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Experimental Study on the Effects of Water-in-Oil Emulsions to the Pressure Drop in Pipeline Flow

S. S. Dol, M. S. Chan, S. F. Wong, J. S. Lim

Abstract**—**Emulsion formation is unavoidable and can be detrimental to an oil field production. The presence of stable emulsions also reduces the quality of crude oil and causes more problems in the downstream refinery operations, such as corrosion and pipeline pressure drop. Hence, it is important to know the effects of emulsions in the pipeline. Light crude oil was used for the continuous phase in the W/O emulsions where the emulsions pass through a flow loop to test the pressure drop across the pipeline. The results obtained shows that pressure drop increases as water cut is increased until it peaks at the phase inversion of the W/O emulsion between 30% to 40% water cut. Emulsions produced by gradual constrictions show a lower stability as compared to sudden constrictions. Lower stability of emulsions in gradual constriction has the higher influence of pressure drop compared to a sudden sharp decrease in diameter in sudden constriction. Generally, sudden constriction experiences pressure drop of 0.013% to 0.067% higher than gradual constriction of the same ratio. Lower constriction ratio cases cause larger pressure drop ranging from 0.061% to 0.241%. Considering the higher profitability in lower emulsion stability and lower pressure drop at the developed flow region of different constrictions, an optimum design of constriction is found to be gradual constriction with a ratio of 0.5.

Keywords**—**Constriction, pressure drop, turbulence, water cut, water-in-oil emulsions.

I. INTRODUCTION

WATER production is detrimental to oil production. As the majority of the reservoirs are supported by huge aquifer and one of the most conventional methods of enhanced oil recovery is by water injection, many companies have paid a fortune to reduce the water production to increase profits. Normally, in a situation when water cut is increasing, companies will shut down the water zone because the upsurge of water production results in oil production reduction. Emulsions are easily formed due to the high-speed shearing of pumps and other mechanical devices along the transportation line [1], which mostly occur in the crude processing unit as shown in Fig. 1.

In recent years, concerns about emulsion in pipeline flow have become central to the formation of emulsions problem faced by many companies such as Esso Production Malaysian Incorporated (EPMI) and PETRONAS Carigali. Emulsions in the pipeline will result in lost in both chemical used and production. EPMI contract areas in East Cost of Malaysia and PETRONAS oil fields of East Malaysia are having severe emulsion issues. The formation of water-in-oil emulsions causes substantial reduction of crude production rates [2].

Pipeline pressure approximation is one of the principal aspects of the oilfield transportation. Inaccurate estimation leads to failures in crude oil export, violation of safety precautions and also breach in the pipeline.

II. BACKGROUND

Development of stable inverse emulsions endorses viscosity reduction and ΔP along the pipeline [5], [6]. Study on phase inversion has determined that the viscosity of W/O emulsions is significantly reduced due to O/W emulsion formation [1]. As depicted in Fig. 2, water droplets begin to coalesce and entrap oil into droplets, as water having higher viscosity than oil, this will thus cause sudden reduction in viscosity of emulsion as the continuous phase changes to water.

The main reason for a reduced viscosity of the 40% water cut is due to the phase inversion (Fig. 3) [7]. This was confirmed by a rheology measurement of Bintulu Light Crude.

An experimental study [8] on ΔP for different water cuts in emulsions also shows an exponential increase in flow rate and ΔP. It is evident that ΔP varies in parabolic with flow rate. Emulsion ΔP has a greater magnitude than single phase ΔP of water alone [9]. The experiment was carried out using low-density oil, 801 kg/m^3 at room temperature of 17 °C corresponding to oil viscosity of 2.16 cP. After the experiment, the author compared the results of the ΔP with another two authors who have the same trend in the ΔP data that is ΔP was maximum at the inversion point, generally around 40% water cut. Under certain conditions, injection of water into crude oil pipeline results in a significant reduction of pressure loss [10].

Pressure loss reduction benefits the transportation of crude oil as less pump energy facilitates the pressure loss throughout the pipeline for the oil to flow. In an experiment conducted by using emulsions with 20% water cut, crude oil with a density of 967 kg/m^3, pipeline test section made of stainless steel; it is proven that ΔP increases exponentially as velocity increases in turbulence flow [11]. The results are as shown in their Fig. 2.6 where ΔP increases exponentially as velocity increases.

