Asphaltenes Precipitated by a Two-Step Precipitation Procedure. 2. Physical and Chemical Characteristics

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Effect of the Pipe Diameter on the Restart Pressure of a Gelled Waxy Crude Oil

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ABSTRACT: Restart pressures for a gelled crude oil were determined experimentally for three pipes with a length of 5.8 m and diameters of 28 mm (1 in.), 55 mm (2 in.), and 82 mm (3 in.). A comparison of extrapolated restart pressure values based on data from a 4.3 mm (0.17 in.) pipe using the same oil was performed. The objective was to investigate the relation between the restart pressure of a gelled crude oil and the pipe diameter used to determine the yield stress used for extrapolation to larger pipe diameters. It was shown that the restart pressure was not proportional to the pipe diameter and that yield stress values obtained from small pipe diameters will overpredict the restart pressure compared to experimental values for larger pipe diameters. As a consequence, extrapolation of restart pressures based on small diameter pipe experiments may lead to very conservative estimations of restart pressure.

■ INTRODUCTION

Most crude oils have a threshold temperature below which they exhibit non-Newtonian behavior. Wax precipitation combined with the presence of asphaltenes and resins are usually responsible for this behavior.[1] During operation of crude oil flow lines, the non-Newtonian domain may be encountered during transient conditions, such as temporary shutdowns. The resulting cooling of the fluid can initiate wax precipitation, which, in some fluids, is a precursor to the formation of gels. With gel-forming systems, an overpressure will be required during restart of flow to break the gel structure.[2] The force per unit area required to break any gel formed is known as the yield stress. The yielding behavior of gelled oils is associated with the rupture of linkages within a network of wax crystals and is often assessed in terms of the static yield stress. The static yield stress determines the overpressure required to initiate flow during restart.[1] Laboratory restart experiments can be performed to assess the magnitude of the yield stress. Techniques include small pipe diameter restart experiments,[1,2] use of a rheometer,[2−6] and studies of the physics of the gel during formation and breaking using an applied external shear force.[4,5] Numerical simulations are also performed using predictive models.[7−9] The literature, however, indicate a severe paucity of data relating to larger diameter pipes and the dependence of the yield stress upon the pipe diameter. However, Wardhaugh and Boger[10] did a review where the study by Davenport and Somper[11] was among the cited work. They compared pipe diameters from 6 to 75 mm. The general trend was that yield values increased by decreasing the pipe diameter. Also, some recent experiments have been performed by Phillips et al.,[9,12] although also with relatively small pipe sizes of 5.9 mm ($^1/_4$ in.) and 12.7 mm ($^1/_2$ in.) inner diameter tube. On the basis of experiments and numerical simulations, they suggested several model predictions related to fluid volume shrinkage, shrinkage flow, and void formation during gel formation. It is known that larger pipe diameters give lower surface area/volume ratio and, thus, lower pressure drop.[12] The accuracy in the estimated required overpressure for restart of flow lines in actual use may well suffer when based on data from experiments performed on a small pipe diameter.

The current work provides experimentally determined restart pressures at different pipe diameters larger than what is reported in the literature. Phillips et al.[9,12] provides a thorough overview of the current knowledge of wax morphology and the techniques normally used to investigate the restart pressure for waxy crude oils. They point out that the issue is a complex one with a number of factors contributing to the observed behavior, including the rate of fluid cooling and shear forces acting on the fluid during the cooling process. They also point out that a complicating factor for fluid with gelling tendencies is that some form of axially directed asymmetry must be present to direct the shrinkage flow that is engendered by molecular cohesion.[9] The presence of such asymmetry in the form of an axially directed vector component of gravity or by exposure of one or both pipe ends to atmospheric pressure is suggested as responsible for inducing an axial flow direction.

Under actual operating conditions, the cooling rate will be dependent upon the fluid temperature, flow line insulation level, and surrounding thermal conditions. The cooling rate will affect the wax crystallization and aggregation process. A detailed study on the sample preparation, where the temperature history was of importance, was performed by Marchesini et al.[13] to determine appropriate test conditions. Lee et al.[2] reported that, at low rates of cooling, the wax molecules were sufficiently mobile to form large crystals, resulting in a decrease in the number density of crystals. This, in turn, influenced the resulting gel strength as measured in a small diameter pipe and rheometer experiments.[2] They proposed that a high cooling rate resulted in an increased adhesive and reduced cohesive strength between wax crystals. They offered this shift as an

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explanation for why rapidly cooled crude oils typically required lower (or none at all) overpressures for restart than fluids cooled at a slower rate. With reduced cooling rates, the wax crystals grew larger with a sheet-like structure, giving a higher degree of interconnectivity compared to wax crystals formed under faster cooling rates. At the higher cooling rate, the number density of crystals increased but the crystal sizes were smaller and the shape of the crystals were needlelike (average surface area of the crystals was $1 \times 20\ \mu$m).[2]

Wardhaugh and Boger[10] described qualitatively the yielding of waxy crude oils in detail and quantified three mechanisms for yielding: (1) elastic response, (2) creep, and (3) sudden and dramatic failure (fracture).

