The Effect of Dissipation Energy on Pressure Drop in Flow-Induced Oil-Water Emulsions Pipeline

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Abstract: - In the oil production industry, crude oil is usually produced together with water from the reservoirs, and the immiscible mixtures of oil and water result in emulsions flow in the transporting pipelines. Emulsions cause higher pressure drop, create difficulties in water-oil separation process, require more retention time in the separation vessels, take larger volume in separators and pipelines, and affect the flow behaviors due to changes in density and viscosity of the fluid. The presence of stable emulsions also reduces the quality of crude oil and causes more problems in the downstreams refinery operations, such as corrosion and higher heat capacity. In this research work, a lab-scale flow loop was constructed to investigate the formation of emulsions solely through flow shear, and the effect of emulsions on pressure drop. The effect of emulsions on flow pressure drop is established with the presentation of flow pressure drop profile and dissipation energy profile. The flow pressure drop profile shows that as more stable emulsions droplets are formed at higher flow rate, the pressure drop continues to increase until a maximum peak. The maximum peak is also the phase inversion point, where further water addition beyond this point triggers phase inversion of the emulsions system. Higher flow rate also brings the emulsions system to an earlier phase inversion. Stable water-in-oil (W/O) emulsions, which require dissipation energy to form, resulted in significant pressure drop. The dissipation energy is directly proportional to the pressure drop and flow velocity. After the phase inversion, the pressure drop starts to decrease, until it reaches the pressure drop of pure water, due to the presence of unstable emulsions, irregular size distribution of emulsion droplets, non-aggregated emulsions with less dense packing, and water as the continuous phase. The flow pressure drop profile is an important optimization tool in the industry to determine the values of flow rate and water content, in mitigating the adverse pressure drop effect of emulsions.

Key-Words: - pressure drop, emulsification, water-in-oil emulsions, dissipation energy, phase inversion point

1 Introduction

In the upstream oil production industry, emulsions flow always exists in the pipelines exporting the natural production of crude oil and water. Due to the presence of a subsurface water aquifer in the reservoirs, water will flow into the wellbores together with crude oil, and as the field ages, the amount of water will be more significant.

Emulsification occurs when one immiscible liquid is dispersed as droplets (dispersed phase) in the other continuous phase of immiscible liquid [1]. The dispersion energy required for emulsions to form is inherently available through the turbulence, mixing, and agitation as the fluid flow across downhole wellbores, surface chokes, valves, pumps and pipes [2]. The emulsions system can either be present as water-in-oil emulsions or oil-in-water emulsions, depending on the volumetric ratios of the phases involved, where the larger ratio will usually be the continuous phase. Phase inversion is the point where water-in-oil emulsions are inverted to oil-in-water emulsions or vice versa, due to changes in the volumetric ratios of the phases [3].

In the formation of emulsions through cylindrical pipe flow, which is achieved via flow shear, Johnsen and Rønningsen [4] discussed on the dissipation energy required to disperse the emulsion droplets. The dissipation energy for emulsification, ε, can be related by:

$$\varepsilon = 2f\frac{V^3}{D}$$

where f stands for Fanning friction factor, V stands for flow rate and D stands for internal diameter of the pipe. The presence of emulsifying agents or surface active agents will help to reduce the required dissipation or mixing energy, thus favouring the formation of emulsions.

Stable emulsions cause a larger value of flow pressure drop [5-9], which result in flow assurance challenges in transporting the crude oil. These challenges can adversely affect the economic feasibility of the operations, due to the arising needs of higher pumping power or possible facility upgrades. As an example, Plasencia *et al*. [9] reported that the pressure drop of water-in-oil emulsions could increase up to 8 times higher than the pressure drop of pure oil. Higher pressure drop, if exceeded the limitation of export pump design discharge head, will negatively impact the delivery of crude oil.

In Malaysian offshore brownfields, a big majority of the pipelines are transporting around 10% - 50% of water [10]. As emulsions significantly affect the flow behaviours, which differ compared to two-phase stratified or annular oil-water flow [5-7 & 11-13], this research aims to study and discuss the effect of flow-induced emulsification on pressure drop. The effect of emulsions on pressure drop will be deliberated and correlated with the dissipation energy in forming the emulsion.

Flow-induced emulsification is the formation of emulsions via flow shear only, and this replicates the actual application in the industry. Existing literature provides studies done on annular or stratified flow of water and oil phases, and growing research on emulsions flow, but flow-induced emulsification has not been widely researched yet. In a study conducted by Plasencia *et al*. [9], flow-induced emulsification was investigated, but a full spectrum analysis was not available, as the water content could not be increased beyond 60% due to prohibitive backpressure to the pump.

This research covers the full range of emulsions, as the water volumetric content was increased from 0% up to 100%. Flow pressure drop profile of water-in-oil emulsions, oil-in-water emulsions and phase inversion point is obtained and deliberated. Understanding of emulsions flow behaviours can give significant contribution to pipeline flow assurance studies. Although emulsions cannot be fully eradicated in the upstream pipelines, but the emulsions can be controlled and mitigated through flow rate and water content optimization, to allow efficient transportation and pumping operations.

