

ON THE ISSUE OF THE RESTART TIME OF A CORE ANNULAR FLOW OIL PIPELINE AFTER SHUT-DOWN OPERATIONS

By
Aniefiok Livinus*

Abstract

There is a growing number of proposed models for the estimation of the time needed to restart a core annular flow line after shutting down, pertaining the improvement of core annular flow (CAF) technology for transportation of high viscous oil. Existing restart time models tend to predict that the flow line needs to be completely clean. However, this is practically not feasible. Firstly, this work revisits the results of the flow pattern trends and pressure drop evolutions during the restart of a core annular flow experiments. Based on the analyses of the transient pressure drop profiles, deduction of a 'realistic and economical' re-start time, expressed as a function of the pressure drop, has been made. This approach can be helpful in control engineering design of an efficient and cost-effective re-start process of a core annular flow (CAF) line.

Keywords: Water-assisted flow; viscous oil flow in pipes; realistic restart time; lubricating flow.

1.0 Introduction

Though there is a strong drive to transit from fossil fuels to renewable fuels, however currently speaking, the world will continue to rely on fossil fuels and as such the technological designs of facilities for the production and transportation of fossil fuels from both conventional and non-conventional oil need to keep improving. The world's oil resources are majorly heavy and extra heavy viscous hydrocarbons; they make about 70% of the world's total oil resources of 9 to 13 trillion barrels as reported by Alboudwarej et al¹ as shown in Figure 1. This is more than twice the amount of world reserves of conventional oil.

*Department of Chemical and Petroleum Engineering, University of Uyo, P.M.B 1017, Uyo, Akwa Ibom State. E-mail: aniefioklivinus@uniuyo.edu.ng Telephone: +234(0)9013534429.

This work revisits work revisits the results of the flow pattern trends and pressure drop evolutions during the restart of a core annular flow experiments conducted by Livinus, A., Yeung, H. and Lao, L. (2017) "Restart time correlation for core annular flow in pipeline lubrication of high-viscous oil." J Petrol Explor Prod Technol 7, 293–302 (2017). <https://doi.org/10.1007/s13202-016-0241-y>

¹ Alboudwarej, H., Felix, J., Taylor, S., Badry, R., Bremner, C., Brough, B., Skeates, C., Baker, A., Palmer, D., Pattison, K., Beshry, M., Krawchuk, P., Brown, G., Calvo, R., Triana, J. A. C., Hathcock, R., Koerner, K., Hughes, T., Kundu, D., De Cárdenas, J.L. and West, C. (2006) 'Highlighting heavy oil', Oilfield Review, 18(2), pp. 34–53.

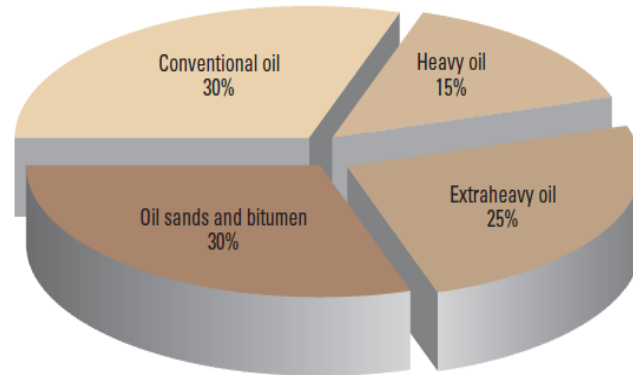


Figure 1: Total World Oil Reserves Alboudwarej et al¹

Pipeline transportation has long been considered as the most economical and feasible method for moving large amount of crude oil from wells to gathering facilities and refineries. However, due to the high pressure drop associated with the transportation of heavy crude oil by conventional pipelines because of their viscous nature, additional treatments are required. Research articles by Saniere et al², Gosh et al³, Adewusi and Ogunsola⁴, Ngan et al⁵ show that various methods of reducing the pressure drop have been studied; these include thermal method, addition of diluent, chemical and water assist. Of these, water assist flow (WAF), or core annular flow (CAF) as it is commonly called, seemed to be the most environmentally friendly approach.

The operation of 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 (Peysson et al⁶).

Following the pioneer studies carried out by Russel and Charles⁷ and Charles et al⁸, the advantages of core annular flow for the transport of viscous oils have been fully re-confirmed (Angeli and

² Saniere A., Henaut I., and Argillier J.F., (2004) Pipeline transportation of heavy oils, a strategic, economic and technological challenge, *Oil & Gas Science*, 59(5).

³ Ghosh, S., Mandal, T.K., Das, G., Das, P.K., (2008). Review of oil water core annular flow. *Renewable and Sustainable Energy Reviews* 13, 1957-1965.

⁴ Adewusi, V.A., Ogunsola, A.O. (1993) Optimal formulation of caustic systems for emulsion transportation and dehydration of heavy oil. *Chemical Engineering Research & Design* 71, 62-68, 1993.

⁵ Ngan, K.H., Linnenberg, S., Al-Wahibi, T., Angeli, P., (2007) Effect of drag reducing polymers on oil-water flow. *6th International Conference on Multiphase Science and Technology* 2, 427-476.