Constriction installation in a pipeline causes disturbances to the flow. Disturbances to the flow will reduce the pressure drop of the flow when it is in fully developed region. According to research in the flow of two-phase oil-water mixtures through sudden expansions and contractions [12], the pressure profile along the axis of sudden expansion experiences a decline in pressure, i.e., ΔP. As the fluid reaches

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the transitional region, the fluid decelerated in the enlarged diameter area causes an increase in pressure

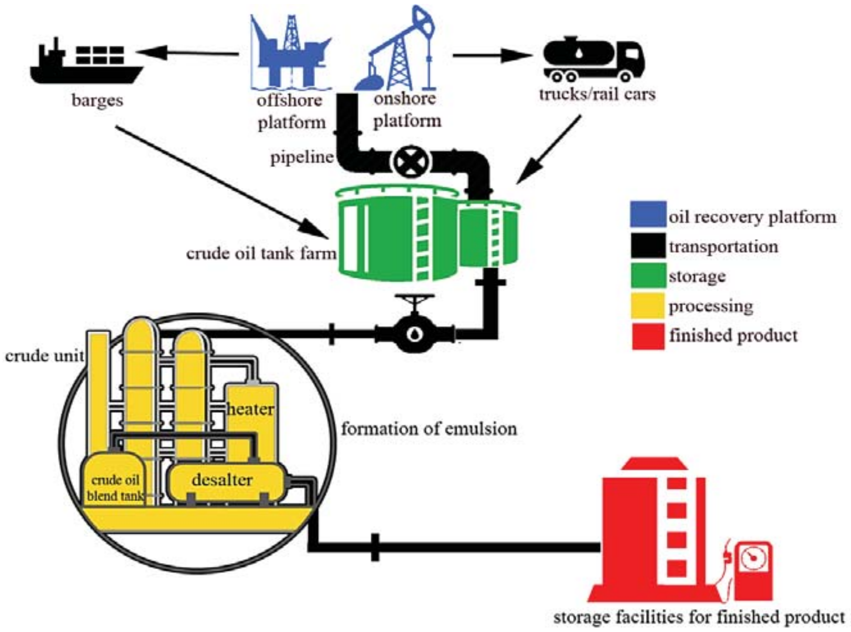


Fig. 1 Crude oil processing flow diagram and emulsion formation processes [3]

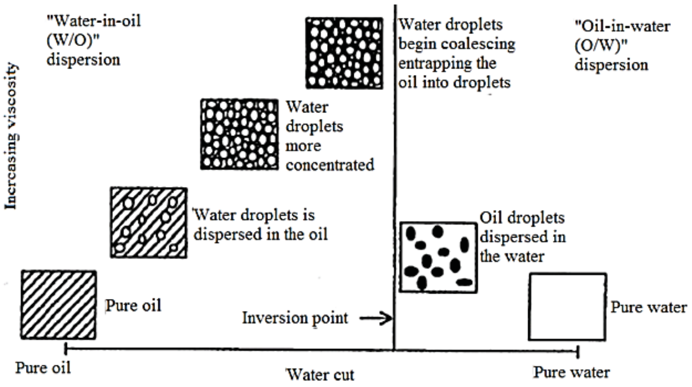


Fig. 2 Phase inversion of W/O emulsion [4]

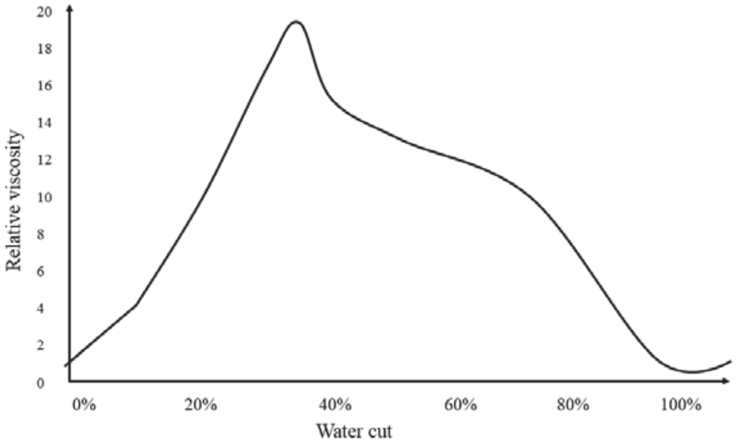


Fig. 3 Measured relative viscosity of different water cut [7]

III. Experimental Set-Up

There are two separate sections to evaluate the effect of emulsions and type of constrictions. The flow is pumped from a reservoir tank that has the capacity of up to 54 liters into a tee junction where the flow is separated into the pressure measurement section and the flow visualization section, as shown in Fig. 4. The pipeline and constriction basic dimensions are tabulated in Table II.

As depicted in photo of the flow loop in Fig. 4, it can be seen that there are two separate sections of the flow loop, one is pipeline made of stainless steel for pressure measurements and the other is plexiglass pipe for flow visualisation. Detailed flow loop plan is shown in Fig. 5.

The pressure tapping points consist of one point before the constriction and the rest is after constriction (Fig. 6).

