of the well-head or reheating station, the flow properties of the oil are independent of time and shear history. Waxy crude oils, low in asphaltenes, remain Newtonian above the wax crystallization point, while heavy (high asphaltene) crudes, such as Daqing crude, may develop (time-independent) non-Newtonian flow characteristics at relatively high temperatures. The flow regime in the first zone is most likely to be turbulent, and only a gradual increase occurs in the viscosity with the decline in the temperature. Pipeline design and operating procedures are well established for this zone for both Newtonian and non-Newtonian (time-independent) fluids (Skelland, 1967; Szilas, 1985).

The second zone begins, by definition, at the point at which the flow properties become time- and history-dependent. For waxy crude oils, this coincides with the wax crystallization point and is accompanied by an order of magnitude increase in viscosity (with a corresponding drop in the Reynolds Number) which would result in most pipelines entering the laminar flow regime. Figures 2 and 5 clearly show that the viscosity in the second zone depends on the cooling rates, the shear rate, and the time of shear.

In laminar flow, radial temperature and velocity profiles constantly change along the length of the second zone of the pipeline, influencing the properties of each element of fluid both directly and through the shear and thermal history experienced by that element as in Figure 11. A numerical procedure required is a relatively straightforward extension of the Ritter and Batycky method (1967) with the addition of a temperature profile and a shear and thermal history profile. In successive iterations, the temperature at the center-line and the velocity profile are adjusted until: firstly, the convective heat lost from each successive radial element balances the heat conducted to the adjacent radial element and the heat loss at the wall; and secondly, the required wall shear stress or flow rate is achieved. The necessary information is a series of viscosity-temperature (or viscosity-time) results (such as Figure 2 or 5) determined for a range of cooling rates and shear histories. Turbulent flow may persist in zone 2 or reappear prior to zone 3 due to the reduction in viscosity with continued shear (as in Figure 2). The design methods are similar to those in zone 3, which are discussed below, although the necessary viscosity and flow behavior index (n') data are more difficult to obtain for the zone 2 calculation.

Given conditions of steady flow and ambient temperature, the oil viscosity eventually reaches a constant value, as in Figure 2, although its value will vary across the pipe due to the radial variation in both the shear rate and shear history. This is by definition the third zone in a waxy crude oil pipeline. Because the shear stress profile is no longer changing axially, only a single calculation is required; however, the design procedures must be modified to account for the shear history effect. These modified design techniques are presented after a brief discussion of the existing design procedures for waxy crude oil pipelines. For long buried pipelines that would experience negligible diurnal temperature change, the majority of the pipeline would be at a constant (ambient) temperature so that a single (zone 3) calculation may provide a quick estimate of the pressure drop-flow rate relationship for the entire pipeline.

In this simple case, we are still dealing with steady-state flow (constant flow rate, and inlet and ambient temperature). The time-dependent properties are manifested in a variation of the differential pressure drop ($\partial P/\partial z$) along the length of the line. The $\partial P/\partial z$ profile itself does not vary with time. The unsteady-state situations of varying flow and temperature would be manifested in a movement of the border between the three zones (and of the profiles within each zone) as a function of time. The calculations would, of necessity, be more complex, but the design philosophy would not be altered.

Existing design procedures

Most pipeline design methods available in the literature (Govier and Aziz, 1982) assume flow properties described by a single flow curve. Yet, as shown above, because of the shear history effect, waxy crude oils are described by a complete family of flow curves (as in Figure 7). This poses the question: Which flow curves or value(s) of viscosity should be chosen for design?

The original design procedure for waxy crude oil pipelines were established by Ford, Ells and Russell (1965) and have not been altered in the intervening years (Withers and Mowll, 1982). Ford and his coworkers recognized that the viscosity changed with the shear and thermal history and chose a test shear rate equal to 8 V/D (the wall shear rate for Newtonian fluids only). The resulting single value of viscosity (assumed to be Newtonian) was then used in the Hagen-Pouisuelle equation:

$$\frac{\Delta P}{L} = \mu \cdot \frac{8V}{D} \cdot \frac{4}{D} \qquad (1)$$

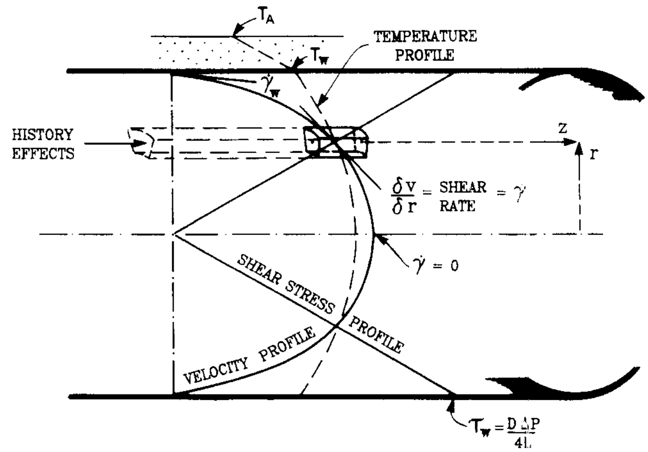

Figure 11. Factors affecting flow properties of each fluid element in a waxy crude oil pipeline.

to calculate the total flow rate-pressure drop relationship. To determine an appropriate value for the test shear rate for the case of the turbulent flow regime calculation, the value 8 V/D was multiplied by a factor (C_f), which is equivalent to the ratio of turbulent to laminar friction factors at a given Reynolds Number:

$$C_f = \frac{f_{\text{turbulent}}}{f_{\text{laminar}}} = \frac{f_{\text{turbulent}}}{16/Re} \approx 4.94 \times 10^{-3} Re^{0.75} \text{ for } (Re > 2{,}100) \qquad (2)$$

where the approximate solution is derived by inserting the Blasius equation for the turbulent friction factor. The resulting value of the "effective viscosity" is then used in conventional Newtonian turbulent flow equations. This approach does not account for the variation in the flow properties with shear history that occurs in each streamline across the radius of a pipe in laminar flow nor for the non-Newtonian characteristics of the fluid in turbulent flow.