⁶ Peysson, Y., Bensakhira, A., and Antonini, G. (2005) Pipeline lubrication of heavy oil: Experimental investigation of flow and restart problems. SPE 97764 first presented at 2005 SPE Internal Thermal Operations and Heavy Oil Symposium, Calgary, 1-3 November, revised publication, 2007.

⁷ Russell, T.W.F. and Charles, M.E. (1959) 'The effect of the less viscous liquid in the laminar flow of two immiscible liquids', *The Canadian Journal of Chemical Engineering*, 37(1), pp. 18-24. Available at: 10.1002/cjce.5450370105 (Accessed: 26 June 2015).

⁸ Charles, M.E., Govier, G.W. and Hodgson, G.W. (1961) 'The horizontal pipeline flow of equal density oil-water mixtures', *The Canadian Journal of Chemical Engineering*, 39(1), pp. 27-36. Available at: 10.1002/cjce.5450390106 (Accessed: 27 June 2015).

Hewitt⁹, Abduvayt et al¹⁰, Vuong et al¹¹, Al-awadi¹² and among others). The pressure drop reduction factor has been pointed out (Bensakhira et al¹³ (2004), Peysson et al⁶). Stability of CAF has also been studied showing the interface between the annulus and the core (see, Joseph and Rennardy¹⁴). However, with the vast studies on CAF, only very little attention has been paid pertaining issues of shut-down and re-start of a CAF line. In pipeline system operation, maintaining a steady and continuous flow without any interruption, such as shut-down of a pipeline, is desirable. However, due to operational and emergency reasons shut-down may occur. When flow is impeded in a CAF line perhaps because of blockage or pump failure, the flow pattern can no longer be maintained, the water settles down on the bottom of the pipe while the oil floats to the upper part due to difference in density leading to stratified flow regime. The pressure drop in the stratified configuration is high compared to the CAF. Thus, the shut-down and restart mechanisms have to be considered. Operational question such as; ‘what time is needed to restart the core annular flow’ needs to be addressed.

In 1988, Zangustin et al¹⁵, patented a process for the systematic restarting of a viscous oil core annular flow after a long standstill period. The process involves gradually increasing the flow of the low viscosity fluid until a desired steady state condition is reached and then initiating a flow of a viscous oil. Equation for estimating a suitable incremental rate as given below was then presented:

$$Q = (Q_{max}T_o)T \quad 1$$

where; Q is low viscosity fluid mass flow rate increase; Q_{max} is maximum low viscosity fluid mass flow rate at the steady state condition; T_o is time corresponding to the establishment of core annular flow conditions; and T is elapsed time from restart.

T_o can be estimated from the equation below;

$$T_o = kT_s^{1/2} \quad 2$$

where; T_s = time of standstill in hours, and k = a constant depending upon the characteristics of the oil and the treatment of the pipeline wall. For the case provided, which involves a pipeline with 8-inches diameter, 1-km length, after a standstill period of 121 hours. $k = 1/65$. Arney et al¹⁶ conducted a partially restart experiments to compare fouling and ease of cleaning of cemented-

⁹ Angeli, P. and Hewitt, G. F. (2000) ‘Flow structure in horizontal oil-water flow’, *International Journal of Multiphase Flow*, 26(7), pp. 1117–1140. doi: 10.1016/S0301-9322(99)00081-6.

¹⁰ Abduvayt, P., Manabe, R., Watanabe, T. and Arihara, N. (2006) ‘Analysis of oil/water-flow tests in horizontal, hilly terrain, and vertical pipes’, *SPE Production and Operations*, 1(1), pp. 123–133.

¹¹ Vuong, D. H., Zhang, H. Q., Sarica, C. and Li, M. (2009) ‘Experimental study on high viscosity oil/water flow in horizontal and vertical pipes’, in *2009 SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 4-7 October 2009*, pp. 2454–2463.

¹² Al-awadi, H. (2011) *Multiphase Characteristics of High Viscosity Oil*. PhD. Cranfield University, UK.

¹³ Bensakhira, A., Peysson, Y. and Antonini, G. (2005) Making Light of Heavy Oil. Institut Français du Pétrole, September, 2005.

¹⁴ Joseph D.D., Rennardy Y.Y. (1993) *Fundamentals of Two-fluid Dynamics*, Springer-Verlag, New York.

¹⁵ Zagustin, K., Guevara, E., Nunez, G., (1988) Process for restarting core flow with very viscous oils after a long standstill period” US Patent 4745937.

¹⁶ Arney, M.S., Ribeiro, G.S., Guevara, E., Bai, R., Joseph, D.D., (1996) Cement-lined pipes for water lubricated transport of heavy oil. *International Journal of Multiphase Flow* 22, 207-221.

lined, 0.0245 m internal diameter and 6.3 m length, and carbon steel, 0.0265 m internal diameter and 6.27 m long pipelines. They found out that the cement-lined pipe was completely cleaned (even in the critical region close to the injection nozzle) and the steel pipe was heavily fouled. Barbosa et al¹⁷ presented experimental results of stop-and-go experiments where an initially stable horizontal core flow with oil viscosity of 4127 cP was suddenly stopped for 61 hours then restarted with water only flowing at 0.59 m/s superficial velocity. A physical model as presented in Equation 3 for predicting the re-start time was then proposed based on some assumptions imposed for applying the time-average of the Darcy-Weisbach equation for the oil phase.

$$\Delta t = \frac{64\mu_o L}{\rho_w D J_w^2 \left[\frac{2\beta f_{w,f}}{\varepsilon_{w,i}} + (1 - \beta) f_w \right]} \quad 3$$

where, the value of parameter β is estimated from the experimental results, μ_o is oil viscosity, L is the obstructed pipe length, ρ_w is water density, $f_{w,f}$ is friction factor of water, f_w is friction factor for pipe flow, $\varepsilon_{w,i}$ is the initial volume fraction of water, D is internal pipe diameter, and J_w is the water superficial velocity.