The transition between elastic response and creep (point A in Figure 1) corresponds to the first yield stress or the elastic-

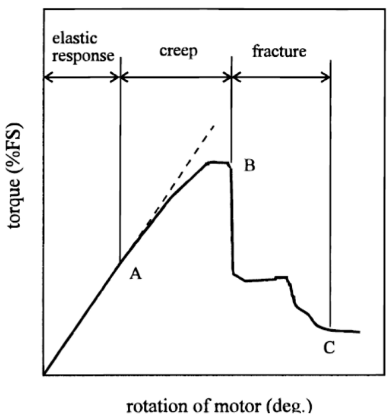

Figure 1. Yielding process of a waxy crude oil (reproduced with permission from ref 3).

limit yield stress (τ_e). The stress at the starting point of the fracture (i.e., point B) corresponds to the second (or the static) yield stress (τ_s). The third (or the dynamic) yield stress (τ_d) (which was not determined in the work by Wardhaugh and Boger) can be measured after the structure of the sample is ultimately broken through sustained shear (after point C).[3] Both the elastic-limit and static yield stresses are dependent upon the strength of the interlocking network of wax crystals in the oils before the structure is disturbed, while the dynamic yield stress is related to the concentration and size of the wax particles in the oils after the structure is completely destroyed.[3]

Chang[3] investigated the effect of the stress loading and stress loading rate and found that both dynamic and static yield stress decreased when the stress loading and stress loading rate decreased. Furthermore, they argued that the dependence of the static yield stress upon the stress loading rate may imply that the overpressure required to initiate pipeline flow is not only controlled by the strength of the wax structure of the oil but also how quickly flow is restarted. They further recommended that the pump pressure, when starting or restarting a pipeline transporting waxy crude oil should be increased as slowly as possible, because a slower operation will require a lower pump pressure not only in initiating the flow but also in transporting the oil in the final broken state after the restart.

Concern was raised that the calculated restart pressures based on small diameter pipe experiments would be too conservative, leading to an overestimation in required pump capacity. It was therefore decided to conduct experiments on larger diameter pipes to address the effect of the diameter on yield stress.

EXPERIMENTAL SECTION

Three carbon steel pipes with diameters of 28 mm (1.1 in.), 55 mm (2.2 in.), and 82 mm (3.2 in.) (referred to as 1, 2, and 3 in. pipes) were used. The pipes were mounted horizontally and leveled. The pipes had a length of 5.8 m and were equipped with two pressure sensors (P1 and P2) located some 70 cm from each pipe end, giving a distance between P1 and P2 of 4.4 m, and the distance from P1 to the atmospheric part of the pipe was 5.1 m. Figure 2 shows a sketch of the setup, indicating positions of the pressure and temperature sensors. The pressure sensors were mounted horizontally and flush with the inner wall of the pipe. A piston was mounted at one pipe end and fitted with a screw for position adjustment. At the other, atmospheric, pipe end, a trough was placed, making it possible to fill the pipe with oil without closing. Furthermore, being open to atmosphere, no pressure buildup would occur and resistance from the non-pipe part of the outlet, when inducing pressure at the other end, would be minimal. The piston had a diameter of 32 mm, with a distance from the piston to the expansion of the pipe diameter of 120 mm. The expansion from piston to pipe was conic to reduce effects from the sharp diameter transition between the piston cylinder and the pipe. The piston was moved by turning a threaded rod having a pitch, giving a horizontal movement of 1 mm per turn, equivalent to some 0.8 mL of oil per turn. The arrangement provided for a controlled and steady displacement of fluid.

