SPE Brazil Flow Assurance Technology Congress
Rio de Janeiro, Brazil, November 15 – 18 2022

The role of volume shrinkage in the startup flow of gelled waxy crude oils in pipelines

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Abstract
Predicting an accurate startup pressure for gelled waxy crude oils in pipelines is an old challenge yet to be overcome. It is known that the conventional force balance grossly overestimates the minimum axial pressure gradient required. Some researchers suggest that the occurrence of volume shrinkage due to gelation affects the gelled oil morphology and consequently the startup pressure. In this paper, the volume shrinkage of gelled crudes in rheometric and tube flows is investigated. We also study the relationship between the rheological properties and the minimum pressure gradient required for the onset of flow in the presence of volume shrinkage. Two different waxy crudes were used in the investigation. A method for predicting the minimum startup pressure by accounting for shrinkage as a correction to the conventional force balance is outlined.

Keywords
startup flow; gelled waxy crude; shrinkage.

Introduction
The goal of this work is to examine the volume shrinkage of waxy crude oils upon gelation as a potential explanation for the failure of the simple force balance ($\Delta P_{min}/L$ is the minimum pressure gradient required to start up the flow, R is the tube radius, and σ_y is the gelled crude static yield strength)

$$\frac{\Delta P_{min}}{L} = \frac{2}{R}\sigma_y \qquad (1)$$

in providing acceptable predictions for the pressure needed to start up the flow of gelled crude oils in pipelines, and then to propose a method to remedy this situation. To this end, we investigated the effect of oil shrinkage on the static yield strength and on the required minimum pressure gradient to start the flow in a tube. With this information, we were able to propose a simple modification to Eq. (1) that considers the effect of shrinkage. Detailed information can be found in [1].

Methodology
We performed different tests to assess the relationship between shrinkage and the failure of Eq. (1) observed in field applications.
To ensure the reproducibility of the experiments, a single initial state for all the rheometric and flow-in tube tests was established. It was required to control the shear history, aging, time dependence of the materials, wall slip, as well as the thermal history. Therefore, to obtain this controlled initial condition, in this work we opted for using fixed temperature periods, i.e. a controlled gelation procedure before each test. This means imposing a fixed heating period above WAT (when the oil is Newtonian) followed by a fixed quiescent cooling period (to mimic the shutdown situation) at 4 ℃ (the temperature of the ocean bed), which is below the pour point. The heating temperature can be either 30 ℃ or 45 ℃ (well above the experimental WAT), depending upon the experimental circumstances. The heating duration is selected as 1 hour, with the purpose of also mimicking the initial condition in the tube flow experiments. Subsequently, the temperature is abruptly changed to 4 ℃, so that the sample is subjected to static cooling for 1 hour. In this manner, all samples used in the experiments will possess the same initial microstructure and viscosity.

Rheological measurements
For the two waxy crude oils investigated, we measured the static and the dynamic yield strength performing creep and flow-curve experiments, respectively. Two different geometries were employed, namely parallel plates and Couette. Tests using the Couette geometry were performed independently in two different rheometers, for validation purposes. In all geometries the walls were roughened to eliminate apparent wall slip effects. It was observed that the measured value of both the static and the dynamic yield strength was considerably higher when the parallel plates

geometry was employed, as illustrated in Fig. 1. Moreover, the discrepancy was larger for the crude with higher paraffin content.

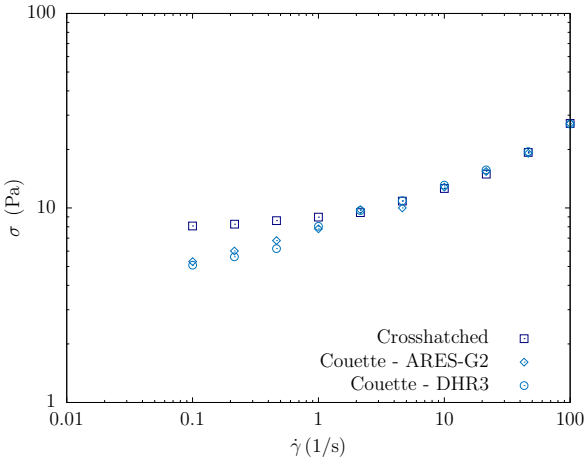

Figure 1. Flow curve of Petroleum # 1, indicating that the measured dynamic yield strength is higher for the crosshatched parallel-plate geometry.

Assessment of bulk shrinkage

Two shrinkage visualization cells were designed and manufactured, consisting of two square parallel plates mounted together such that a gap between them is formed. Each cell has a different gap, namely 0.3 and 0.6 mm. The rims of the cells are sealed. The bottom plate is made of aluminum, and the top one is made of Plexiglas. At two diagonally opposed corners there is a 1 mm diameter hole in the top plate of each cell. One of the holes is for injection, and the other is an air vent.

It was observed that in the small-gap cell the macroscopic shrinkage around the injection hole is clearly smaller, due to a larger resistance to the motion caused by shrinkage. Since the thermodynamic conditions are the same, we conclude that microscopic voids are formed in the bulk. We call this effect *bulk shrinkage*.

(a)

(b)

Figure 2. Macroscopic shrinkage around the injection hole. (a) smaller gap; (b) larger gap.

Bulk shrinkage is also believed to occur in the Couette geometry due to confinement, which explains the lower measured values for the yield strength.