Non-Newtonian design techniques (reviewed by Szilas, 1985) also assume that the oil is described by a single flow curve to which an existing plastic or pseudoplastic fluid model is fitted. For turbulent flow calculations of non-Newtonian fluids, the Dodge and Metzner method (1959) has been shown to give reasonable accuracy for yield stress fluids (Mun, 1988) and not to require the use of a fluid model. The Dodge-Metzner method also assumes a single $\tau_w - 8\ V/D$ relationship for non-Newtonian fluids and therefore must be modified to account for the family of flow curves resulting from the shear history effect in waxy crude oils.

Modified design procedure for laminar flow in zone 3

In laminar flow in a pipeline, the shear rate varies from a high value at the wall to zero at the center of the pipe. Each streamline across the radius has seen a different shear history as it has cooled. The viscosity of any element of crude oil across the radius therefore depends not only on the temperature and the current shear rate, but also on the entire shear history experienced by that element as illustrated in Figure 11. The single flow curve given by a shear history equivalent to the ratio 8 V/D (the wall shear rate for Newtonian fluids only) represents the fluid in only one streamline (and not necessarily

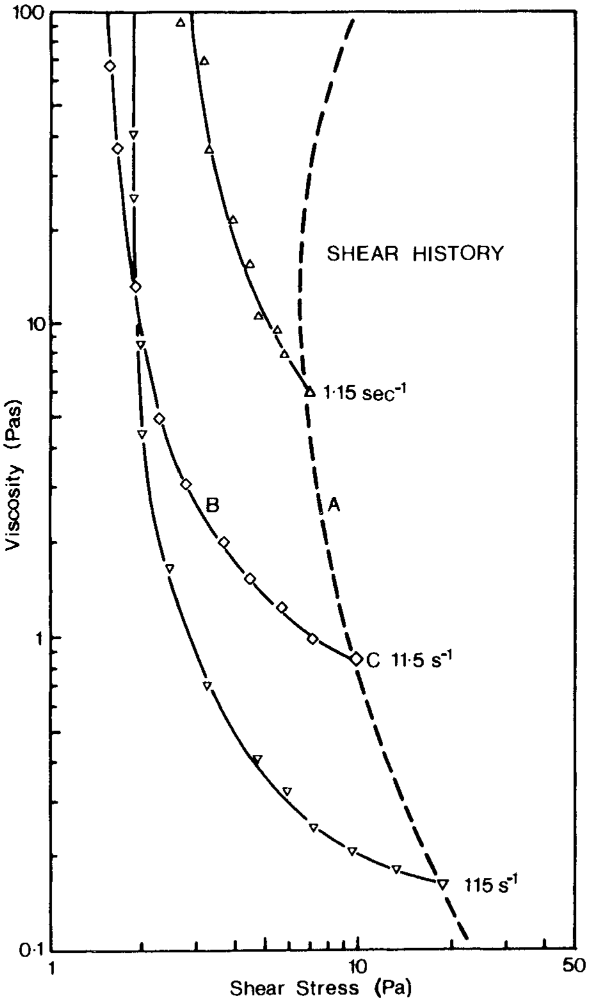

Figure 12. Shear-history-dependent data used in calculating laminar and turbulent flow rate including the locus of equilibrium viscosities.

Curve A, — — —, Jackson-Hutton crude at 11°C

the streamline adjacent to the wall). The total flow rate is the cumulative effect of each streamline. Since the flow properties of waxy crude oil are no longer changing axially, the shear stress distribution is linear with radial position and therefore known at every point across the radius. The wall shear stress ($D\Delta P/4L$) is therefore a convenient starting point for the calculation.

To illustrate the calculation procedure, consider the shear-history-dependent data for Jackson-Hutton at 11°C given in Figure 7 and replotted in the more convenient form of viscosity vs. shear stress in Figure 12.

Since the shear rate will have changed very slowly along a streamline in the pipe, it is reasonable (in the absence of any data to the contrary) to assume that, in zone 3, each streamline has reached equilibrium with the viscosity determined by a shear history equal to the current local shear rate. Therefore, the fluid (at equilibrium) is represented by the pseudoflow curve labeled in Figures 8 and 12 as the "locus of equilibrium viscosities," which is identical to the plot of equilibrium shear stress vs. shear history given in Figure 10. Since the shear stress is known at each point across the radius, it is possible to determine the viscosity at each point (or the shear rate distribution) and hence the total flow rate. The total flow rate can be determined in one of two ways. First, a suitable equation can be fitted to the locus of equilibrium viscosities (as a pseudoflow curve, the dashed line in Figure 12) and this result used to integrate the Rabinowitsch-Mooney equation:

$$\frac{8V}{D}=\frac{4}{\tau_w^3}\int_{\tau_w}^{\tau_y}\tau_{rz}^2 f(\tau_{rz})\,d\tau_{rz} \tag{3}$$

where $f(\tau_{rz})$ is the shear rate given by the velocity gradient $-dv_z/dv$ in the tube flow (Boger and Yeow, 1991). This pseudoflow curve does not conform to any of the existing yield stress fluid models (as seen in the shape of such a locus in Figures 10 or 12). Nevertheless, the function $f(\tau_{rz})$ can be determined and the integral in Eq. 3 evaluated.