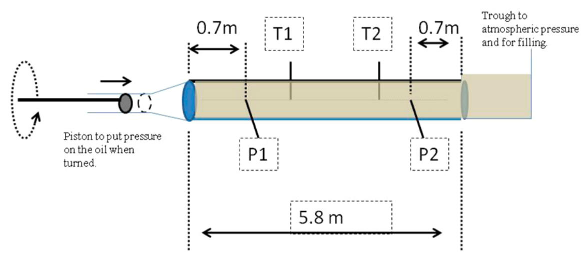

Figure 2. Schematical drawing showing the experimental setup for the restart tests. The conic part was also filled with the crude oil. P1 will experience the pressure resulting from restarting the plug from P1 to the end of the pipe, which was 5.1 m.

With pressure induced by the piston, the oil level at the other end (right part of Figure 2) was practically constant because of the small volume displacement in the cylinder when the piston was moved. The two pressure sensors of type DMP 331 had a range of 250 mbar, with an absolute accuracy better than ±0.1% of full scale. The two temperature sensors (PT100, class B) were located to measure the center pipe fluid temperature. Table 1 show the dimensions of the pipes used in the experiments and the total volumes of oil necessary, as well as the total wall area for each pipe section.

The crude oil used was an API 37.1 grade from a single batch. The pressure−volume−temperature (*PVT*) data reported a density of 840 kg/m^3 at 15.6 °C, and the reported wax appearance temperature (WAT) at atmospheric conditions was 28 °C. Furthermore, the wax

Table 1. Dimensions of the Pipes and Volume/Wall Area Ratio

pipe dimension (in.)	inner diameter (mm)	total pipe volume (L)	total wall area (m^2)	volume/wall area ratio
0.17	4.3	15.2	0.2	1.1
1.1	28	3.6	0.5	7.0
2.2	55	13.8	1.0	13.8
3.2	82	30.7	1.5	20.5

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and asphaltene contents (pentane extracted) were 7.7 and 0.3% by weight, respectively, and viscosity at 30 °C was 5 cSt.

Data Acquisition and Conditioning. A Labview-based system was used for data acquisition, with a logging frequency of 100 Hz. During cooling the unit, T1 was set to 1 Hz to monitor the cooling rate of the fluid. Measured pressure data were offset-corrected to 0 mbar based on readings at the onset of each experiment. The offset was defined as the deviation from 0 mbar at the start of the experiment after filling but before gel formation occurred. The range of the offset, which was corrected, was from 3.4 to 12.8 mbar, with the highest values for the 1 in. pipe. Tabulated values are given in Table 2.

Table 2. Offset Values Used To Adjust the Pressure Profiles To Start at 0 mbar

test	offset P1	offset P2
1 in. pipe	12.8	11.1
2 in. pipe	5.6	3.4
3 in. pipe	4.0	4.3

Reasons for the offset could be small deviations in the liquid height above the sensors and shrinkage of the oil. Offset values increased for an increasing pipe diameter because of the increased liquid height above the pressure sensors.

Figure 3 depicts how offsets were determined and shows how the pressure readings started to oscillate at a temperature around 20 °C.

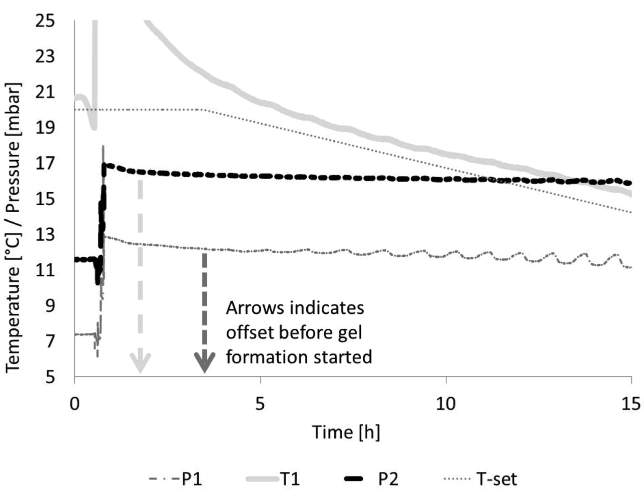

Figure 3. Example illustrating how the value of the offset of the pressure was determined. It was observed that the pressure was higher than 0 mbar at the start of the experiment and, thus, had to be offset-adjusted.

Offset values were determined prior to the onset of oscillation and are found in Table 2. Oscillation of the pressure was suggested to result from small oscillations in the temperature in the cooling room, making the gelled oil system respond by contraction and expansion, detectable by the pressure sensors.

