PRESSURE DROP AND RE-START TIME DURING STOP-AND-GO EXPERIMENTS IN CORE-ANNULAR FLOW

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Abstract. *The production and transportation of heavy oils using water-assisted flow technologies such as core-annular flow has been recently proposed for onshore and, particularly, for offshore deep-water fields. The viscosity reduction obtained thanks to lubrication by water is significant since the pressure drop in steady state core flow becomes comparable to water flow only. However, oil adhesion on the pipe wall may occur for certain crudes and oleophlilic pipe materials, possibly resulting in severe fouling and increasing pressure drop continuously. Adhesion effects may be particularly critical in re-starting the pipeline after an unwanted, sudden stop of the flow. In this work, we present laboratory results of stop-and-go experiments where an initially stable horizontal core flow was suddenly stopped for 61 hours then re-started with water only, until pressure drop reaches its final value for water flow. The oil used is an 4127 cP, 999.2 kg/m^3, aromatic-asphaltenic Brazilian crude. The initial oil holdup was 0.85. The pipe is predominantly horizontal with 2.8 cm i.d., partly made on commercial steel and glass (for flow visualization). A physical model for predicting the re-start time is proposed.*

Keywords*: Heavy oil, Water-assisted flow, Core-flow, Re-start, Stop-and-go*

1. Introduction

The exploration of petroleum in Brazil in the last few years has been leading to the discovery of significant accumulations of high viscosity, API < 19 oils. These so-called “heavy oils” are difficult to produce in view of their immiscibility and high viscosity among the existent fluids in the formations (Mezzomo, 2000).

Since 1950 interest has been appearing in the investigation of water-assisted flow of viscous oil in order to reduce the frictional pressure gradient (Angeli *et al*., 1998). Russel *et al.* (1959) and Charles *et al.* (1961) studied technologies of pipeline transportation of heavy oils and developed the tecnology known as *core flow* (Vara, 2001). Later progress occurred in Holland with Ooms (1972) and Oliemans *et al.* (1987), and in the United States with Joseph *et al.* (1984). Bannwart and Vanegas (1999), based on the successful investigation by Vanegas (1999) proposed the application of this technique to heavy oil production.

The operation of an oil production or transportation line in the core-flow mode consists in injecting small amounts of water in order to create a lubrication layer around the viscous oil and avoid oil-wall contact. The resulting annular flow pattern reduces drastically the friction pressure gradient, allowing the oil to be pumped up to the surface at a flow rate similar to single phase water flow (Vanegas, 1999). The long term stability of this technique requires minimization of fouling (i.e. oil adhesion) of the pipe wall, which cause a reduction in the useful diameter of the pipe (Ramos, 2001).

Besides, it is important to investigate the start-up procedure after shut-down of certain core-flow lines. In the case of near-horizontal lines, gravity segregation causes the oil to accumulate at the whole upper part of the pipe, leaving a thin water by-pass in the lower part. If the water pump is re-started prior to the oil’s, the water drains through the by-pass and gradually removes the oil at the upper part. However, for inverted U-shape line configurations the oil may totally block the straight section of the pipe an the only way to remove the blockage, in this situation, is to pressurize the line with water and stand by the formation of the water by-pass, until the complete removal of the lid (Ribeiro, 1994).

Ribeiro (1994) presents data collected by INTEVEP for a 11 ºAPI, 996 kg/m³, 115 Pa.s oil at 25ºC in a 20.32 cm i.d., 1 km long pilot pipeline of San Tomé (Zuata, Venezuela), with injection of 4% of water and speed of 1,5 m/s, showing the increase of the pressure drop, in 72 hours, from 200 kPa up to 1200 kPa, due to the gradual growth of the amount of oil incrusted on the pipe wall. A study of oil deposition in oil-water core-flow pipe by Núñez & Joseph (1998) indicated that steel carbon tubes will be fouled by petroleum with high asfalthene concentrations and that accumulation of some of the deposited oil can be removed by increasing the water flow. Vanegas (1999) observed that for hydrocarbon oils, adhesion is not generally observed in glass pipes, whereas plastic pipes such as PVC or Plexiglass are fouled.