In an alternative numerical procedure that is easily extended to more complicated cases, the pipeline can be divided radially into annular segments, which, if small enough in cross section, can be considered to contain a fluid with a constant, but unique viscosity. The relationship between each annular segment is a simple extension of the problem of two immiscible fluids between flat plates (Bird et al., 1960). The resulting equations are summarized in the Appendix and the development of the numerical model is provided elsewhere (Wardhaugh, 1990). This numerical model is the preferred method for the calculation of pressure drop in zone 3. The input data necessary for the numerical calculation are the viscosity of the fluid in each annular segment which can be read directly from a plot such as Figure 12.

To illustrate the dramatic difference between the existing design procedures which do not account for the shear history effect and the modified technique outlined above in laminar flow, a trial calculation is carried out using the data of Figure 12. The starting point of the calculation is a fixed-wall shear stress (10 Pa) and wall shear rate (11 s^{-1}). Thus, the flow rate Q is being calculated for fixed τ_w and $\dot{\gamma}_w$ be several procedures.

If all of the available information (the locus of equilibrium values labeled as "A" in Figure 12) were used to calculate the velocity profile using the numerical procedure outlined in the Appendix, then the result is shown as velocity profile A in Figure 13 (corresponding to a flow rate of, say, 100 normalized flow units). The complete set of (shear-history-dependent) data, represented by the pseudoflow curve (A) therefore results in a flattened velocity profile (profile A in Figure 13) with a large unyielded core making up 55% of the cross-section of the radius.

Existing non-Newtonian design procedures, while they may recognize the effect of shear history in terms of a single set of test conditions, assume that one flow curve (curve B in Figure 12) is sufficient to describe the fluid within the pipe. Had only one flow curve been used in the calculation (that determined at the apparent wall shear rate, $8\ V/D = 11.5\ s^{-1}$, flow curve B in Figure 12), the predicted velocity profile would resemble profile B in Figure 13 showing only a very small unyielded core (in line with the small measured yield stress of 1.45 Pa for a shear history of 11.5 s^{-1}). The predicted flow rate for the same set of conditions as above is calculated as 195 flow units.

Conventional Newtonian design methods (including the

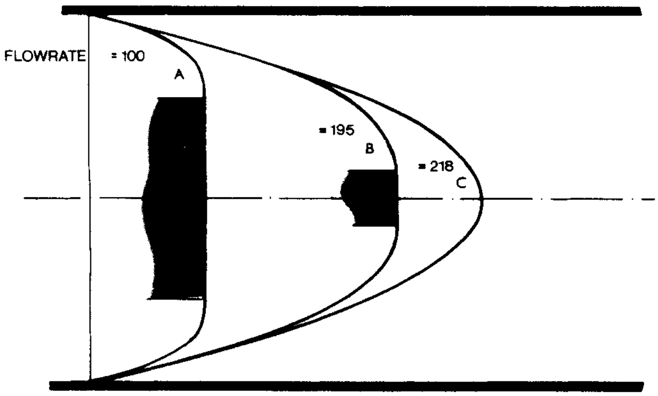

Figure 13. Velocity profiles resulting from the calculation of flow rate (normalized) at $\tau = 10$ Pa.

Using (A) locus of equilibrium viscosities, (B) single non-Newtonian flow curve, and (C) Newtonian viscosity

method of Ford, Ells and Russell) assume that the fluid has a viscosity that is independent of the shear rate (even if this viscosity is influenced by the shear history). The use of a single Newtonian viscosity (point C) in Figure 12 means that the velocity profile is assumed to resemble the familiar parabolic profile (C) in Figure 13, and the predicted flow rate is larger again (at 218 flow units).

The vastly different velocity profiles (and calculated flow rates) are a result of the different amount of information that is used in each of the calculations. Whether the fluid is assumed to be Newtonian or non-Newtonian, a single test condition does not provide enough information to calculate the pipeline flow rate and overpredicts the flow rate of the order of 100% in laminar flow.

The calculations of total flow rate are repeated for a 1-m-dia. pipeline over a series of wall shear stresses (available pumping pressures) using the data of Figure 12, and the results are plotted in Figure 14 (note that this is a hypothetical example). The modified design technique, accounting for the effect of shear history, predicts a minimum operating condition that is $Q \rightarrow 0$ at 26 kPa/km. For a pipeline handling Jackson-Hutton crude at pumping pressures below this value, flow would cease if the temperature were to drop to 11°C. Calculations using the (Newtonian) method of Ford, Ells and Russell (Eq. 1), also shown in Figure 14, do not predict a minimum point and predict flow rates that are increasingly higher than those from the modified techniques up to the transition point (according to the method of Ford, Ells and Russell) at 38 kPa/km.

Comparison of design procedures for turbulent flow in zone 3

In turbulent flow, the fluid can be assumed to be well mixed across the radius, hence only axial division of the pipeline is required in any of the three zones. As with laminar flow, a single calculation only is necessary in the third zone since, by definition, the nature of the fluid is not changing along the length of the pipeline. Two of the existing design methods, discussed above, are compared using the data of Figure 12. The first, that of Ford, Ells and Russell, is most easily carried out using a graphical technique, in which viscosity vs. the effective shear rate for a series of given flow rates is plotted on the same graph as the experimental data. The intersection of the two is defined as the "effective viscosity," which is used in conventional turbulent flow equations to determine the total pressure drop per unit length.