Cooling and Restart Procedure. A crude oil known to gel was used. The oil was preheated under circulation at 60 °C for at least 24 h before sampling for experiments. This ensured a homogeneous fluid. The pipes were placed inside a climate chamber, which, during filling of oil, was held around 20 °C. Hot oil was transferred to the pipe by pouring at the trough side (Figure 2), while the pipe was tilted slightly to completely ventilate out trapped air. The time scale for the entire oil plug to reach 20 °C was 35 min, 2 h, and 4.5 h for the 1, 2, and 3 in. pipes, respectively. After filling, the chamber was gradually cooled to 4 °C (Figure 4). The cooling of the climate chamber from 20 to 4 °C in the experiment with the 1 in. pipe was 6 h, with an additional 20 h resting time. For the 2 and 3 in. pipes, the cooling rate was prolonged to 32 h, with another 32 h for "resting", to make sure the entire plug was gelled. In comparison, the oil in the 0.17 in. pipe reduced from 45 to 4 °C over a 6 h period. This temperature was maintained for a further 16 h before the content of the pipeline was displaced by pumping distilled water into it at a rate of 0.1 mL/min. The cooling rate for the fluid core was higher for the 1 in. pipe compared to the 2 and 3 in. pipe experiments because of the faster cooling of the climate chamber in the 1 in. test. The cooling rate was low enough to obtain gelling of the oil as observed by visual inspection of the oil in the trough and monitoring of the core temperature of the oil plug. "Restart" of flow was performed by moving the piston manually, giving a horizontal speed of the piston of approximately 1 mm/min, equivalent to a flow rate of 0.8 mL/min.

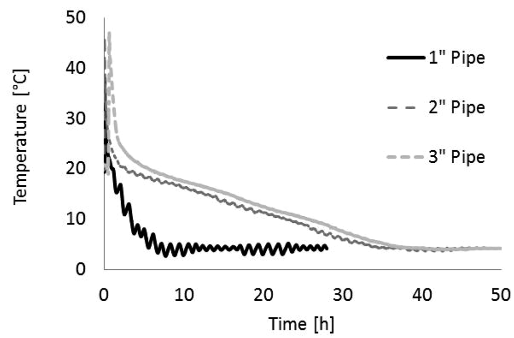

Figure 4. Temperature profiles for the three pipe dimensions during the cooling from warm fluid to 4 °C.

Calculation of Yield Stress. The yield stress (τ_y) was calculated from the measured yield pressure using the quasi-steady force balance between the wall shear stress and the restart pressure (eq 1)[2,6,8,14]

$$\tau_y = \frac{PD}{4L} \tag{1}$$

where P is the yield pressure, D is the inner pipe diameter, and L is the length of the plug or, in this case, between the two pressure sensors.

Yield stress was reported in *PVT* information provided by an anonymous company. These data were experimentally determined by an independent laboratory and reported an experimental yield pressure of 1.03 bar (15 psi) over a 15.24 m long pipe with an inner diameter of 0.17 in. (4.3 mm). Using eq 1, this gave a yield stress of 7.3×10^{-5} bar (0.153 lb/ft^2). The yield stress value can thus be used to calculate, by extrapolation, the restart pressure for any pipe diameter. As an example, Table 3 shows restart pressures for four different pipe diameters (0.17, 6, 8, and 12 in.) based on the experimentally determined yield stress of the 0.17 in. pipe.

Table 3. Calculated Restart Pressure of a Gelled Pipeline Based on Experiments Using a Small Diameter (0.17 in.) Pipeline[a]

pipe dimension (in.)	restart pressure (bar/km)
0.17	67.9
6	1.9
8	1.4
12	1.0

[a]The oil used was the same as that for the experiments performed in this test.

RESULTS AND DISCUSSION

From the measured pressures at position P1, the restart pressure was found by plotting the pressure profile versus the time. Plots of the pressure profiles are given below (Figures 6–8). The pressure development during the experiments followed the trend outlined: (1) linear and simultaneously increase in pressure for P1 and P2 when movement of the piston was started, (2) sudden decrease in the pressure gradient followed by a linear increase, first break (P2 responded before P1), and (3) flattening out or slight decrease in the pressure, second break (this happened simultaneously for P1 and P2).

Our interpretation of the observed behavior was that, when starting to move the piston (point 1 above), a pressure increase was experienced throughout the plug. The gelled oil then started to move, as seen by the break (decreasing gradient) in P2 (point 2 above), followed by P1 shortly thereafter. The pressure continued to increase until the whole plug was in constant movement and the pressure observed was due to steady-state flow (point 3 above). On the basis of these interpretations, the restart pressure was defined as the difference in the pressure immediately before movement of the piston was started and the highest pressure observed, i.e., where the pressure started to approach a constant value (point 3 above). A possible alternative interpretation of the restart pressure based on the current results would be by defining the first break (point 2 above) as the restart pressure because this could be where the gel structure started to break down. However, to obtain a proper restart, the fluid should be fully transportable without pressure changes as long as no other obstructions are present and the pump power is constant. Consequently, we did not consider the first break to fully qualify as the restart pressure.