Since fouling becomes particularly serious in start-up, investigation of transient phenomena in an initially stable core-flow becomes essential. This work presents results for the transient pressure drop in stop-and-go experiments in a laboratory-scale pipe operating in the core flow mode. The results are used to develop a simplified model of the re-start process.

2. Experimental Apparatus and Methodology

The experimental apparatus used in this work is located in the Multlab of the School of Mechanical Engineering (FEM) of the State University of Campinas (Unicamp). It consists of a closed-loop circuit where oil and water are drained from a single 1.5 m^3 vertical separator tank by their respective pumps, as indicated in Figure 1.

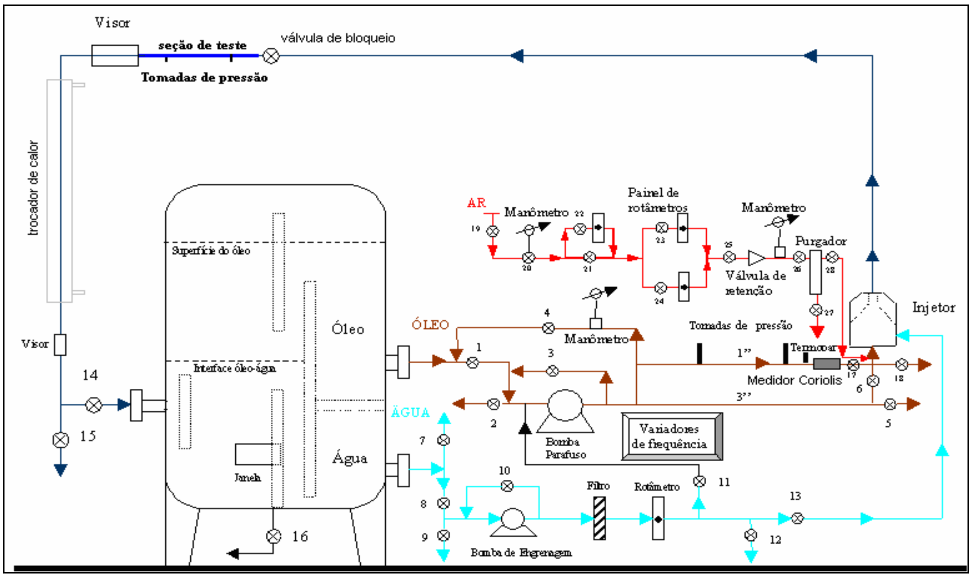

Figure 1. Schematic view of the experimental apparatus.

The oil phase consists of a water-in-crude oil emulsion with a density of 999.2 kg/m³ and viscosity of 4127 mPa.s at 25ºC. This oil is driven by a screw-type pump, whereas the water phase was driven by a gear pump. Both pumps were controlled by frequency inverters. After being measured in their correspondent flow meters (a rotameter for water and a Coriolis-type mass flow meter for oil) the oil and water phases joined each other in an acrylic injector mouthpiece. The oil enters underneath the injector whereas the water enters laterally, in order to induce the desired annular flow pattern quickly.

The two-phase circuit has a 2.84 cm i.d., 1.78 m long vertical section followed by a 3.70 m horizontal section, both made in glass. Past the horizontal section a steel carbon API 5L degree B tube of length 1.20 m and 2.608 cm i.d. was built, which is longitudinally split to allow inspection of its internal surface after the experiments. Past the steel section the oil-water flow returns to the separator through a vertical galvanized steel pipe of 2.76 cm i.d. being cooled by an external water flow countercurrent heat exchanger. A differential pressure transducer was used for pressure drop measurement in the steel carbon tube. Data was acquired and processed in a NI acquisition system in Labview.