Gelled crude oil flow in a tube

We also performed startup flow experiments, to measure the minimum axial pressure gradient required for the onset of flow of a gelled waxy crude oil in a tube, $\Delta P_{min}/L$. The apparatus employed (Fig. 3) is a modified version of the one described in a previous publication [2]. Detailed information can be found in [1].

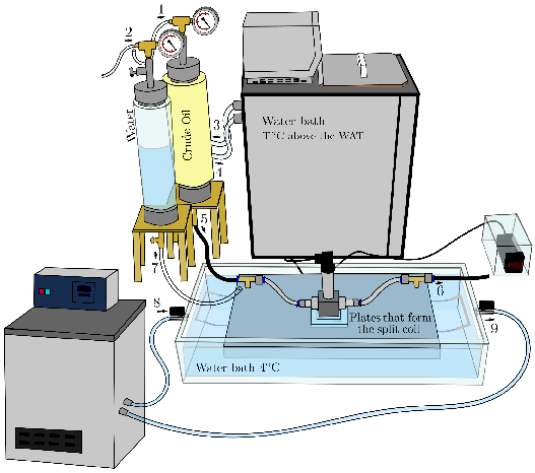

Figure 3. Schematics of the startup flow experiment. The tube is formed by two steel plates on which two identical channels of semicircular cross section were machined, to allow roughening of the tube inner wall.

The measured values of $\Delta P_{min}/L$ measured with this apparatus were "translated" into σ_y using Eq. (1), resulting in yield strength values even lower than the ones obtained with the Couette geometry. This is consistent with our hypothesis that shrinkage under confinement generates microscopic voids in the bulk of the gelled oil,

causing the yield strength to decrease. Note that confinement in the tube flow experiment is much more severe than in the Couette geometry, which in turn is more severe than in the parallel-plate geometry.

Results and Discussion

We now introduce the *shrinkage factor* F_{sh}, defined as

$$F_{sh} \equiv \frac{1}{\sigma_y}\frac{\Delta P_{min}}{L}\frac{R}{2} \quad (2)$$

That is, F_{sh} is defined such that the product $F_{sh}\sigma_y$ is an effective static yield strength that represents a correction for Eq. (1):

$$\frac{\Delta P_{min}}{L} = \frac{2}{R}F_{sh}\sigma_y \quad (3)$$

F_{sh} is expected to be a function of the petroleum composition and of the level of confinement, which for tubes should be well correlated by the dimensionless length L/R. As it is increased, we expect that the confinement effect attains a plateau (this hypothesis remains to be verified), so that, for long tubes ($L/R \gg 1$), F_{sh} would no longer depend on L/R. In our experiments, $L/R = 571$.
We also investigated the effect of the paraffin content on the shrinkage factor. To this end, we performed another set of experiments with three new samples. These samples consist of Petroleum #1 in which three different amounts of pure paraffin were dissolved, as given in Table 1.

Table 1. The shrinkage factor for the 4 samples.

	Sample 1	Sample 2	Sample 3	Sample 4
% wt	0	0.5	1	2
F_{sh}	0.31	0.12	0.08	0.04

For these four samples, we performed the same experiments described above for Petroleum#1 and Petroleum#2, except that the high temperature employed was 45°C, because 30°C was too close to the WAT of Sample 4.

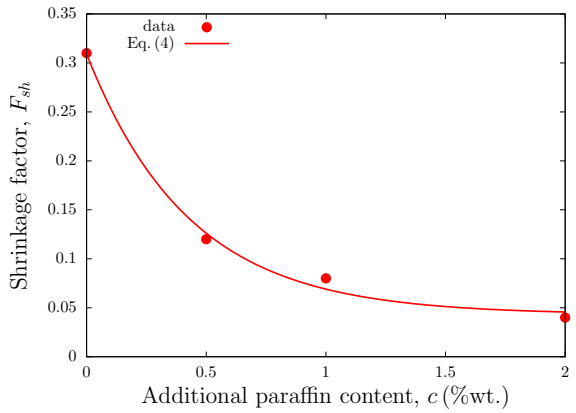

Figure 4. Shrinkage factor as a function of the additional paraffin content.

It is known that higher paraffin contents lead to higher total shrinkage. The results shown in Fig. 4 demonstrate that bulk shrinkage increases as the paraffin content is increased. It is highest for Sample 4, since its paraffin content is the highest and it presents the lowest macroscopic shrinkage. The static yield strength of the four samples was measured via creep tests, using crosshatched parallel plates. Due to a comparatively lower level of confinement, measurements with this geometry are assumed to give results unaffected by bulk shrinkage.

Conclusions

It is demonstrated that the gelation conditions found in tube flow are quite different from the ones found in rheometric measurements, and this difference is responsible for the failure of the simple force balance theory. Based on these findings, we outlined a simple method to create a correction for the simple theory, by introducing the shrinkage factor. Further research is needed to render the method utilizable in field applications. It is important to investigate the effect of the dimensionless length L/R on the shrinkage factor. Moreover, an extensive program using waxy crudes with a wide range of paraffin contents would allow the development of an empirical relation [3] for the shrinkage factor as a function of the paraffin content for different types of waxy crude oils.

Acknowledgments

Thanks are due to Petrobras S.A. (2014/00340-9), CNPq (307976/2018-1), CAPES (PROEX 625/2018), and FAPERJ (E-26/202.834/2017) for the financial support to the Rheology Group at PUC-Rio.

Responsibility Notice

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