Table 4 shows measured pressure drops and calculated restart values resulting from the experiments.

Table 4. Values for the Yield Stress for the Experiments (Given in Bars) and Calculated Restart Pressure for a 1 km Pipeline of the Given Diameter

pipe inner diameter (mm)	distance of P1 to the end of the pipe section (m)	measured pressure drop (bar)	calculated restart pressure (bar/km)
4.3	15.24	1.0	67.9
28	5.1	31.7×10^{-3}	6.2
55	5.1	14.3×10^{-3}	2.8
82	5.1	7.6×10^{-3}	1.5

The calculated restart pressures can be seen to exhibit a significant dependence upon the pipe diameter used to determine yield stress. Moreover, the yield stress extrapolated from small diameter pipe experiments may turn out to be conservative. One reason for this is the effect of the increasing ratio between the volume and surface area upon increasing the pipe diameter, which equals $r/2$ (Table 1). Furthermore, the distance from the pipe wall to the center will affect the cooling profile in the oil plug, and it is not unlikely that also the growth rate and mechanisms will be affected by the inevitable differences in cooling rates for different dimensions. Moreover, the results showed a reduction in the calculated restart pressures for a given pipe dimension when yield stress values were based on an increasing pipe diameter. Figure 5 depicts calculated restart pressures for larger diameter pipes based on the yield stress originating from each of the four experiments in Table 4. It was obvious that an experimentally obtained yield stress from a smaller pipe diameter resulted in higher predicted restart pressures compared to yield stress from larger pipe diameters. The decrease was most pronounced when moving from a 4.3 mm diameter pipe to a 28 mm diameter pipe, although the decrease continued when comparing a 28 mm diameter pipe to a 55 mm diameter pipe and to an 82 mm diameter pipe. A comparison of the restart pressure calculated for the 82 mm diameter pipe using the experimentally obtained yield stress values from the 4.3 mm diameter pipe was 140% higher than the experimentally determined restart pressure for the 82 mm diameter pipe. A summary of the deviations between experimentally determined and calculated restart pressures is given below (Table 5).

Figure 5 show that the calculated restart pressure decreased when the experimentally obtained yield stress values from larger pipe diameters were used.

Comparison of Calculated Restart Pressures Based on the Experimentally Obtained Restart Pressures. The calculated restart pressure for a given pipe diameter will be dependent upon a number of factors, such as the experimental setup, cooling rate, and oil composition. Table 5 holds a comparison in the form of the deviation of the calculated restart pressure from an actual experimental restart pressure. These values were obtained using eq 2

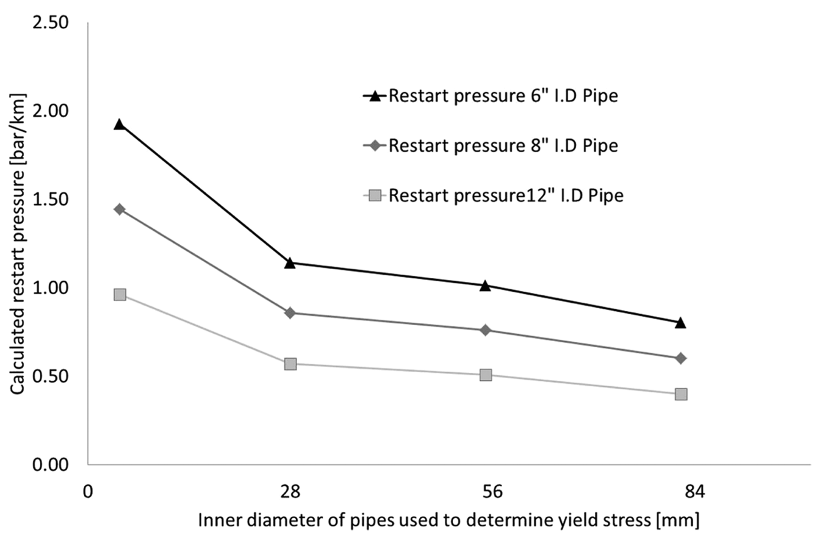

Figure 5. Plot shows calculated restart pressures for 6, 8, and 12 in. pipe diameters based on the yield stress values obtained experimentally for pipes with diameters of 4.3, 28, 55, and 82 mm. Yield stress values from larger pipe diameters resulted in the prediction of lower restart pressures.