The experiments consisted in establishing a stable oil-water core flow in the circuit, by imposing superficial oil and water velocities of 0.90 and 0.13 m/s, respectively. The correspondent oil holdup was 0.85, as calculated by the correlation developed by Vara (2001). Then the oil pump was stopped followed by the water's, so that the tail of the oil core parked at a desired position. At this point the valves of the circuit were closed, and the fluids were imprisoned in the line, with a certain length obstructed by the oil. As expected, the oil occupied most of the cross section of the blocked length, leaving only a thin water layer in the bottom. After 61 hours, the valves were opened again and water was pumped at 0.59 m/s superficial velocity, and the transient response of the pressure drop was measured at intervals of 10 s, until the value correspondent to single phase water flow was attained.

3. Results and Discussion

Two transient experiments were done. In the first, the tail of the oil was placed at the beginning of the steel pipe, thus the length obstructed by the oil was 3.58m. The results are presented in Figure 2.

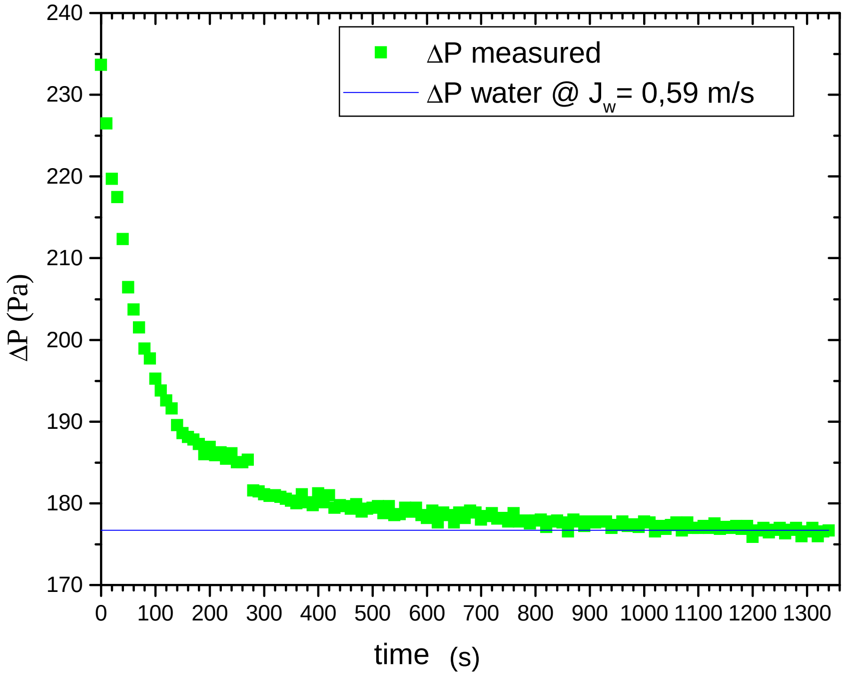

Figure 2. Pressure drop in the steel pipe as a function of time for the re-start test # 1

The horizontal line in Figure 2 represents the value previously measured for steady state single phase water flow at a superficial water velocity of 0.59 m/s. As can be observed, the pressure drop starts at 233.6 Pa and decreases very quickly towards the steady state value. Besides, water flow completely cleans the obstructed section of oil in about 20 minutes.

In the second experiment, the tail of the oil core was stopped at the beginning of the vertical glass section, and the total obstructed length of 9.09 m included the entire glass pipe plus the steel pipe and the return pipe. After 61 hours at rest, the flow was re-started with water at 0.59 m/s superficial velocity, as in the first experiment. The results for the instantaneous pressure drop (measured in the steel pipe section) are presented in Figure 3.