Peysson et al⁶ experimentally investigated the CAF, and the stop and restart of viscous heavy oil with co-injection of water or brine as the lubricating fluid. Their results re-confirm the effectiveness of the lubricating process for heavy-oil transport. They also measured the restart pressure with different salts in the water phase, and show that in some cases, the restart pressure can be limited. Also, they also analysed the evolution of the flow configuration just after the flow stop when 10-20-30-60 seconds short stops were imposed to an initial steady state core annular flow.

Poesio and Strazza¹⁸ presented some experimental results on the start-up of a core annular flow from a stratified condition in a horizontal and nearly horizontal pipe. They look at the start up procedure with particular emphasis on the pressure drops evolution: the maximum pressure drop during the restart is between two to five times the pressure drops during normal core annular flow operations. They finally fitted the shape of the pressure drop evolution against time with a double exponent function such as;

$$\Delta p(t) = \Delta p_1 e^{-\beta_1 t} + \Delta p_2 e^{-\beta_2 t} \quad 4$$

where; β_1 and β_2 are fitting parameters, Δp is pressure drop, and $\Delta p(t)$ is the pressure drop evolution with time.

¹⁷ Barbosa A., Bannwart A.C., and Ribeiro G.S., (2005) Pressure drop and restart time during stop-and-go experiments in core annular flow. 18th International Congress of Mechanical Engineering November 6-11 Ouro Preto.

¹⁸ Poesio, P. and Strazza, D., (2007) Experiments on start-up of an oil-water core annular flow through a horizontal or nearly horizontal pipe In 13th International Conference on Multiphase Production Technology BHR Group 2007, Edinburgh (UK).

Twerda et al¹⁹ presented the simulation results of the detailed experiments of heavy oil performed on their test rig in Porsgrunn using two tools: OLGA® and ANSYS® FLUENT CFD codes. Their objective was basically to identify the performance of each tool for the use in a cold start-up of offshore heavy oil production pipeline; results show that both codes are very well capable of predicting the cool down of the heavy oil.

Domenico and Poesio²⁰, presented results, similar to their 2007 study, of an experimental campaign to study the pressure drop during the restart of a core-annular flow from a stratified configuration. Their experimental results were finally compared with a two-fluid model available in literature- Bannwart²¹ model, and proposed a modified two-fluid model for predicting restart time.

Yang Z. et al²², in their study to understand the physical processes of shut-in and restart of viscous multiphase flowline, conducted experiments on shut-in and restart processes in the multiphase Flow rig at Statoil's research Centre in Porsgrunn. They assessed the performance of OLGA® and ANSYS® FLUENT CFD against the experimental data and theory, and found out that OLGA® predict well the shut-in process, but over-predicts the restart time. The restart is controlled by the oil viscosity and the total oil column length.

Livinus et al²³ formulated a new correlation for the prediction of the restart time of a shutdown core annular flow line. It was based on the result of a laboratory experiment on shutdown and restart of a high viscous oil in a 5.5 m long PVC horizontal pipe, having an internal diameter of 26 mm. Inasmuch as the results predicted by the correlation were high, they were still reasonable, and were in good agreement with the experimental data. They also stated that the correlation is better applied to a cold-water restart and to heavy oil with API gravity greater than 10°. The correlation is shown below:

$$\Delta t = \frac{1344h_oL}{U_{sw}} \left\{ \left[0.008 + \left(\frac{\Delta P(t^*) - \Delta P_w}{\Delta P_i - \Delta P_w} \right) \right] \right\} \quad 5$$

$$\Delta P(t^*) = \Delta P_w + 0.221[\Delta P_i - \Delta P_w] \quad 6$$

$$t^* = \frac{12.51h_oL}{U_{sw}} \left[1 - \frac{\Delta P_w + 0.221(\Delta P_i - \Delta P_w)}{\Delta P_i - \Delta P_w} \right] \quad 7$$

where Δt is the restart time, s; h_o is the Oil holdup; L is the length of blocked pipeline, m; U_{sw} is the superficial velocity of water; $\Delta P(t^*)$ is the pressure drop evolution at time, t^* , when

¹⁹ Twerda, A., Yang, Z., Nennie, E. and Velthuis, H. (2012) 'Experimental and numerical assessment of cold restart process of viscous oil pipeline', WOrld Heavy Oil Congress. Aberdeen, Scotland, pp. 1–5.

²⁰ Domenico, S., and Poesio, P., (2012) Experimental study on the restart of core-annular flow" Chemical Engineering Research and Design Journal 90, 1711-1718.