There are four types of constriction that were used as shown in Fig. 7 attached from Segment J to Segment K based on the flow direction as shown in Fig. 8.

Overall uncertainty of the flow loop pressure is ±0.087 bar as shown in Table II.

TABLE I
PIPELINE AND CONSTRICTION DIMENSION

	Unit, cm	Unit, m
Length of pipe before constriction	91	0.91
Length of pipe after constriction	320	3.2
Diameter of pipe	4.4	0.044
Radius of pipe	2.2	0.022
Diameter/size of the constriction	2.2 – 3.3	0.034
Area of pipe		0.00152 m^2

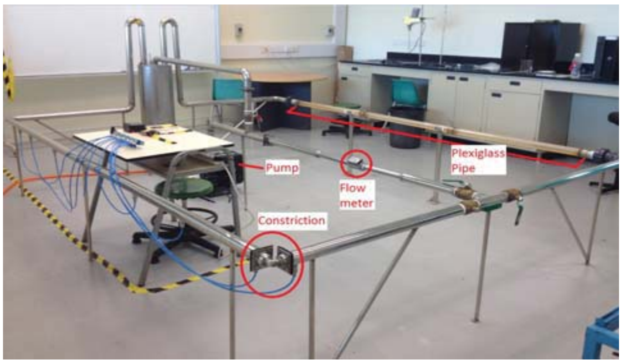


Fig. 4 Photo of the flow loop

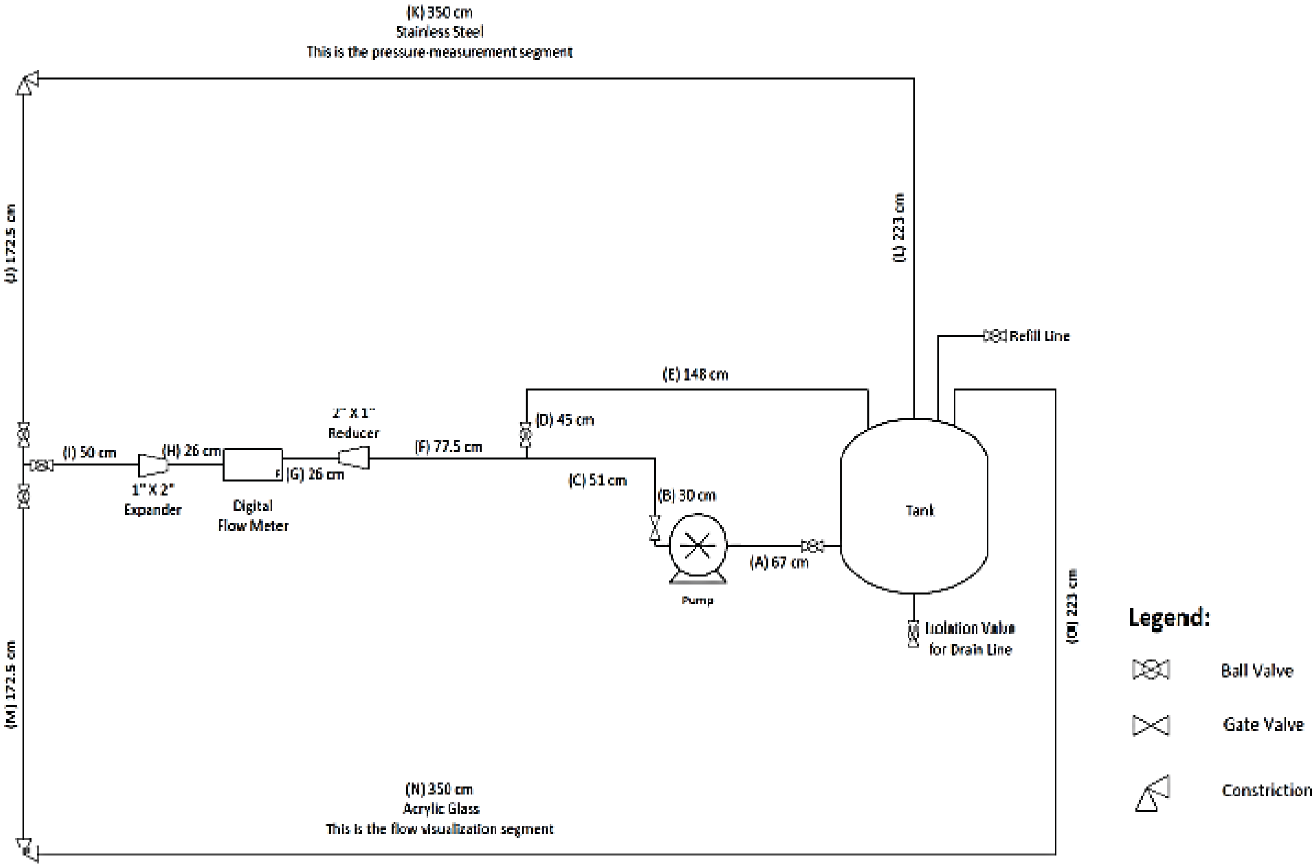


Fig. 5 Flow loop plan

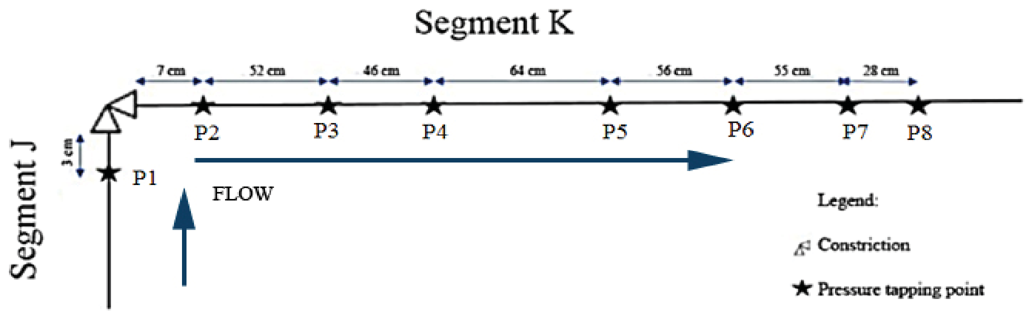
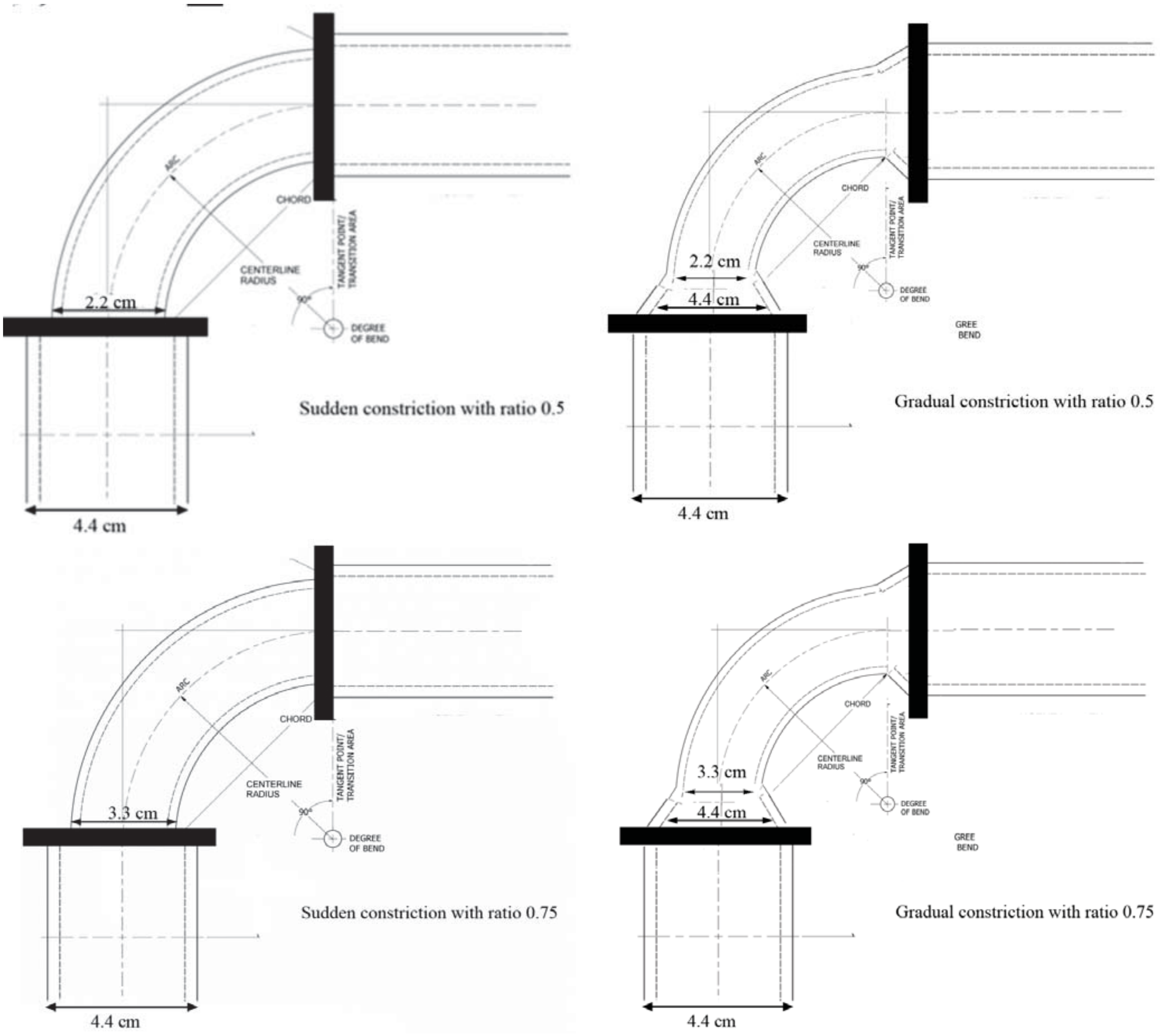