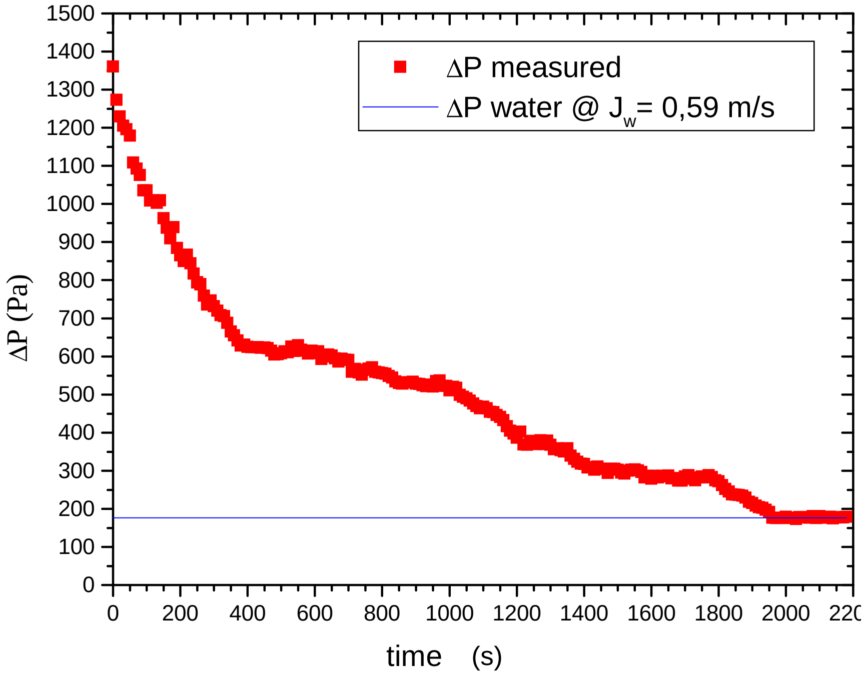

Figure 3. Pressure drop in the steel pipe as a function of time for the re-start test # 2

As can be observed in Figure 3, the pressure drop started at a much higher value (1360 Pa) than in the first experiment (see Figure 2) decreasing continuously until the steady state value. The complete removal of the oil slug lasted about 35 minutes. The decay curve is not as regular as in the first experiment, probably due to the different pipe materials and orientations involved: 1.78 m of vertical glass pipe in upward flow, 3.70 m of horizontal glass pipe, 1.20 m of horizontal steel pipe and 2.38 m of vertical galvanized steel pipe in downward flow. The fact that glass presents a well-known hydrophilic behavior when in a contact with hydrocarbon oil-water systems, may explain why the removal of the oil slug was relatively faster in the second experiment in comparison with the first one, in spite of the large difference in the obstructed lengths.

However, it is possible to interpret the above results with a simple model of the re-start process, which can be useful for practical applications. Since the measured pressure drop in the steel carbon pipe is essentially due to friction, let us take the time-average of the Darcy-Weisbach equation for the oil phase:

$$\overline{\Delta P} = \bar{f}\,\frac{L}{D_o}\,\frac{\rho_o \bar{V}_o^{\,2}}{2} \tag{1}$$

where $\overline{\Delta P}$ is the average pressure difference during the re-start, L is the obstructed pipe length, D_o is the hydraulic diameter of the oil core in the obstructed segment (which is assumed to be nearly equal to the tube diameter D), ρ_o is the oil density, $\bar{V}_o$ is the average velocity of the oil and $\bar{f}$ is the average friction factor. For application of Eq. (1), the following assumptions are adopted:

- H1 The annular flow configuration is kept, where the oil nucleus is dragged by a water ring;
- H2 Laminar flow is valid for the oil phase;
- H3 Turbulent flow is valid for the water phase;
- H4 The instantaneous pressure drop decays exponentially with time;
- H5 The measured instantaneous pressure drop along the steel pipe segment follows the same behavior as the pressure drop in the obstructed length.