In the method of Dodge and Metzner (1959), the pressure drop-flow rate relationship is determined by the fluid properties measured at the wall shear stress. These fluid properties are the flow behavior index (n') and the fluid consistency index (K') defined by the power law equation:

$$\tau_w = \frac{D\Delta P}{4L} = K' \left(\frac{8V}{D}\right)^{n'} \tag{4}$$

and which are determined by the slope of the individual flow curves (for each shear history) at the intersection of the locus of equilibrium viscosities rather than reading values from the slope of a single flow curve as recommended by Dodge and Metzner (1959). The flow curves should be in the form τ_w vs. $8\ V/D$. Shear rate data can be readily converted to $8\ V/D$ data by numerical integration of Eq. 3. Over the range of the shear histories required for the calculation (0.115 s^{-1} to 115 s^{-1}), the value of n' varies from 0.525 to 0.78 and K' from 7.5 to 0.5, and are most conveniently read from a plot of n' and K' vs. τ_w. An iterative calculation is required in which either the wall shear stress or flow rate is altered until the calculated wall shear stress matches the selected value. New values of the n' and K' are required for each new value of wall shear stress. The calculation proceeds by selecting a value of wall shear stress, reading values on n' and K', and then carrying out an iterative calculation for the friction factor using the equations developed by Dodge and Metzner (1959):

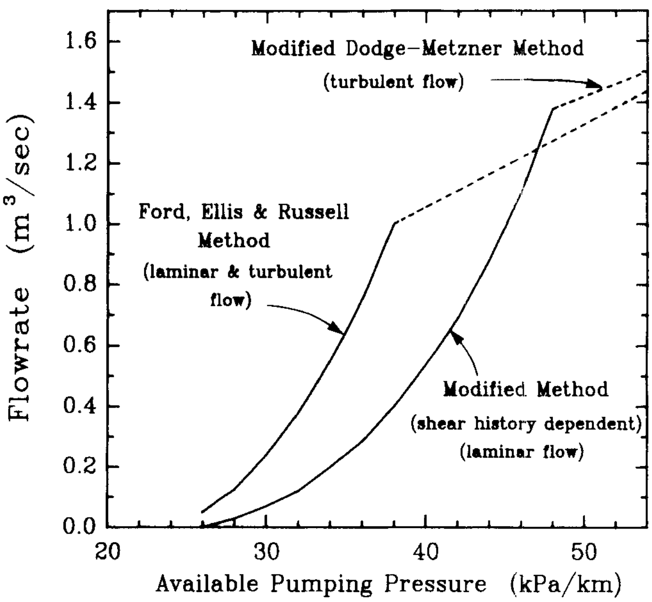

Figure 14. Comparison of flow rate-pressure drop calculations in laminar and turbulent flow for Jackson-Hutton 11°C in a 1-m-dia. pipeline.

Using the original method of Ford, Ells and Russell, modified laminar flow, and the modified Dodge-Metzner (turbulent flow) methods (with the data of Figure 12)

$$\sqrt{\frac{1}{f}}=\frac{4.0}{(n')^{0.75}}\log[N_{Re}'(f)^{1-(n'/2)}]-\frac{0.4}{(n')^{1.2}} \tag{5}$$

where

$$N_{Re}'=\frac{D^{n'}V^{2-n'}\rho}{K'(8)^{n'-1}} \tag{6}$$

The new value of wall shear stress (or velocity and flow rate) can now be determined from the equation defining the friction factor:

$$\tau_w=f\frac{\rho V^2}{2} \tag{7}$$

The results of a series of calculations for the transportation of Jackson-Hutton crude oil at 11°C in a 1-m-dia. pipeline in turbulent flow using both the modified Dodge-Metzner method and the method of Ford, Ells and Russell are plotted in Figure 14 using the data of Figure 12. The largest discrepancy between the two methods is the predicted transition point from laminar to turbulent flow regimes, occurring at much higher flow rate and pressure drop according to the modified Dodge-Metzner method. This is due partly to the much lower Reynolds number transition value in the method of Ford, Ells and Russell ($Re=1,250$) and partly to the shift in the transition point to higher Reynolds numbers as the flow behavior index (n') reduces to lower values (as the shear history is reduced) predicted by the Dodge-Metzner method. In turbulent flow, the modified Dodge-Metzner method predicted slightly higher flow rates than that of Ford, Ells and Russell (by at most 8%) with the difference diminishing at higher pressure drops, consistent with the reduced influence of fluid properties on the friction factor as the Reynolds Number approaches fully developed turbulent flow.

The agreement between the two methods in turbulent flow is encouraging; however, it should be pointed out that most oil pipelines transporting waxy crude oils at temperatures below the pour point operate in the laminar or transition flow regimes where the largest discrepancy between the methods exists. Note that the method of Ford, Ells and Russell makes no allowance for calculations in the transition region. Such calculations are possible with the method of Dodge and Metzner (although the accuracy has not been verified), but these have been omitted in the results shown in Figure 14.

Ford et al. (1965) recommend using the viscosity data obtained during the cooling program (such as Figure 5), cross-plotted as viscosity vs. 8 V/D. As discussed above, such data are not equilibrium data, and may be 70%–100% higher than the equilibrium value for a given temperature (as in Figure 2). This translates as a 14–18% increase in the turbulent flow pressure drop (Newtonian calculation). While this would reduce the discrepancy between the two methods in both laminar and turbulent flow, it would depend on many factors including the cooling rate and the oil sample and in fact on all of the factors influencing the zone 2 calculation. Both methods require the same quantity of experimental data (that is, a series of runs at different shear histories); however, in the Dodge-Metzner method, account is taken of the non-Newtonian fluid properties, which influence both the calculated friction factor and the transition from laminar to turbulent flow regimes making this method more appropriate for fluids with more extreme non-Newtonian behavior than the one presented in the worked example (Jackson-Hutton at 11°C). For this reason, the Dodge-Metzner method modified to account for the shear history effect is preferred for turbulent flow calculations in zone 3 of a waxy crude oil pipeline.