Table 5. Deviation in Percent between the Actual Yield Stress and the Yield Stress Extrapolated from the Experimental Values from Other Diameters

pipe inner diameter (mm)	percent deviation based on $\tau_{0.17\ \text{in.}}$ (%)	percent deviation based on $\tau_{1\ \text{in.}}$ (%)	percent deviation based on $\tau_{2\ \text{in.}}$ (%)	percent deviation based on $\tau_{3\ \text{in.}}$ (%)
4.3	0	−41	−42	−58
28	68	0	−11	−30
55	90	13	0	−21
82	140	42	26	0

$$RP_{dev}\ (\%) = \frac{RP_{calc} - RP_{exp}}{RP_{exp}} \times 100\% \tag{2}$$

where RP stands for restart pressure and the subscripts dev, calc, and exp refer to the deviation in percent between the calculated and experimentally determined restart pressures related to the experimentally obtained value for the given pipe diameter of which the restart pressure was calculated. It was shown that a calculation of the restart pressure based on a 4.3 mm diameter pipe gave an overestimate of 140% higher for an 82 mm diameter pipe compared to the experimentally obtained value. In comparison, using the yield stress values obtained from an experiment using a 55 mm pipe, the overestimate was reduced to 26% higher than the actual measured restart pressure. Basing the necessary pump capacity on experiments performed on too small pipe diameters may lead to excessive overprediction of required pressures for restart of a given flow system. This clearly showed that the correlation between the restart pressure and pipe diameter was not predicted by eq 1.

Experimentally Obtained Pressure Profiles. The pressure profiles from the experiments on the three different pipe diameters are given below (Figures 6−8). Profiles for both pressure sensor P1 and P2 are given in each plot. It was seen that the highest obtained pressure decreased for an increasing pipe diameter. Furthermore, the difference between the highest pressure and the start pressure for P1 (indicated in the figures) is given as the yield pressure in Table 4. From the yield pressure, the gel strength was calculated using eq 1 and the results are given in Table 4. In each plot, there was an increase in the pressure at the end of the experiment just before the pressure decreases, because of shut-in of the flow. This pressure increase was due to an increase in the movement of the piston and was merely a consequence of higher shear because of the higher flow rate. For the sake of clarity, it was the time when restart was initiated that should be seen as the initiation point.

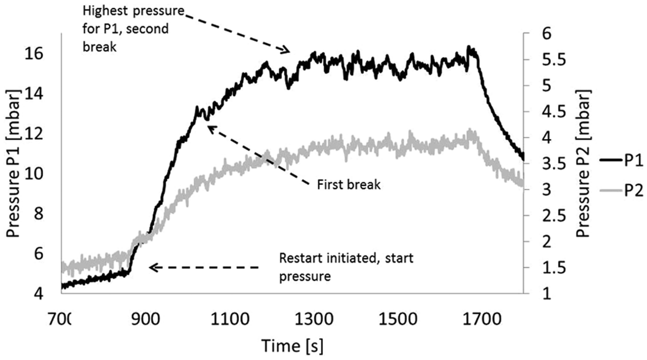

Figure 7. Pressure profiles from the 2 in. (55 mm) pipe experiment. The values are offset-adjusted. The arrow indicates where restart was initated, and the first and second breaks are pointed out in the plot.

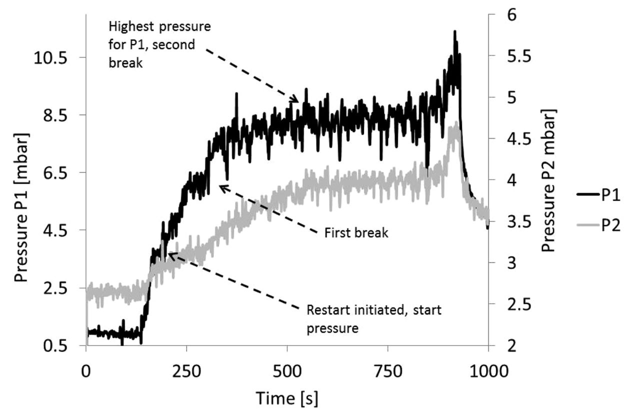

Figure 8. Pressure profiles from the 3 in. (82 mm) pipe experiment. The values are offset-adjusted. The arrow indicates where restart was initated, and the first and second breaks are pointed out in the plot.