Let us make the approximation $\bar{V}_o \cong L/\Delta t$, where Δt is duration of the transient flow (i.e. the re-start time). In view of H2 the friction factor can be expressed as $\bar{f} = 64\mu_o/(\rho_o \bar{V}_o D_o)$, thus Eq. (2) becomes

$$\overline{\Delta P} = \frac{32\mu_o L^2}{D^2 \Delta t} \tag{2}$$

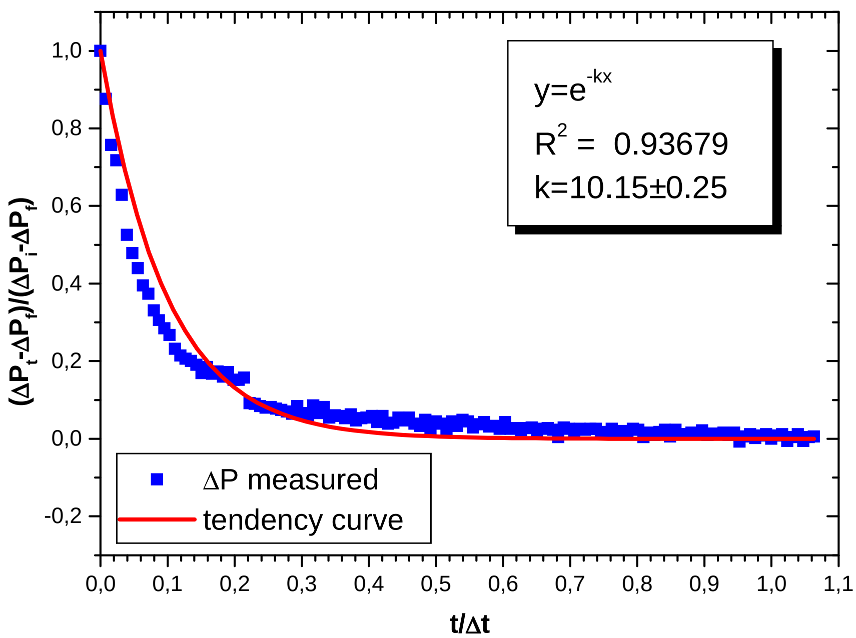

Figure 4. Normalized pressure drop in the steel pipe as a function of time for the re-start test # 1.

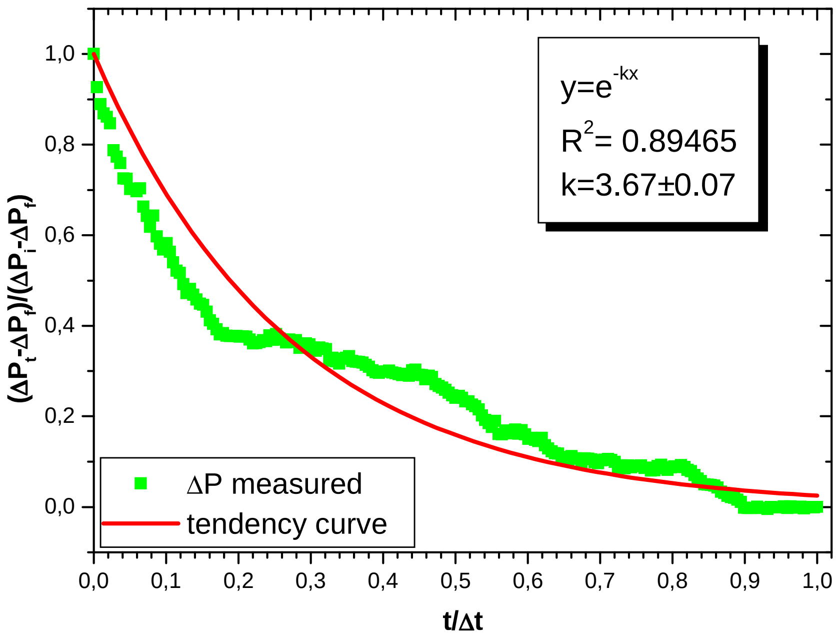

Figure 5. Normalized pressure drop in the steel pipe as a function of time for the re-start test # 2.

Due to H4 and H5 the instantaneous pressure drop in the obstructed length can be expressed as:

$$\Delta P(t) = \Delta P_f + (\Delta P_i - \Delta P_f)e^{-k\,t/\Delta t} \tag{3}$$

where ΔP_f is the steady state single-phase water flow pressure drop, ΔP_i is the initial pressure drop imposed to the obstructed length and k is a constant to be determined.