²¹ Bannwart, A.C., Barbosa, A. and Ribeiro, G.S. (2007) 'A model for interpretation of a re-start experiment of viscous oil-water annular flow', Proceedings of the IASTED International Conference on Modelling and Simulation., pp. 215–220.

²² Yang, Z., Velthuis, J., Veltin, J. and Twerda, A. (2013) 'Cold Restart of Viscous Multiphase Flowline by Hot Water Flushing', 16th International Conference on Multiphase Production Technology. Cannes, France: BHR Group.

²³ Livinus, A., Yeung, H. and Lao, L. (2017) "Restart time correlation for core annular flow in pipeline lubrication of high-viscous oil." J Petrol Explor Prod Technol 7, 293–302 (2017). <https://doi.org/10.1007/s13202-016-0241-y>

pressure drop evolution drop trend deviates from part a to part b, Pa; ΔP_w is the pressure drop of a single-phase water flow, Pa; ΔP_i is the initial pressure drop at inception of restart process, Pa; t^* is the time when pressure drop evolution trend deviates from part a to part b, s

Only a few experimental data on the pressure drop evolution with time concerning the restart of CAF are available in the open literature; Barbosa et al¹⁷, Poesio and Strazza¹⁸, Bannwart et al²¹ and Strazza and Poesio²⁰. The interest therefore in the restarting of a core annular flow from a stratified flow pattern at rest, emanating after shut-down operations for maintenance or due to pump failure, will continue to get more attention to improve CAF technology. Though these studies highlighted important information on the shut-down and restart of core annular flow, however we believe that CAF analyses in this present study can also contribute to improving the knowledge of practical restart issue of a core annular flow line. Hence, the experimental results of the pressure drop trends as a function of time to find when the pipe surfaces is nearly without oil layer, or at least when the pressure drops are low enough to re-start the oil core annular flow line by flowing water only, is presented. The results are used to highlight a practical restart time that can be helpful in control engineering design of an efficient and cost-effective re-start process of a CAF line.

2.0 Revisit of the experimental work of Livinus et al^{Error! Bookmark not defined.}

Shut-down and restart experiments conducted by Livinus et al^{Error! Bookmark not defined.} involved a 5.5-m long PVC pipe with 26-mm internal diameter. Summary of the experimental set-up and conditions are provided in Appendix A. Data measurements were made for the core annular flow mode, immediately after shut-down and prior to re-start for 30 seconds at sampling rate of 250 Hz. While during the cleaning process, data measurements are collected at sampling rate of 5 Hz for over 1200 seconds. Observations of flow patterns prior and during the restart process were also recorded with a digital HD video camera recorder (SONY HANDYCAM HDR-CX550VE). However, no report was made on the analyses of the observed transient behaviour of the flow patterns. Livinus et al^{Error! Bookmark not defined.} only used the experimental results to formulate a restart time correlation. Unfortunately, their correlation tends to predict that the flow line needs to be completely clean. And as such, the correlation becomes unrealistic and uneconomical for the control engineering design of an efficient and cost-effective re-start process of a core annular flow (CAF) line.

2.1 The experimental results

Owing to the experimental time involved in performing shut-down and restart experiments, just two water cleaning superficial velocities, 0.2 m/s and 0.6 m/s were successfully carried out. The video recordings of the major stages of the cleaning process were undertaken and the pressure drop evolutions were measured using pressure transducers.

2.1.1 Flow Pattern Trends during Clean-up

The images presented in Figure 2(a, b, and c) shows the flow pattern trends during the cleaning operation. Prior to the start of flowing the water into the line, the two fluids are stratified with interface (Figure 2(a)). Depending on the standstill periods, that is the time representing downtime or rest time, the interface can be extremely distinct. As water starts flowing into the pipe when the water pump is turned on, the oil is sheared from the interface to the upper section of the pipe. For water cleaning velocity of 0.2 m/s, during the shearing, oil bubbles are formed and then transported

by the water (Figure b). This continues until a thin layer of oil at the top section of the pipe is reached (Figure c). Then, the removal of the thin layer of oil occurs slowly and lasted for about 70 to 80% of the entire cleaning period until the pressure drop is close to single water phase flow. In the case of water cleaning velocity of 0.6 m/s, there is no thin layer of oil at the top of the pipe rather a spiral thin layer of oil is observed moving gradually along the wall of the pipe. The thickness of this thin layer of oil depends on many parameters: the cleaning water velocity, surface tension, pipe properties, viscosity of the oil, adhesive properties.