Effect of Flow Improver Additives

Behavior of a treated crude oil

Flow improver (pour point depressant) additives are chemicals that in some respect resemble the *n*-alkanes which comprise the bulk of the wax. The additives are able to take part in and thereby alter the crystallization process; however, the precise mechanisms, by which any additive improves the flow properties, have never been firmly established and may vary from additive to additive or from oil to oil. Several explanations have been put forward. Flow improvers may act on the crystallization of wax by the inhibition of the growth at the edges of the sheet-like crystals, resulting in a change in aspect ratio (Holder and Winkler, 1965) or by altering the kinetics of growth (Simon et al., 1974). X-ray diffraction studies (Chichakli and Jessen, 1967) suggest that the basic morphology of the wax crystal does not change in the presence of a flow improver, but that both the number and size of the crystals are reduced.

Although the suppliers of flow improver additives have built up an impressive body of experience, the selection of a suitable flow improver remains basically a trial-and-error process. Existing test procedures such as the pour point test are "pass/fail" tests that do not provide any quantitative data that would allow the cost effectiveness of a particular additive or dosage level to be determined and are often too severe. The flow improver additive can be used only once and represents a significant increase in the production cost per barrel. It is difficult to justify the use of an additive merely on the basis of an insurance policy used in the event of a pipeline shutdown. It would be far more economically acceptable to justify the use of an additive on the basis of a quantitative improvement in the steady-state flow rate in an operating pipeline with the benefits derived on pipeline shutdown an added bonus. This, of course, requires a quantitative assessment method under steady-state conditions. In the following section, the action of a flow improver additive is shown to be sensitive to and acts to reduce the effect of the shear history. The design procedures outlined above can be used to fully quantify the improvement in flow under steady-state conditions.

Most of the work carried out at the University of Melbourne for the Australian oil industry was aimed at selecting suitable additives using the comparative test (viscosity vs. temperature) data such as that shown in Figure 15 for Jackson-Hutton crude oil treated with 500 ppm of additive #1. Although much better responses are possible for other waxy crudes (Wardhaugh, Boger and Tonner, 1988), the result of Figure 15 is a good response of a flow improver additive applied to Jackson-Hutton crude oil.

The comparative test applied to a series of additives or dosage levels can allow the selection of the best additive and dosage rate. However, the quantitative question of "how much improvement" is not answered in such a straightforward man-

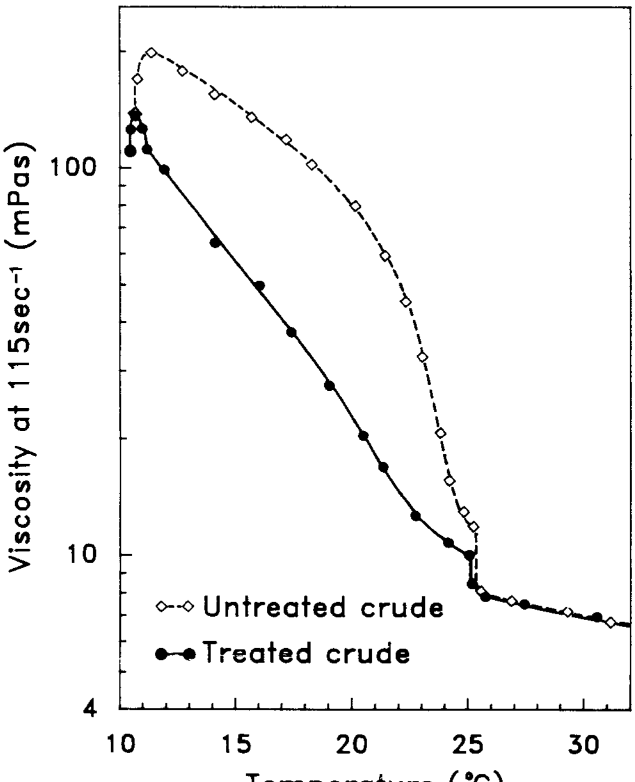

Figure 15. Comparative test result for an untreated crude and the crude oil treated with 500 ppm additive no. 1.

Jackson-Hutton crude oil; R19 Weissenberg Rheogoniometer; shear history = 115 s^{-1}; cooling program as for Figure 2C

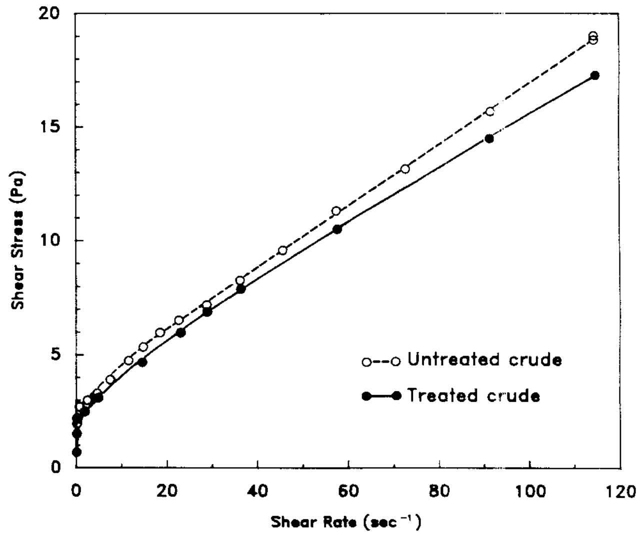

Figure 16. Equilibrium flow curves showing a comparison of an untreated crude with crude oil treated with 500 ppm additive no. 1.