2 Methodology

2.1 Experimental set-up

A closed-circuit flow loop was fabricated as depicted in Figure 1. The flow loop consists of a 55-L cylindrical storage tank, a 1.5-kW electrical regenerative turbine pump, a battery-operated GPI® A100 digital flow meter, BCM 130C digital pressure transmitters, Autonics MT4W-DA-41 digital pressure indicator, 1-inch-right-angle-constrictions and connecting pipes made of stainless steel as well as acrylic glass. The design of the constriction replicates a choke valve, and it serves to contribute to emulsification by inducing higher flow turbulence. The pressure-measurement segment (Segment K) is a 2-inch-stainless steel pipe with the horizontal length of 350 cm. There are 8 pressure recorder points in the flow loop, along Segments J and K (refer to Figure 1 and Figure 2).

The flow-visualization segment (Segment N) is a 2-inch-acrylic glass pipe, and the flow is only diverted to this segment if there is a need to physically observe the emulsions patterns. Otherwise, for the purpose of measuring the pressure drop, Segment N is to be isolated. The main flow in this loop goes through pipes with nominal diameter of 2 inches, except for the inlet and outlet of the flow meter, where the nominal diameter of 1 inch is used.

Oil-and-water mixtures were circulated for 25 minutes at a constant flow rate and constant volumetric ratio of oil and water. Samples were taken at the end of the period to determine the extent of emulsification, followed by pressure drop measurement. The similar steps were repeated for another pre-determined flow rate (from 20 L/min to 100 L/min) and a volumetric ratio of oil and water (from 0% water content to 100% water content). For each repeat, new mixtures of oil and water were used, to rule out the presence of prior emulsions. As continuous circulation caused the temperature to rise, the flow loop system was cooled down to room temperature after each run.

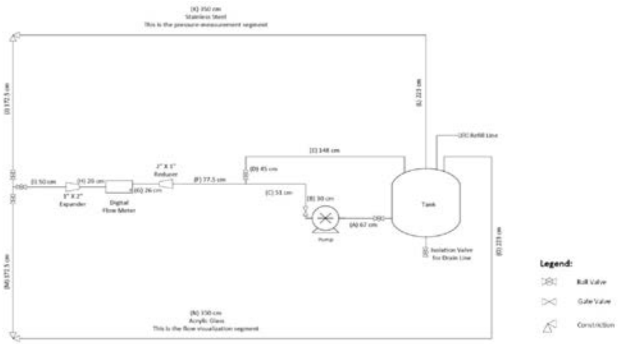

Figure 1: Schematic diagram of the flow loop (dimensions are not to scale)

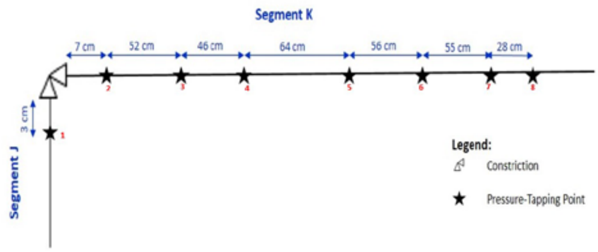

Figure 2: Pressure recorder points

2.2 Crude oil and water properties

Malaysian Miri Light Crude (MLC) oil was used in this research, and this crude oil was obtained from PETRONAS Carigali. The physicochemical properties of MLC oil are given in Table 1.

SARA (Saturates, Aromatics, Resins and Asphaltenes) analysis was also performed by using High Performance Liquid Chromatography (HPLC) method. The result of SARA analysis is given in Table 2. The HPLC method actually has its minor limitations, such as the inaccuracy in determining macro/micro-crystalline wax, naphthenates and volatiles.

Water was sourced from a local municipal water supply, and it was filtered to remove unwanted rust and sediment particles, before introducing it into the flow loop. In this research, the composition and characteristics of water (*e.g.* salinity) are not the main parameters to be studied.

Table 1: Physicochemical properties of MLC oil

No.	**Parameter**	**Test Method**	**Unit**	**Result**
1	Density @ 15 °C	ASTM D 5002	g/cm^3	0.8768
2	API Gravity @ 60 °F	Calculated	Degree	29.79
3	Total Sulphur	ASTM D 4294	wt %	0.0771
4	Nitrogen Content	ASTM D 5762	ppm wt	255
5	Total Acid Number	ASTM D 664	mgKOH/g	0.24
6	Flash Point	IP 170	°C	< -20
7	Pour Point	ASTM D 5853	°C	-30
8	Colour ASTM	ASTM D 1500	-	D 8.0
9	Salt Content	ASTM D 3230	lb/1000bbls	3.5
10	Ash Content	ASTM D 482	wt %	0.002
11	Mercaptan Sulphur	UOP 163	ppm wt	23
12	Wax Content	UOP 46	wt %	4.5
13	Kinematic Viscosity @ 25°C	ASTM D 445	cSt	4.785
14	Gross Calorific Value	ASTM D 240	MJ/kg	44.482
15	Sodium (Na)	ASTM D 5863	ppm wt	14.0

Table 2: SARA analysis

Component	**Unit**	**Result**
Saturates	wt%	69.30
Aromatics	wt%	26.60
Resins	wt%	3.65
Asphaltenes	wt%	0.43

3 Results and Discussions

This section provides the results of the effect of emulsions on pressure drop and to explain the pressure loss along a pipe length by relating it to emulsions and associated energy in forming the emulsions.