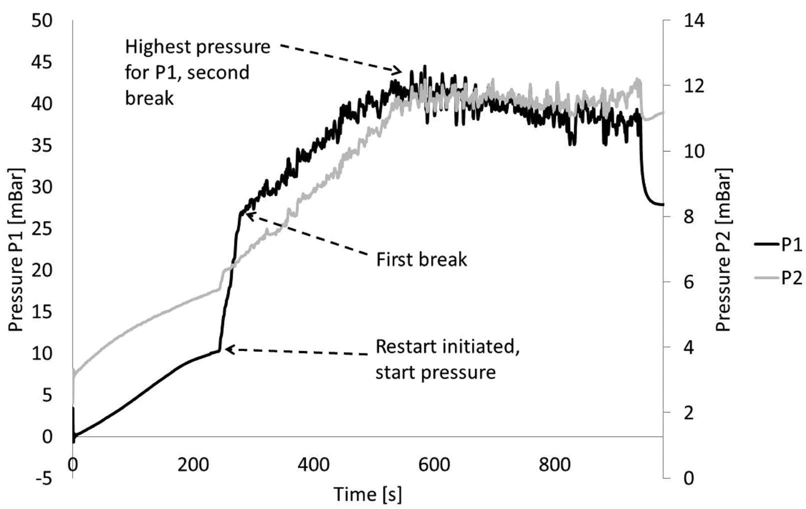

Figure 6. Pressure profiles from the 1 in. (28 mm) pipe experiment. The black line is P1, and the gray line is P2. The values are offset-adjusted. The arrow indicates where restart was initated, and the first and second breaks are pointed out in the plot.

The period up to this shows that only a time lag from starting the logging program to restart was initiated and did not affect the experiment as such. This lag was longer for the 55 mm diameter pipe experiment because it was decided to record a longer period prior to the restart to obtain temperature–pressure data when the wax plug was still intact.

Comparison of the Rate of Pressure Increase. From the profiles of pressure versus temperature (Figures 6–8), it was seen that the rate of increase in pressure was different for the static and dynamic yields (after first and second breaks). Furthermore, the profile was different for the different pipe diameters. These differences are shown in Table 6, where the values of the rates of pressure increase are given for both pressure sensors for the three pipe diameters.

Table 6. Rates of Increase in Pressure (Pa/s)

pipe inner diameter (mm)	P1 elastic (Pa/s)	P1 creep (Pa/s)	P2 elastic (Pa/s)	P2 creep (Pa/s)
28	30.9	4.2	4.2	1.3
55	3.7	2.2	1.0	0.3
82	5.1	1.6	0.5	0.2

The rate was higher for the 28 mm diameter pipe than for the 55 and 82 mm diameter pipes, which was probably due to the larger pipe diameters containing more mass, which results in higher elasticity. This is in agreement with the study by Chang et al.,[3] who found that both dynamic and static yield stress decreased when the stress loading and stress loading rate decreased. The stress loading for larger pipe diameters will be lower with the same force. Further, the elastic responses were higher than the responses observed in the creep region because of the relatively higher incompressibility and the fact that, during creep, a lot of the pressure is released through the movement of the oil. The values indicated indirectly the importance of the pressure increase and that it should be a factor in the determination of the design restart pressure to estimate the rate of pressure increase related to both the mass and elasticity of the gelled oil.

In the present work, both shrinkage and reduction in pressure were observed during cooling. In conformity with the work by Phillips et al.,[9,12] a decrease in fluid volume during cooling was observed in our experiments. The associated pressure decrease has been attributed to what can be termed shrinkage flow. The shrinkage flow appears dependent upon the cooling rate.[9,12] Furthermore, the restart tests clearly demonstrated that the pipe diameter had a significant effect on the yield stress. They further showed that the yield stress dependence upon diameter became less significant at larger diameters. The experimental setup showed that there was a large difference in restart pressures when increasing the pipe diameter. Nevertheless, an overestimate of 140% on the necessary restart pressure may or may not affect the design of a given field. Moreover, the current tests were performed on one fluid only. A comparison of different fluids giving wax gelling during cooling would give more knowledge on the diameter effects and potential overestimates using small pipe diameters.