Jackson-Hutton crude oil at 10°C, test conditions as for Figure 15

ner. Taking Figure 15 as an example, the degree of improvement (reduction in viscosity) varies from at best 70% to 20°C to 30% at the peak shear stress (occurring at 11°C). Continued shear results in a reduction in the shear stress (as in Figure 2) for both the untreated and (to a lesser extent) the treated sample reducing the improvement to 20% at equilibrium (10.4°C). With the measurement of the equilibrium flow curves for the two samples, shown in Figure 16, the difference between the two seems to have almost disappeared. Although additive no. 1 has reduced the yield stress slightly (from 1.9 Pa to 0.7 Pa), the reduction in shear stress (viscosity) due to the additive has diminished further to an average of 9%.

Effect of the shear history on the performance of flow improvers

To test the effect of the shear history on the performance of a flow improver, samples of a blended Jackson crude oil and the same crude treated with 1,000 ppm of additive no. 2, were subjected to an identical thermal history (as listed) and three different shear histories (114 s^{-1}, 11.4 s^{-1}, and 1.14 s^{-1}). In each of the six experiments, an equilibrium condition was established at a test temperature of 11°C using the experimental techniques outlined above. The resulting equilibrium shear stress is plotted as a function of the applied shear history in Figure 10 and indicates that the response of a flow improver changes with the shear history. The greatest improvement (reduction in shear stress) of 40% occurs at the lowest shear history tested (1.14 s^{-1}). The improvement is reduced to 20% at a shear history of 11.4 s^{-1}, while at a shear history of 114 s^{-1} the response of the flow improver becomes negative. That is, at the highest shear history, the flow improver has actually made the oil more viscous. A repeat experiment for the treated sample at a shear history of 115 s^{-1} confirmed this result (shown in Figure 10 as the double diamond).

The effectiveness of the flow improver therefore increases as the shear history is reduced so that a test carried out at a single shear history could give an entirely misleading impression of the effectiveness of a given flow improver (as will be shown in a worked example in the next section). A single comparative test conducted at a shear history equivalent to the maximum flow rate does, however, represent the worst case and would therefore be a conservative test. The reversal of the performance of a flow improver with shear history may explain the apparently anomalous result, often seen, that a particular flow improver could give a large reduction in the pour point [the equivalent of test carried out at a very low (but unknown) shear history] and yet fails to give a good response in a dynamic (flow) test carried out at a shear history equivalent to operating conditions.

At the conclusion of each experiment, the equilibrium flow curves were determined and plotted in Figure 17 as viscosity vs. shear stress to enable flow rate calculations (as in Figure 12). For the untreated crude, the effect of shear history is quite substantial, with an increase in both the yield stress (vertical asymptote in Figure 17) and viscosity as the shear history is reduced. As with Figure 12 above, the locus of equilibrium values for the untreated crude (dash-dot line) is quite unlike the individual flow curves and reaches a minimum shear stress (minimum operating condition) of approximately 1.9 Pa.

The addition of an additive does not (contrary to that often stated in the literature) convert the non-Newtonian untreated crude into a Newtonian fluid, which would appear as a hor-