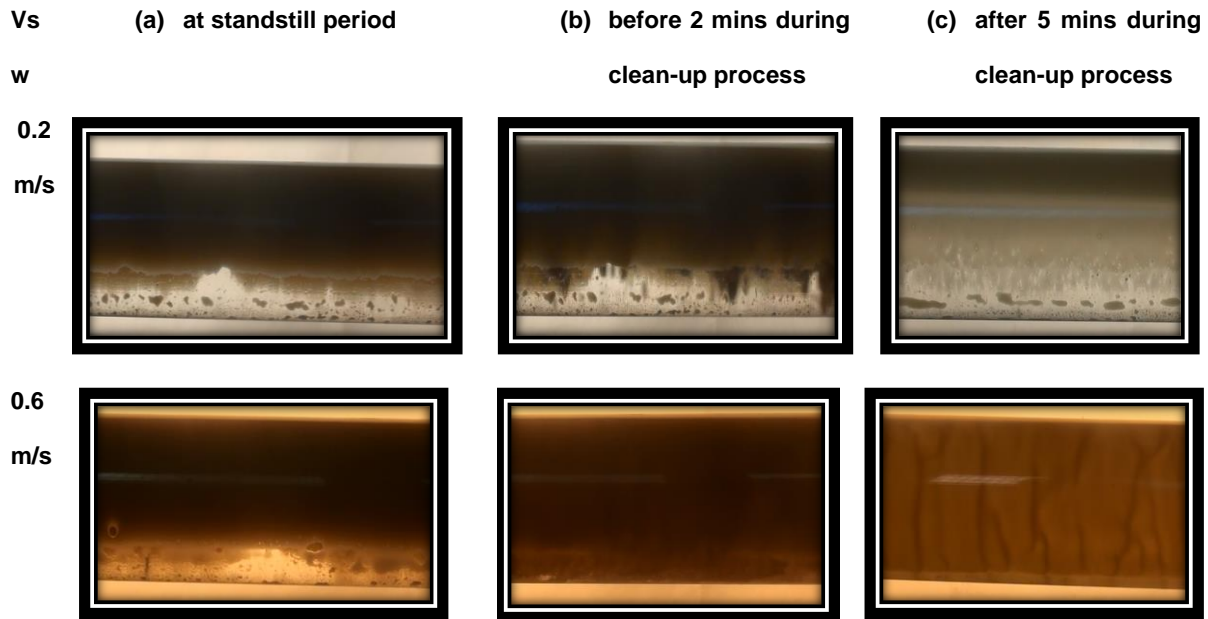


Figure 2: Stages of the Cleaning process.

2.1.2 Pressure drop Profiles

The pressure drop evolutions with time were obtained from the measurement of two pressure transducers positioned 2.21-m apart along the test section of the pipe. Once the cleaning water was introduced into the blocked line through the water inlet, there was increase in pressure drop. As the differential pressure between the inlet and outlet of the tubing started to drop because of the removal of the oil from the outlet of the pipe, the initial high pressure drop began to fall. Figures 3 through 6 show some of the recorded pressure drop profiles. As can be seen, the drop starts drastically and decreases to a value near the steady state pressure drop of single-phase water flow; the PDF plots of Figures 7 through 10 clearly depict the amount of data points for various cases investigated.

The pipe was not completely clean, very thin oil film still remains at the top section of the pipe. This is perhaps the superficial water velocity used was insufficient to provide the momentum needed to shear the oil from that section of the pipe. The transient behaviour of the pressure drop seems to have two major parts: the first, which happens rapidly is due to the bulk shearing of the oil by the water. The second part which seems to be constant account for the pressure drop during the gradual removal of the thin layer of oil at the top section of the pipe, because the shear velocity

has become smaller. In the case of the 0.2 m/s cleaning water superficial velocity, the pressure drop during this period shows gradual fluctuations of about 1 kPa. There was no fluctuation observed when cleaning water velocity of 0.62 m/s was used.

The standstill period does not appear to have a great influence on the pressure drop evolution. However, investigation of the pressure signals prior to restart shows that standstill period influences the rise of the pressure in the line.

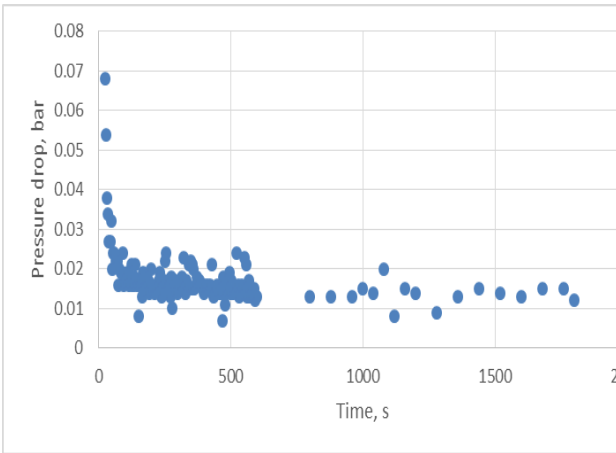


Figure 3: Pressure drop profile during clean-up with $U_{sw} = 0.2$ m/s for standstill period of 1 hour

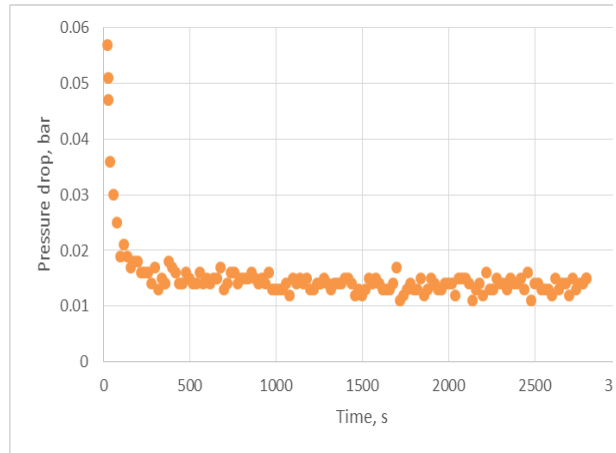


Figure 4: Pressure drop profile during clean-up with $U_{sw} = 0.2$ m/s for standstill period of 3 hours