Fig. 6 Pressure tapping point



Sudden constriction with ratio 0.5

Gradual constriction with ratio 0.5

Sudden constriction with ratio 0.75

Gradual constriction with ratio 0.75

Fig. 7 Types of constriction

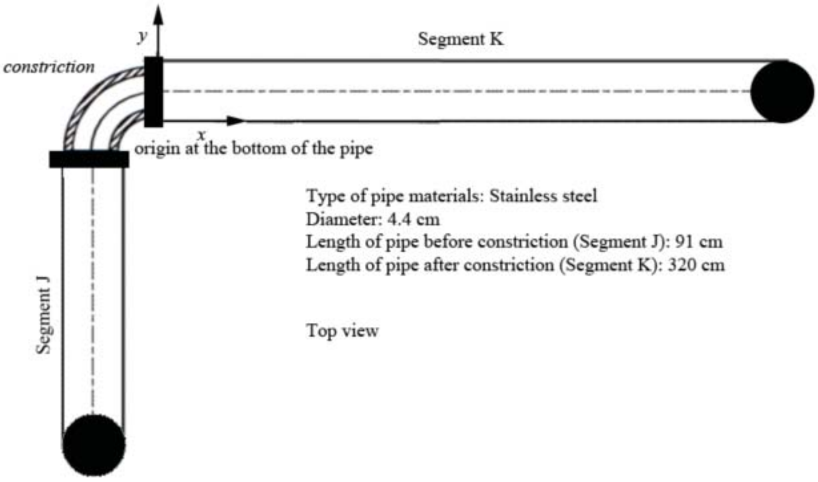


Fig. 8 Constriction location

TABLE II
UNCERTAINTY OF THE FLOW LOOP PRESSURE MEASUREMENT

Quantity	Absolute uncertainty	Percentage uncertainty
Pressure	±0.087 bar	
Bias uncertainty		
a. Pressure indicator display		±0.085 %
Precision uncertainty		
a. Pressure transmitter		±0.25%
b. Due to temperature change		±0.15%
c. Flow meter		±3.00%

IV. RESULTS AND DISCUSSIONS

The emulsions stability was obtained and analyzed through visual observation. After letting the emulsions in the flow to flow for 20 minutes, samples were taken through one of the pressure tappings point and photos were taken on the spot as shown in Fig. 9. Eventually, an emulsion settling period of 48 hours was given for all the samples and another picture of the samples collected for comparison, as shown in Fig. 10.

Initially, all samples of same water cuts exhibit same appearances regardless of the type of constriction used for the flow. When the samples were collected, water droplets do not have sufficient time to coalesce to be visible for observation. Hence, only a reduction in intensity of the color of the crude oil can be observed.

By comparing all the photos obtained from the samples, when water cuts are increased, the emulsions droplet formed with higher stability are also increased. Stability is measured by the ability for the emulsions to separate in given amount of time. In microscopic point of view, the resin and asphaltenes' role in crude oil is crucial in increasing the stability of the emulsions. As water cuts upsurge, the surface area of water molecules in contact with resins and asphaltenes chemical composition in the crude oil increases [13]. Resins and asphaltenes act as stabilizing agents for emulsion formation. By comparing types of constriction for same water cuts, it can be seen that constriction ratio of 0.5 forms emulsion with higher stability as the amount of separated water is found to be lesser than the case of constriction ratio 0.75. By comparing the types of constriction, gradual constrictions give emulsions secondary stability. There are three regions [14] along the pipeline which are the fully disturbed flow right before entering the constriction, the transitional region and fully developed outlet flow region, as shown in Fig. 11. The pressure data that spikes high before the constriction shows that the flow has been triggered due to the obstructed flow pipe. The backflow of the emulsion increases the pressure thus showing the highest pressure point at P1 [15]. As a result, pressure is exceptionally high at P1. At P2, pressure is particularly low as it is the transitional region where flow experiences an expansion after constriction. Fig. 11 shows typical trend of the pressure along the pipeline. Fig. 12 shows pressure of laminar flow using gradual constriction 0.50. Sudden constriction with the same ratio has the same trend, but with a higher pressure drop at the fully developed outlet flow region.