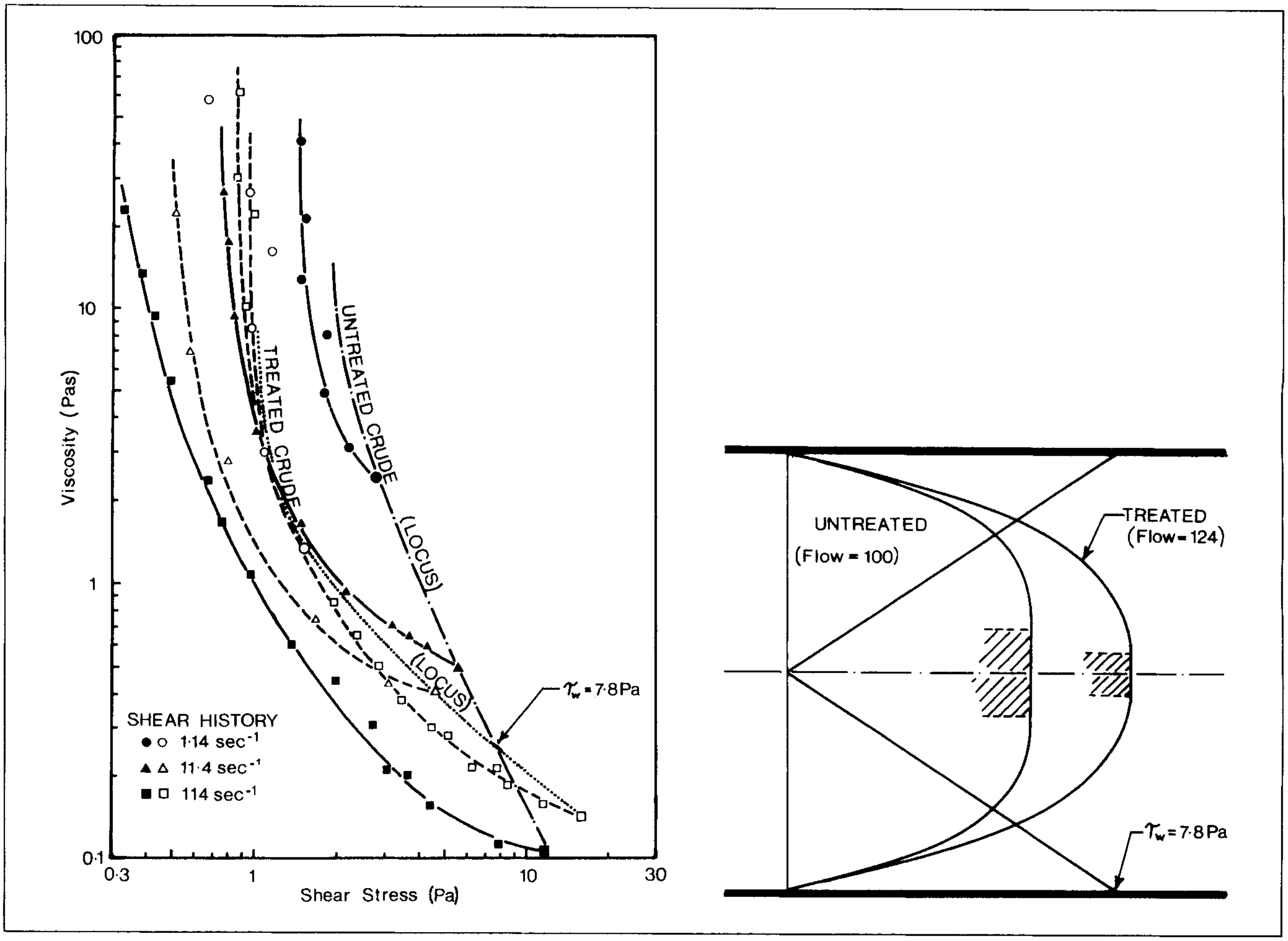

Figure 17. Effect of flow improver (1,000 ppm additive no. 2) on a blended Jackson oil.

Showing shear-history-dependent equilibrium data, ———— ; locus of equilibrium viscosities for the untreated samples, ·—·—·; and for the treated samples, ····, velocity profiles calculated using the locus of equilibrium viscosities (inset)

izontal line on Figure 17 nor has the additive substantially reduced the yield stress. The flow curves for the treated oil, however, are much closer together. Two of the flow curves ($1.14\ s^{-1}$ and $114\ s^{-1}$) almost overlap, while the intermediate shear history ($11.4\ s^{-1}$) results in lower viscosities and yield stress indicating a complex relationship between the shear history and the overall flow properties. The locus of equilibrium viscosities (dotted line in Figure 17), coincides with the individual flow curves more closely than does that for the untreated samples. The flow improver, therefore, has the effect of compressing the flow curves together, thus reducing the shear history effect. The minimum shear stress for this locus is 0.95 Pa, which corresponds to the minimum operating point for this treated oil at 11°C. In other words, if the treated crude is cooled to 11°C, then a minimum wall shear stress of 0.95 Pa is required to maintain flow, whereas for the untreated crude, a minimum wall shear stress of 1.9 Pa is required.

Quantitative assessment of flow improvers

Using the modified design procedures described above, for shear-history-dependent materials, the flow rate of a treated and untreated crude can be calculated taking into account the shear history experienced by each streamline, thus providing a quantitative measure of the effectiveness of flow improvers under steady-state conditions. To illustrate this, consider the hypothetical case of comparative tests carried out on samples of treated and untreated Jackson blend, arriving at the same result. This result would correspond to the intersection of the two equilibrium loci of Figure 17 (which occurs at 7.8 Pa, 0.256 Pa·s) and would correspond to an applied shear history of $78\ s^{-1}$. The result of the comparative tests carried out using one value of shear history, taken at face value, would lead to the conclusion that the flow improver additive has not had any effect on the oil. However, as described above, the oil in the pipeline does not see a single value of shear rate and hence is described by the locus of equilibrium viscosities rather than a single flow curve or viscosity.

The two equilibrium loci from Figure 17 can, therefore, be used to determine the velocity profiles (shown in the inset of Figure 17) and hence the flow rates. At a wall shear stress of 7.8 Pa, a 0.3-m-dia. pipeline would transport $0.053\ m^3/s$ (29,000 BOPD) of untreated crude but would transport $0.066\ m^3/s$ (35,900 BOPD) of crude treated with 1,000 ppm of additive no. 2, an increase of 24%. At the wall, the viscosity of the two oils would be identical, but moving toward the center of the pipe, the untreated crude becomes increasingly more viscous compared to the treated crude at the same radial position, having experienced a lower shear history. Note that the Newtonian solution would lead to a calculated flow rate (for both) of $0.081 m^3/h$ (43,900 BOPD), which again overestimates the flow rate by a considerable margin (23% for the treated crude and 52% for the untreated crude).

The quantitative assessment of flow improvers under steady-state conditions requires measurements to be carried out over a range of shear histories on both treated and untreated samples. From the example given, it is quite feasible for the flow improver additive to increase the flow rate of an oil even though a single test comparing a treated and an untreated crude, carried out at the pipeline 8 V/D may show no difference in the measured viscosity.

Capillary Viscometer

The capillary viscometer and the pilot-scale pipeline are favored by the oil industry for measuring the flow properties of waxy crude oils or the testing of additives and other treatment techniques due to their obvious close resemblance to the full-scale pipeline. The pilot-scale equipment is, however, very expensive to run and generally shows poor agreement with other laboratory data and operating pipelines. On closer examination, there are some technical and rheological difficulties that make the capillary viscometer or pilot-scale pipeline less than the ideal choice for the measurement of the flow properties of difficult materials such as waxy crude oils.