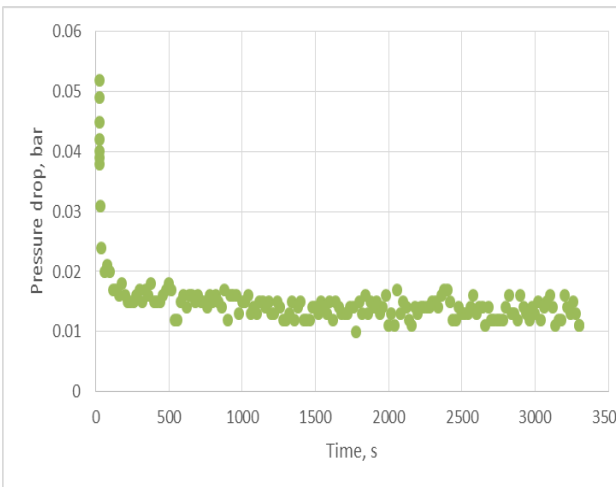


Figure 5: Pressure drop profile during clean-up with $U_{sw} = 0.2$ m/s for standstill period of 20 hours

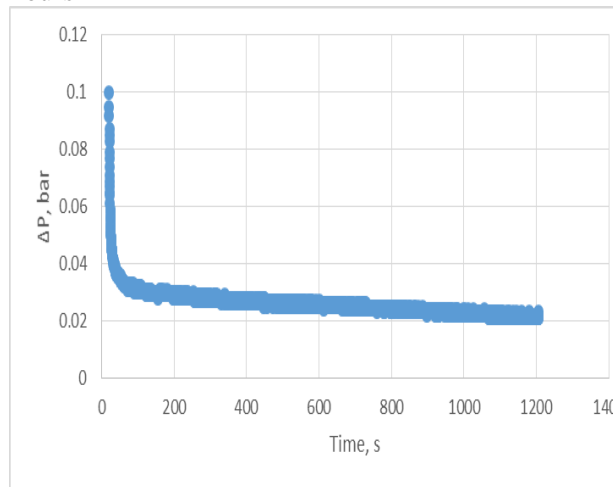


Figure 6: Pressure drop profile during clean-up with $U_{sw} = 0.62$ m/s for standstill period of 1 hour

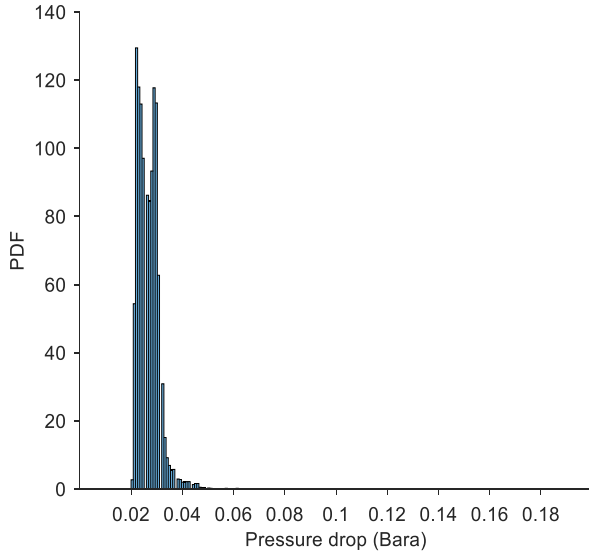


Figure 7: PDF plots for pressure drop profile during clean-up with $U_{sw} = 0.2$ m/s for standstill period of 1 hour

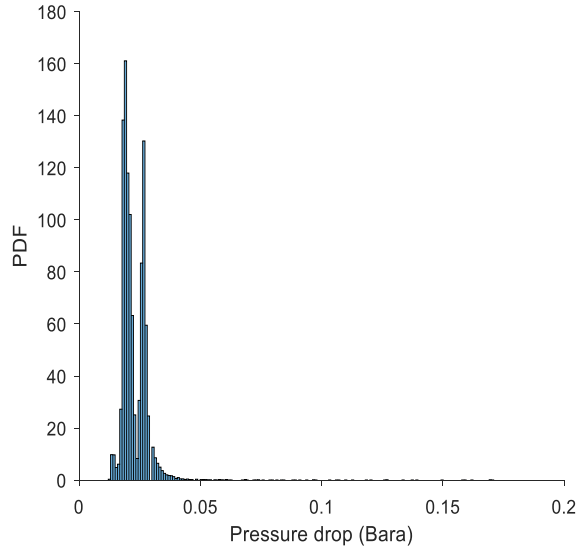


Figure 8: PDF plots for pressure drop profile during clean-up with $U_{sw} = 0.2$ m/s for standstill period of 3 hours