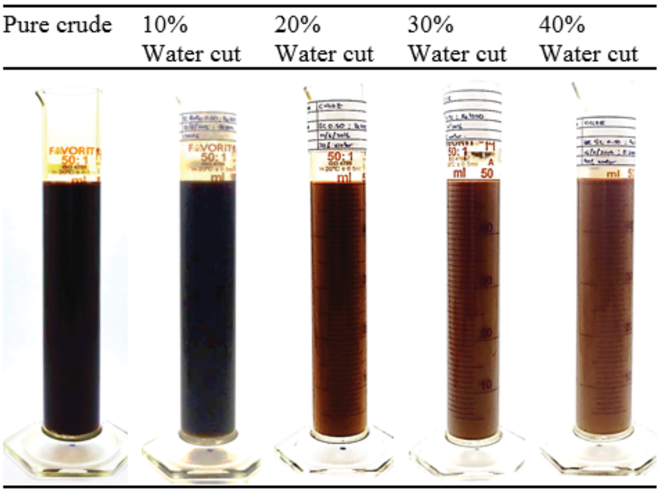


Fig. 9 Initial condition of the crude oil

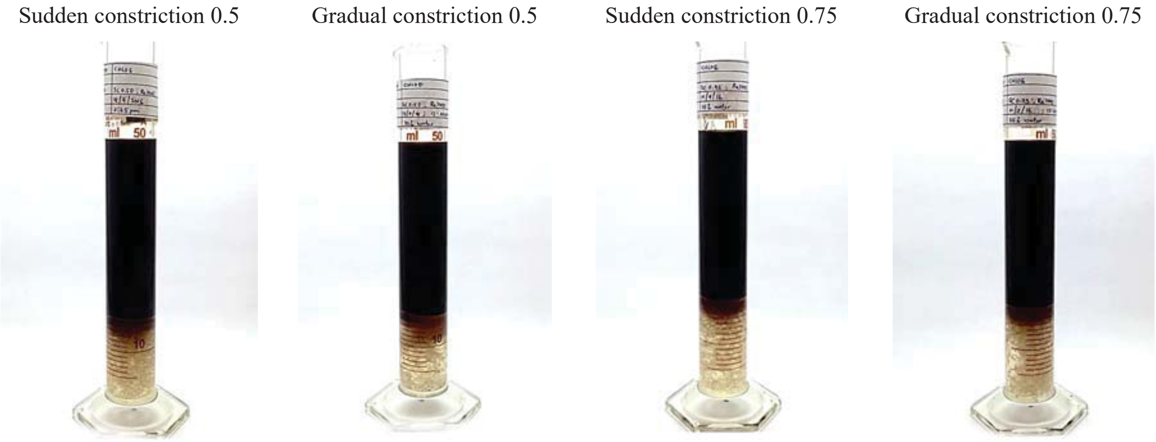

Sudden constriction 0.5
Gradual constriction 0.5
Sudden constriction 0.75
Gradual constriction 0.75

Fig. 10 Condition of 40 % crude oil after separation

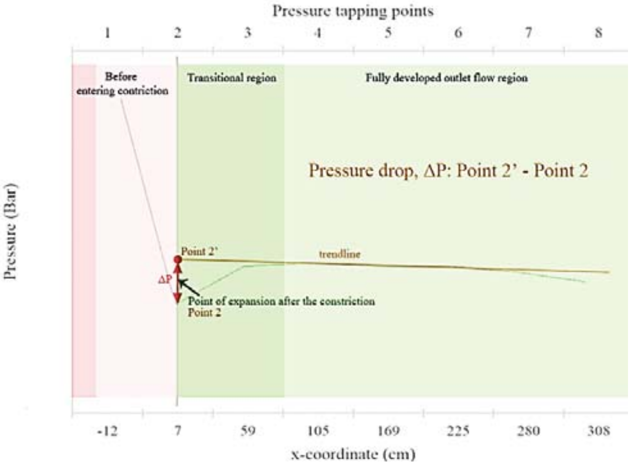


Fig. 11 Pressure drop regions

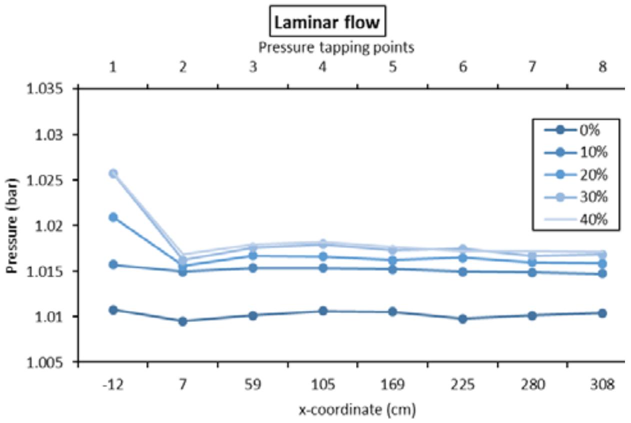


Fig. 12 Pressure of laminar flow (Re < 1000) using gradual constriction ratio 0.50