As noted by Ford et al. (1965), it is necessary to adopt a forward and backward pumping action to prevent the test oil being exposed to the high shear in the pump. Each streamline experiences a constant, but different, shear and thermal history due to velocity and temperature gradients that exist across the radius of the pipe. The resulting pressure drop–flow rate measurements are the result of a composite effect as shown in the example calculation above. The same composite effect, however, does not occur in an operating pipeline where the fluid properties vary along the length of the line as well as across the radius. Because it is experiencing a range of shear rates (hence, shear histories), a capillary viscometer or pipeline cannot be expected to give the same results as a rotational viscometer under identical test conditions.

An additional problem is that external cooling results in temperature profiles across the radius. At the wax crystallization point, the sudden change in viscosity (as in Figures 1 and 5) would lead to a substantial change in the velocity profile (and hence the shear history). The lack of control over the velocity profile leads to continued low measured pressure drops until the oil at the center of the pipeline has begun to crystallize.

Capillary viscometers and pilot-scale pipelines have often been used to measure the yield point of gelled crude oils. However, the slow advance of the pressure front (Smith and Ramsden, 1978), which leads to a nonlinear axial stress distribution and the compressibility of the oil and of the pipeline (Perkins and Turner, 1971), makes it impossible to correctly define the yield stress in such devices. It is worth noting that on the topic of capillary viscometer or pilot-scale pipeline, no data that show agreement of flow curves of a waxy crude oil obtained from two pipeline diameters have been published.

Conclusions

Waxy crude oil is a rheologically complex material whose flow properties are determined by the shear and thermal history imparted to the oil. The need to take an oil sample through a controlled shear and temperature program results in experimental difficulties that are not normally encountered in the flow property measurement. Measurement techniques are outlined that ensure reproducible time-independent data from rotational viscometers of differing geometry, thus ensuring that material data are obtained. The experimental difficulties associated with the flow property measurement of waxy crude oil make it much more difficult to utilize the capillary viscometer or pilot-scale pipeline.

The equilibrium flow properties obtained depend strongly on the shear history with very low shear histories resulting in the highest shear stresses. This results in a minimum operating condition below which flow in a pipeline would cease. This is of particular concern in the operation of declining oilfields and points to the need to design a waxy crude oil pipeline, not only for the maximum flow but also for the minimum anticipated flow. In the rheological sense, flow improver additives act to reduce the effect of the shear history and to reduce the minimum operating condition to lower shear stresses (pressure drops) and shear rates (flow rates).

Modified design procedures are outlined that account for the variation in the flow properties across the radius requiring a series of measurements over a range of shear histories to be made. Comparison with existing techniques, which are based on a single test shear rate, shows that the largest discrepancy occurs in the laminar and transition flow regimes—the most likely operating regime for an oil pipeline—with the existing techniques (both Newtonian and non-Newtonian), thus overpredicting the flow rate by the order of 100%. In turbulent flow, the method of Dodge and Metzner, modified to account for the effect of the shear history, is preferred over the method of Ford, Ells and Russell, due to its ability to handle non-Newtonian flow properties and the resulting shift in the laminar to turbulent transition point. The modified design techniques can be applied to the quantitative assessment of flow improvers allowing their economic evaluation under steady-state conditions.

Acknowledgment

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Notation

C_f = correction factor for the shear rate in turbulent flow
D = inside diameter of pipe
f = friction factor
K' = fluid consistency index
n = total number of radial segments
n' = flow behavior index
N_{Re}' = generalized Reynolds number
$\Delta P/L$ = pressure drop per unit length
r = radial distance
R = pipe radius (internal)
Re = Reynolds number (Newtonian) $= \rho VD/\mu$
T = temperature

v = local velocity
V = average velocity
z = axial distance

Greek letters

$\dot{\gamma}$ = shear rate
μ = Newtonian viscosity
ρ = fluid density
τ = shear stress
τ_y = yield stress

Subscripts

A = ambient condition
w = value at pipe wall

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Appendix: a Numerical Technique for Laminar Flow in a Pipeline

In situations where the viscosity of a fluid is not represented by a single flow curve but where viscosity-shear stress data are available (e.g., for shear-history-dependent fluids, radial temperature gradients), the total flow rate in a pipe can be determined by dividing the radius into n annular segments (of equal thickness) that are of sufficiently small size to allow the assumption of constant (Newtonian) viscosity μ_i to apply within each ith segment. The solution for the flow of two immiscible fluids between flat plates (Bird et al., 1960, p. 54) can be readily extended to the case of laminar flow in a tube. From the equations of motion and continuity, it can be shown that the velocity profile in each annular segment is given by:

$$V_{z,i}(r) = \frac{\Delta PR^2}{4L}\left\{\sum_{j=n}^{i+1}\left(\frac{2j-1}{n^2\mu_j}\right) + \frac{\left(\frac{i}{n}\right)^2 - \left(\frac{r}{R}\right)^2}{\mu_i}\right\} \tag{8}$$

from which the total flow rate in each segment can be calculated as:

$$Q_i = \frac{\pi\Delta PR^4}{4L}\left\{\sum_{j=n}^{i+1}\left(\frac{2j-1}{n^2\mu_j}\right) + \frac{(2i-1)}{2n^2\mu_i}\right\}\frac{(2i-1)}{n^2} \tag{9}$$

Commencing from the calculation at the pipe wall, the average velocity and flow rate are determined in each successive segment until the pipe center is reached. Using model fluids, it can be shown that an accurate flow rate (within 1% of the analytical solution) can be obtained with as few as ten segments.

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