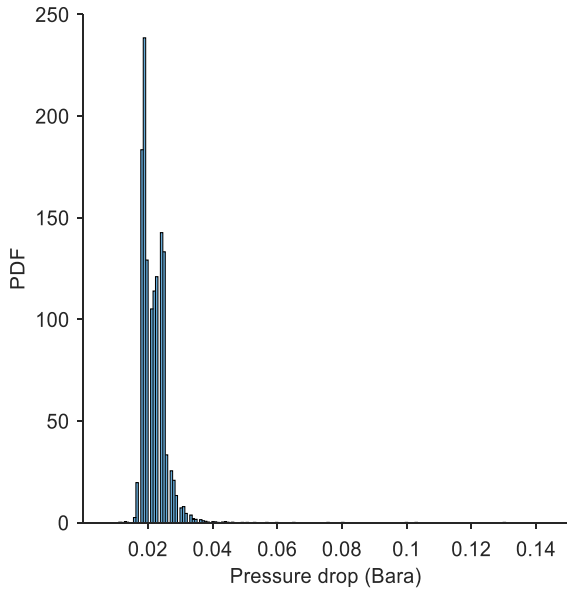


Figure 9: PDF plots for pressure drop profile during clean-up with $U_{sw} = 0.2$ m/s for standstill period of 20 hours

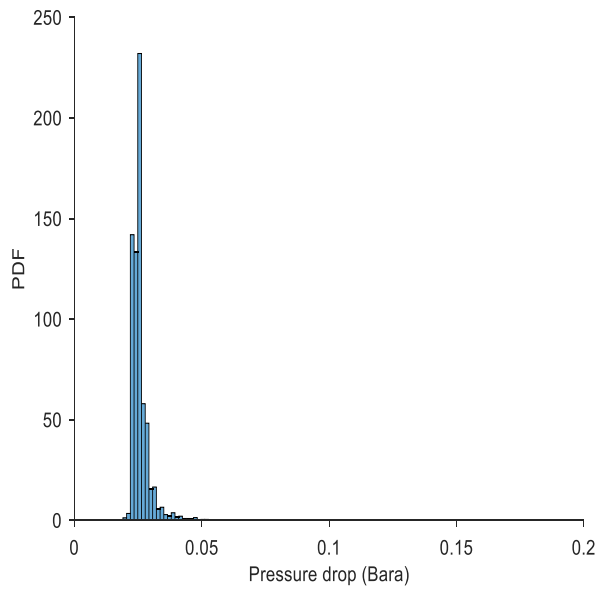


Figure 10: PDF plots for pressure drop profile during clean-up with $U_{sw} = 0.62$ m/s for standstill period of 1 hour

3.0 Expression of re-start time as a function of pressure drop due to cleaning fluid

From practical point of view, it is really difficult to completely clean the pipe. As a result, re-start time as defined and determined by previous researchers becomes unrealistic. Recall that the transient pressure drop profile has a unique trend as seen in Figures 3 through 6: the drop starts drastically and decreases to a value near the steady state pressure drop of single-phase water

flow; the PDF plots of Figures 7 through 10 clearly depict the amount of data points for various cases investigated.

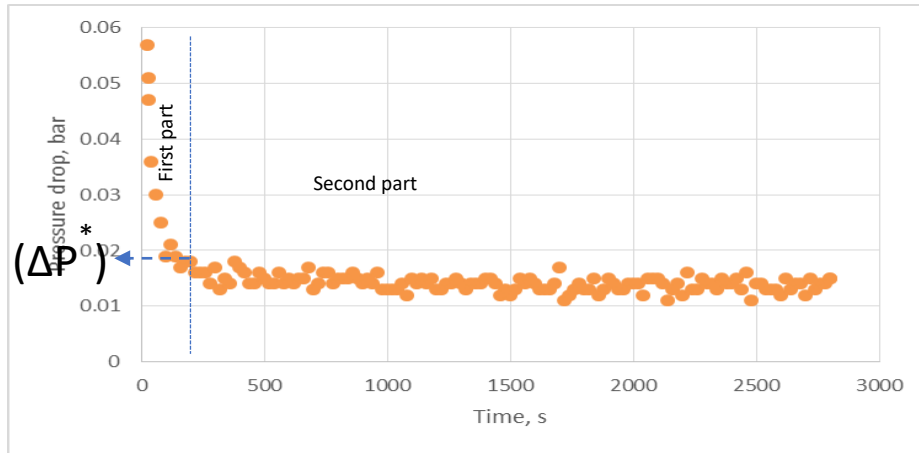


Figure 11: Typical Pressure drop profile during clean-up with emphasis on the pressure drop (Δp^*) values at the end point of the first part.

To deduce a realistic and economical re-start time, considerations of the pressure drop (Δp^*) values at the end points of the first part of the pressure drop evolutions obtained from the various test matrices investigated are made (as shown in Figure 11) and then a fraction (which we call the ‘re-start time factor (Δt factor’) for each of the test matrices is then determined using Equation 8.

$$\Delta P_{index} = \frac{\Delta p^* - \Delta p_w}{\Delta p_i - \Delta p_w} \quad 8$$

The average value of the ‘pressure drop evolution index of the first part of the profile (Δt factor)’ obtained from the thirteen experimental cases is 0.192 and with a standard deviation of 0.0437. Thus, the ‘realistic and economical’ re-start time expressed as a function of the pressure drop of a single phase cleaning fluid (in this study, it is water) is given as;

$$\Delta t = t@(1 + \Delta t factor)\Delta p_w \quad 9$$

$$\Delta t = t@(1.192)\Delta p_w \quad 10$$

The ‘realistic and economical’ re-start time is therefore the time it takes for the pressure drop profile to reach 1.192 times of the pressure drop for a single phase cleaning fluid during the restart process. This can be helpful in control engineering design of an efficient and cost-effective re-start process of a CAF line.