The plots of Figures 2 and 3 can be put in normalized form using Eq. (3). Figure 4 shows the normalized plot of Figure 2, with the correspondent data fit by an exponential function, which results in k = 10.2. In Figure 5, the normalized plot of Figure 3, the data fit gave a much lower value k = 3.7.

Once that, in the second test, part of the obstructed length was made in glass and part in metal, it was decided to decompose the plot in Figure 5 in two parts: the first one consisting of the monotonic decrease down to $t/\Delta t \cong 0.20$, and the second from this point on. This decomposition is shown in Figures 6 and 7, giving a better data fit for both parts, with k = 5.7 for the first part and k = 3.3 for the second.

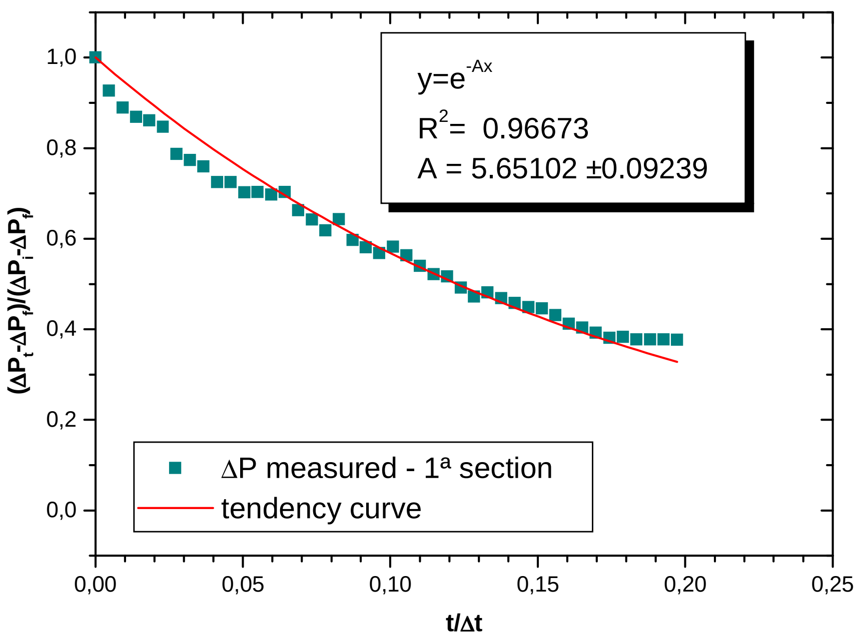

Figure 6. Normalized pressure drop in the steel pipe as a function of time for the re-start test # 2 for $t/\Delta t < 0.20$.

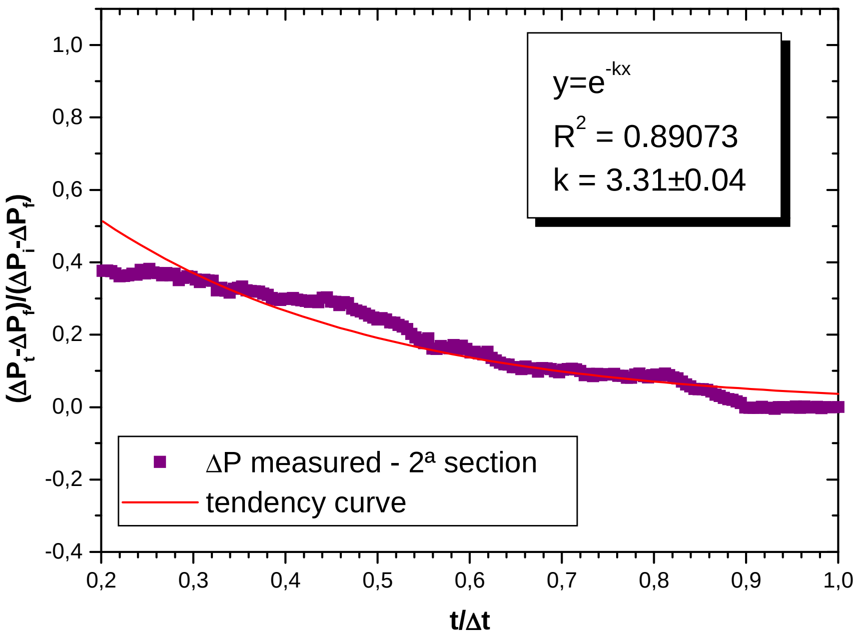

Figure 7. Normalized pressure drop in the steel pipe as a function of time for the re-start test # 2 for $t/\Delta t \geq 0.20$.