Other Observations. Wax is a highly temperature-sensitive compound, and a gelled wax system will respond to temperature changes. This was observed during the experiments where the pressure varied in a sinusoidal manner because of a sinusoidal variation in room temperature (Figure 9). The

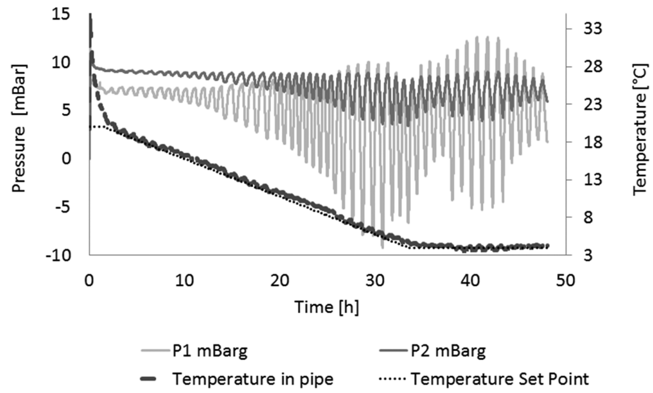

Figure 9. Temperature and pressure profiles during cooling of the 55 mm pipe. This figure shows the sinusoidal temperature as well as pressure variation for the 55 mm pipe as an example. The large variations in the pressure were suggested to be due to contraction–expansion cycles of the gel.

room temperature variation was up to 2 °C absolute. There was approximately 30 min between the highest and lowest values, and P1 and P2 responded simultaneously, with P1 responding more than P2. The sinusoidal behavior of the pressure readings was more or less constant for the last 4 h before the experiment was performed. The explanation for this sinusoidal behavior in the pressure readings was that the gel contracts and expands because of the temperature variations that occurred because of the setup of the cooling system of the climate chamber. To what extent these variations affected the wax crystallization and growth process could not be investigated within the scope of this work. Nevertheless, this behavior was observed for all three pipe diameters, and it was assumed that the systems, being exposed to equal conditions, would respond equally, resulting in comparable experimental data.

It was also observed that this sinusoidal behavior of the pressure readings started around 26 °C and began to increase in intensity at around 12 °C. WAT for the fluid was given to be 28 °C by differential scanning calorimetry (DSC). Gelling may therefore be assumed to start at around 28–26 °C, and the effect of the temperature on the contraction–expansion of the gel may have increased from around 12 °C for the current system.

Another observation was that, at higher cooling rates for the fluid, wax precipitation seemed to occur but did not lead to gelling. This was observed in one test where the climate chamber and pipe were precooled prior to filling of hot oil. The oil did not gel but seemed to be in its normal liquid state. However, lumps of more viscous substances were observed to be present at the lower part of the pipe when it was emptied. This may indicate that wax precipitation occurred but that the cooling rate was too fast for the wax to build structures associated with gelling, in accordance with Lee et al.,[2] who, as mentioned in the Introduction, stated that a high cooling rate resulted in an increased adhesive and reduced cohesive strength between wax crystals and that rapidly cooled crude oils typically required lower (or none at all) overpressures for restart. Furthermore, the restart pressure for this test did not follow the profile of the gelled oil tests and was, as expected, lower. Nevertheless, it could not be determined from this observation if a fast cooling would be more or less beneficial for the restart of pipelines compared to a gelled oil system.

■ CONCLUSION

A quantitative effect of the pipe diameter was determined experimentally by performing experiments on steel pipes with diameters of 28, 55, and 82 mm. The restart pressures were calculated from experimentally obtained yield stress values for the three pipe dimensions and for a 4.3 mm diameter pipe. For the 4.3 mm diameter pipe the restart pressure was 67.4 bar/km, while for the 82 mm diameter pipe, it was only 1.5 bar/km. Current equations are based on the fact that the change in the restart pressure is directly proportional to the change in the pipe diameter. However, a comparison of the predicted restart pressure for an 82 mm diameter pipe deviated by as much as 140% when it was based on yield stress values obtained from a 4.3 mm diameter pipe. In comparison, the deviation between actual and extrapolated restart pressure was +26% for the 82 mm diameter pipe when the yield stress from the 55 mm diameter pipe was used. The model used to calculate restart pressure is proportional to $4L/D$ for a given yield stress. Using this model, the current results strongly indicate that restart pressure can be overpredicted when based on yield stress values from small diameter pipe experiments. Therefore, using larger pipe diameters for determining the yield stress of a given gelled oil system should improve the accuracy of the prediction of restart pressure. Furthermore, it was observed that the rate of pressure increase did decrease by increasing pipe diameter. This may be due to the gelled system in larger pipe diameters obtaining a higher elasticity because of the larger dimensions and mass. Finally, it was observed that a rapid cooling did prevent the wax from forming a gel structure but rather seemed to precipitate the wax as lumps accumulating at the lower sections of the pipe.

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Notes

The authors declare no competing financial interest.

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