4.0 Conclusion

Laboratory results reported by Livinus et al¹ on the flow pattern trends and pressure drop evolutions during the restart of a core annular flow after shut-down in a 5.5-m long PVC horizontal

pipe with internal diameter of 26-mm have been presented. The cleaning water superficial velocity has significant impact on the transient multiphase flow behavior during the restart process.

Based on the analyses of the transient pressure drop profiles, deduction of a realistic and economical re-start time, expressed as a function of the pressure drop of a single-phase cleaning water, has been made. The ‘realistic and economical’ re-start time is defined as the time it takes for the pressure drop profile to reach 1.192 times of the pressure drop for a single-phase cleaning fluid during the restart process. This can be helpful in control engineering design of an efficient and cost-effective re-start process of a CAF line.

APPENDIX A

Table A-1: Experimental conditions for the shut-down and re-start experiments

Parameters/Conditions	Values
Water density, ρ_w	998 kg/m ³
Oil density, ρ_o	903 – 915 kg/m ³
Water viscosity, μ_w	0.001 kg·m ⁻¹ ·s ⁻¹
Oil viscosity, μ_o	1.9 – 3.2 kg·m ⁻¹ ·s ⁻¹
Oil holdup	0.62 and 0.66
Water cleaning superficial velocity	0.2 and 0.6 m/s
Standstill periods	1, 3, 20 Hours
Pipe angle	0°
Oil-water surface tension	0.02 N/m

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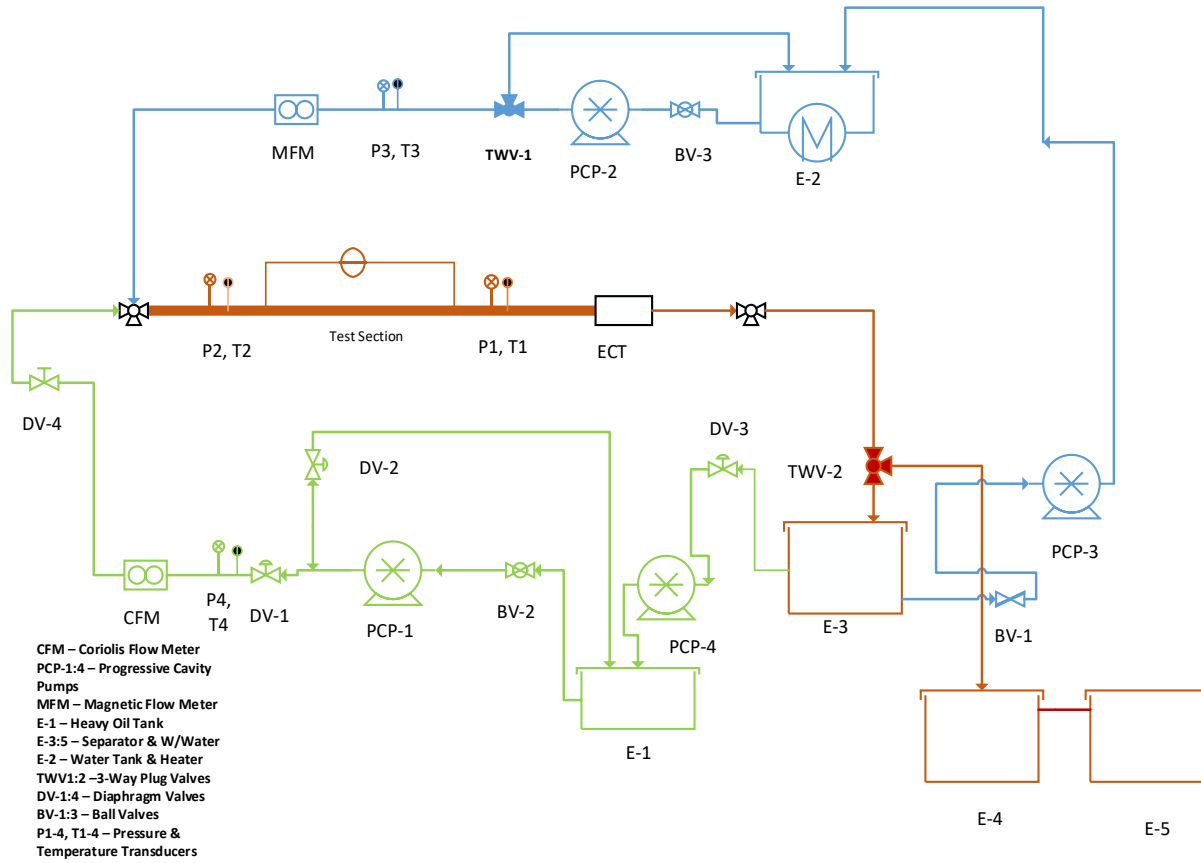


Figure 1-A: Schematic of the Experimental section of the 1-inch Test Rig