It should noted that bigger values of parameter k can be associated with the situations where the oil is easily removed by water flow. From Eq. (3) we can determine $\overline{\Delta P}$ by using Eq. (4):

$$\overline{\Delta P} = \frac{1}{\Delta t}\int_0^{\Delta t} \Delta P(t)dt = \beta\,\Delta P_i + (1-\beta)\Delta P_f \tag{4}$$

where $\beta = \left(1-e^{-k}\right)/k$. For the above determined range 3.3 < k < 10.2, one obtains 0.1 < β < 0.3. The steady state pressure drop ΔP_f is given by:

$$\Delta P_f = f_w \frac{L}{D}\frac{\rho_w J_w^2}{2} \tag{5}$$

where J_w is the water superficial velocity and f_w the friction factor (White, 1994):

$$f_w = \sqrt{-1.8\log\left[\frac{6{,}9}{Re_D} + \left(\frac{e/D}{3.7}\right)^{1.11}\right]} \tag{6}$$

where $Re_D = \rho_w J_w D/\mu_w$ is the number of Reynolds, e is the roughness of the pipe wall, taken as the value for commercial steel pipe (e = 0.046 mm), μ_w is the water viscosity (=9.11x10^{-4} Pa.s at 25ºC).

According to H1, the initially imposed pressure drop ΔP_i *to the obstructed length* can be modeled as for the forced flow of water through an annular gap, resulting in a similar expression, i.e.:

$$\Delta P_i = f_{w,f}\frac{L}{D_{h,f}}\frac{\rho_w J_w^2}{2} \tag{7}$$

where $f_{w,f}$ is the friction of the water flow through the annular gap, $D_{h,f} \cong \varepsilon_{w,i}D/2$ represents the hydraulic diameter of the annular gap and $\varepsilon_{w,i}$ is the initial volume fraction of water ($\varepsilon_{w,i}$ = 0.15 in the present experiments). The friction factor $f_{w,f}$ can be calculated from Eq. (6) using the Reynolds number $Re_D = \rho_w J_w(D/2)/\mu_w$ and relative roughness $e/D_{h,f}$. Substitution of Eqs. (4), (5) and (7) into Eq. (2), gives the following result for the re-start time Δt :

$$\Delta t = \frac{64\,\mu_o\,L}{\rho_w D J_w^2 \left[\dfrac{2\beta\, f_{w,f}}{\varepsilon_{w,i}} + (1-\beta) f_w \right]} \tag{8}$$

The value of parameter β can be estimated from the tests, since the re-start time was measured. From Table 1 the representative average value of this parameter is $\beta \cong 0.1$ in reasonable agreement with previously determined range $0.1 < \beta < 0.3$.

Table 1. Data from tests #1 and #2 to estimate β

Test #	**1**	**2**
μ_o (Pa.s)	4.127	4.127
ρ_w (kg/m^3)	999.2	999.2
J_w (m/s)	0.59	0.59
f_w	0.03	0.03
$f_{w,f}$	0.056	0.056
L (m)	3.58	9.09
ΔP_i (Pa)	4730	12011
Δt (s)	1260	2180
$\boldsymbol{\beta}$	**0.07**	**0.13**

Thus, the proposed equation for the estimation of the re-start time is:

$$\Delta t = \frac{64\,\mu_o\,L}{\rho_w D J_w^2 \left(\dfrac{0.2\, f_{w,f}}{\varepsilon_{w,i}} + 0.9 f_w \right)} \tag{9}$$

This simple result involves all the important physical variables of the re-starting process. Clearly, new and careful experiments should be performed to confirm the validity of Eq. (9).