Generally, increase in water cut in emulsions results in a higher pressure drop along the horizontal pipeline [10]. The increase of ΔP is due to the growth of dispersed phase volume in W/O emulsions which is immiscible with the continuous phase causes a difference in density of two fluids in the pipeline. Since water has a higher density and a higher viscosity, water phase tends to travel slower than oil phase in the pipeline [16]. Therefore, the increase of water cut enhances the amount of water in the emulsion which will results in higher drag to the flow thus increasing the ΔP.

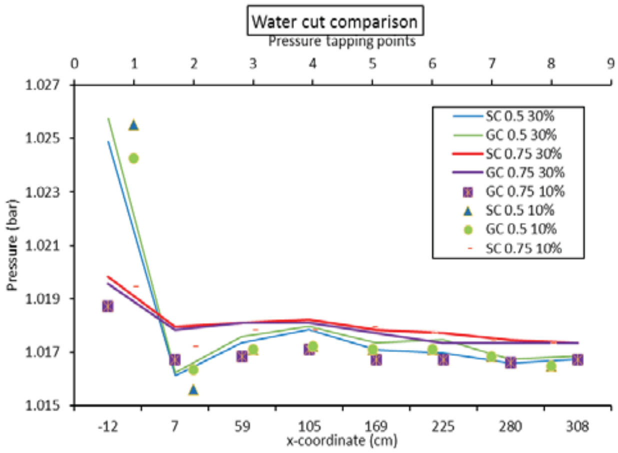


Fig. 13. Water cut comparison of the same flow rate

To compare the water cut, the flow rate is kept constant in the range of 74 L/min to 76 L/min (Fig. 13). For GC, higher water cut will result in a higher ΔP. This high ΔP difference shows that there is an effect of water cut in the experiment. For gradual constriction, the ΔP is caused by density difference and also the emulsion effect. Emulsions droplet size is more likely to be preserved in a gradually decreasing and increasing the diameter of the pipe condition. Larger emulsions droplet size results in the emulsion effect, where the two immiscible phases, water, and oil experiences drag due to the difference in densities. This drag reduces the velocity, increases the pressure. In 30% WC, where there is more dispersed water phase, this drag effect was larger, hence resulting in a much higher ΔP. As example, for GC 0.5, 30% WC ΔP is 0.18% compared to 10% WC which is 0.10%. However, as for SC, the difference is smaller which is within ±0.02%. This shows that the effect of water cut is low. For

SC, the difference in pressure is due to the momentum of the fluid.

Fluid flow in sudden constriction experiences a sudden change in velocity before entering the constriction which causes the pressure to drop. The dominant ΔP due to momentum reduces the effect of different water cut to the change in pressure. As the flow hits the sudden constriction at high velocity, the partial fluid that hits perpendicular at the constriction wall experiences backflow which increases the collision of emulsion particles [11]. As collision increases, bigger emulsion droplets will break down into smaller droplets. When the emulsion droplets are small enough, the velocity difference in both phases will reduce, and the continuous phase will carry the dispersed phase in sync.

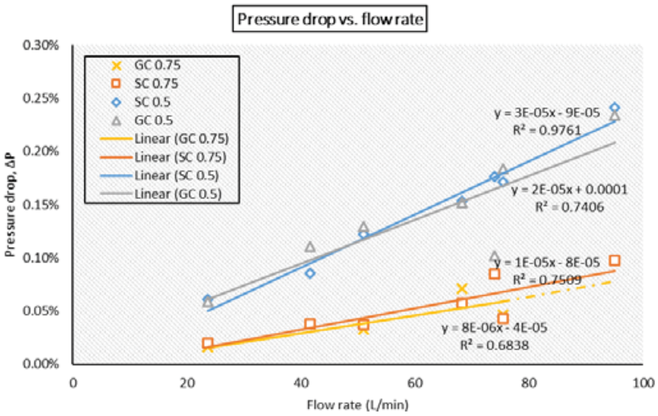


Fig. 14 ΔP vs. flow rate graph

To validate the results, the ΔP can be compared against the flow rate. As shown in Fig. 14, the R^2 of GC 0.75 trendline has increased from 0.00008 to 0.6838. Since the flow rate is independent of the fluid properties itself, it can be seen that SC always has a steeper gradient line of best fit compared to GC. This shows that when emulsion properties such as droplet size are not taken into consideration, property such as flow rate in SC dominates compared to GC. This outcome is also supported by an experimental study on horizontal two-phase flow [17], where the experiment concludes that ΔP is higher in a sudden expansion compared to gradual expansion.