4. Conclusions

In this paper, re-start experiments of an initial heavy oil-water core flow pattern are described. For this purpose, a laboratory-scale line operating in the core flow mode was stopped during 61 hours them re-started with water only. The results were analyzed through a physical model that incorporates the effects of relevant properties such as oil viscosity, length of the obstructed segment, pipe diameter, water volume fraction of the initial flow, etc. A single constant required in this model was estimated from the experiments.

No large pressure picks were observed that could damage the flow circuit. This is an indication that re-starting core flow with water only, prior to re-starting the oil pump, is more appropriate. In fact, water tends to surround the oil quickly, removing it safely from the obstructed region. Another important conclusion is that re-start seems to be affected by the wettability of the pipe wall: hydrophilic pipes probably have lower re-start times in comparison with oleophilic ones. Thus, more experiments with specific materials are required to confirm this effect.

5. References

Angeli, P & Hewitt, G. F. Flow structure in horizontal oil-water flow. *International Journal Multiphase flow*, 1998, vol. 24, pp.1183-1203.

Arney, M. S., Bai, R., Guevara, E., Joseph D.D. & Liu, K. Friction Factor and Holdup Studies for Lubrificated Pipeling-I: Experiments and Correlations. *International Journal Multiphase flow*, 1993, vol. 19, nº 6, pp.1061-1076

Bannwart, Antonio C. Modeling aspects of oil-water core-annular flows. *Journal of Petroleum Science and Engineering*, 2001, vol. 32, pp. 127-143.

Bannwart, A.C. & Vanegas Prada, J.W. 1999 Production of heavy oil via core flow, 6th Latin American and Caribbean Petroleum Engineering Conference - LACPEC'99, paper SPE 53688, Caracas, Venezuela, 8 p.

Mezzomo, Roberto F. Pravap. *Technical Paper publicated in Petro&Quimica*, São Paulo, nº 221, setembro/outubro 2000, pp.160 –163.

Núñez, Gustavo A. Joseph, D. D. Drive to produce heavy crude prompts variety of transportation methods. *Oil & Gas Journal International Petroleum News and Technology*. Oct. 26, 1998, pp. 59-68.

Ooms, G. The Hydrodynamic Stability of Core-Annular Flow of Two Ideal Liquids. Applied Science Research, 1972, Vol. 26, p. 147-158.
Oliemans, R. V. A., Ooms, G., Wu, H. L. & Duijvestijn, A. 1987 Core-annular oil/water flow: the turbulent-lubricating-film model and measurements in a 5 cm pipe loop, *Int. J. Multiphase Flow*, v. 13, p. 23-31.
Ramos, Antonio C. S. Asfaltenos em Petróleos Brasileiros: Agregação em solventes aromáticos, desenvolvimento de aditivos e estabilização de emulsões. *Dissertation, University of Campinas, Brasil,* (UNICAMP). 2001.
Ribeiro, Geraldo A. S. M. Topics in the Transport and Rheology of Heavy Crude Oils. *Ph.D. dissertation,* University of Minnesota, Minneapolis, Mn, 1994.
Santos, Ronaldo G. Molhabilidade de Superfícies de Oleodutos no Transporte de óleos Pesados em sistemas de Fluxo Lubrificado Óleo-Água. D*issertation, University of Campinas, Brasil, (*UNICAMP). 2003.
Vanegas, José W. Estudo Experimental do Escoamento Anular óleo-água (Core-Flow) na Elevação de óleos Ultraviscosos. D*issertation, University of Campinas, Brasil, (*UNICAMP). 1999.
Vara, Rosa M. O. Hidrodinâmica do escoamento bifásico óleo pesado - água em um tubo horizontal. D*issertation, University of Campinas, Brasil, (*UNICAMP). 2001.
White, Frank M. Fluid Mechanics. McGraw-Hill, Inc. Hightstown, NJ. 3rd ed. 1994.

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