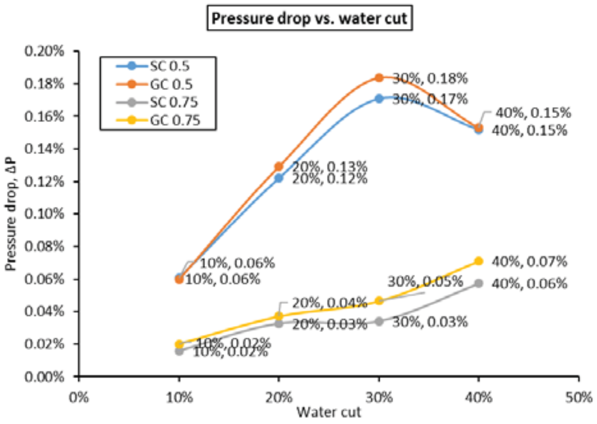


Fig. 15 Pressure drop vs. water cut

As depicted in Fig. 15, the ΔP of both constriction of ratio 0.5 shows a maximum point at 30% WC from 0.18% drops to 0.15% at 40% WC. This indicates that the effect of phase inversion is evident in smaller constriction ratio. According to rheology study on the crude oil emulsion, phase inversion of Miri Light Crude happens at 38% WC [3], [7]. As for SC 0.75 and GC 0.75, the change in the cross-sectional area of the pipe is not significant enough to see a sudden decrease in ΔP at the phase inversion point where water as dispersed phase became continuous phase.

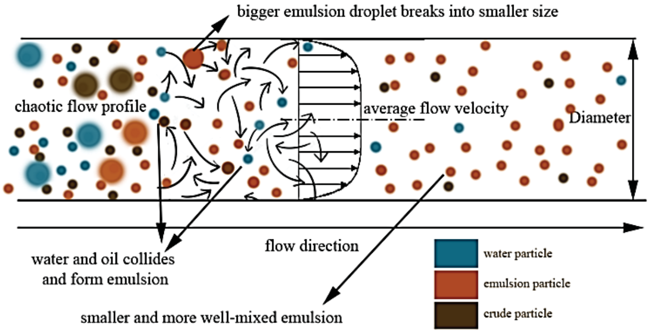


Fig. 16 colliding emulsions in chaotic turbulence flow and explanation on energy dissipation in usual pipeline

Consistently, constriction causes a disturbance in the flow and the type of flow changes to turbulence flow after the constriction for a certain entrance length, regardless of the flow type before the constriction, as depicted in Fig. 16 [18], [19].

V. CONCLUSIONS

- At higher WC, the ΔP is greater due to the emulsion effect. Emulsions that are not well dispersed has higher drag; decreases velocity thus increases ΔP. Therefore, ΔP increases as WC increases.
- Pressure drop increases as WC increases and peaks before phase inversion occurs. After phase inversion, ΔP decreases. W/O emulsions with water as dispersed phase have lesser drag as the dominant continuous phase has lower resistance to flow. Whereas in O/W emulsions, water became the continuous phase and water has higher viscosity, dominating the overall emulsion flow. Thus, this explains the ΔP reduction.
- An abrupt area of change does influence the ΔP across the constriction. The abrupt area of change is more significant in a smaller ratio. SC 0.75 and GC 0.75 shows lower ΔP compared to SC 0.5 and GC 0.5. Higher ΔP across constriction results in lower ΔP of the developed flow is good for the efficiency of flow.
- A contraction in the flow passage reduces the emulsion droplet size as emulsions break into smaller droplets. In emulsion droplet size observations, GC produces emulsions of higher droplet size after settling time of 48 hours as compared to SC with the same WC. The effect of constriction ratio does not affect the droplet size as much as the sudden change of constriction size.

- In SC, the effect of emulsions to ΔP across the constriction is low. In GC, the effect of emulsions to ΔP across the constriction is high. The increase of water in GC significantly increases the ΔP across the constriction.
- The experimental ΔP after the flow developed obtained from a flow through constriction are found to be lower than the theoretical value of flow without constriction.
- Laminar and transitional flows are disturbed by the constriction and behave as turbulence flow at the entrance and exit of the constriction until it reaches a steady ΔP at the fully developed outlet flow region.

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