3.1 Pressure drop

The flow pressure drop was determined from the pressure difference between Point 8 and Point 5 (refer to Figure 2). The reason of using Point 5, which is located 1.69 m after the constriction, is to allow the flow to be fully developed prior to measuring its pressure.

The values of the flow pressure drop as the water volumetric content ware increased from 0% to 100%, at various flow rates, are given in Table 3 below.

Table 3: Flow pressure drop values

Water Content	Pressure Drop for 100 L/min (barg)	Pressure Drop for 80 L/min (barg)	Pressure Drop for 60 L/min (barg)	Pressure Drop for 40 L/min (barg)	Pressure Drop for 20 L/min (barg)
0%	0.07	0.06	0.06	0.04	0.04
20%	0.11	0.09	0.08	0.05	0.04
40%	0.17	0.14	0.11	0.07	0.05
60%	0.14	0.12	0.13	0.10	0.05
80%	0.08	0.05	0.04	0.03	0.02
100%	0.02	0.01	0.01	0.01	0.01

The flow pressure drop profile can be graphically represented as shown in Figure 3, to establish the effect of emulsions on pressure drop.

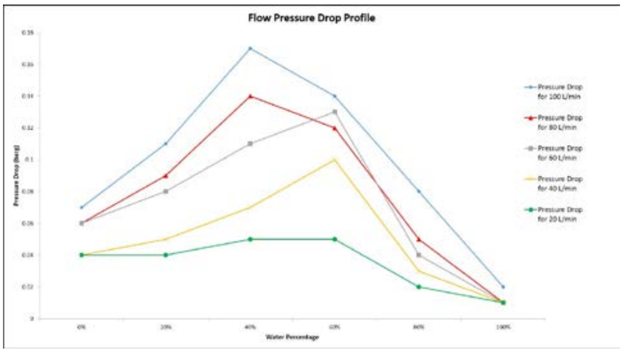

Figure 3: Flow pressure drop profile

Water volumetric content was varied from 0% (pure crude oil), 20%, 40%, 60%, 80% up to 100% (total water), at different flow rates. The water-oil mixtures, which were initially presented as two separated phases, were dispersed into emulsions flow as the circulation continued. The flow shear, turbulence and agitation from the circulation had induced the formation of emulsions. Three major requirements for emulsions to form are [14]:

1) The presence of two immiscible liquids (satisfied by water-oil mixtures)
2) The presence of emulsifying agents, *i.e.* surface active agents
3) The involvement of sufficient mixing energy to disperse one liquid into another liquid phase as droplets (satisfied by the flow circulation)

Emulsifying agents or surface active agents are naturally present in the crude oil, especially in the form of asphaltenes or waxes. This can be determined from the SARA analysis and Colloidal Instability Index (CII). CII is the ratio of saturates and asphaltenes fraction to aromatics and resins fraction[14], and its relationship is given in the following equation:

$$CII = \frac{Saturates + Asphaltenes}{Aromatics + \mathrm{Re}\sin s}$$

Crude oil with a CII value of greater than 2 has the tendency to form emulsions due to the natural presence of precipitated asphaltenes as surface active agents [15-20]. The CII value of the MLC oil used in this research was calculated to be 2.3.

The pressure drop of pure crude oil (0% water content) was higher than the pressure drop of pure water (100% water content). This can be understood from the viscosity difference between crude oil and water. At a temperature of 25°C, the viscosity of crude oil was 4.7855 cSt, while the viscosity of water was 0.8926 cSt. Liquid with higher viscosity is more resistant towards flow, and it requires more pumping energy to overcome the pressure drop.

The pressure drop profile exhibits an obvious trend of climbing to a maximum peak, and subsequently descending to the pressure drop value of pure water, as the water volumetric content was increased in stages from 0% to 100%. This behaviour occurred due to the presence of emulsion droplets in the system, which affected the flow viscosity and pressure drop. Previous research findings have shown that:

a) Emulsion droplets will increase the flow viscosity, due to hydrodynamic forces and interactions of the droplets [21-24].
b) Flow viscosity depends on the viscosity of the continuous phase and emulsions, apart from being affected by emulsion droplet size distribution [25-26].

As water volumetric content was increased to 20%, water-in-oil emulsion droplets started to form. At higher flow rates, more stable water-in-oil emulsion droplets were formed, resulting in higher flow viscosity and flow pressure drop. The trend continued as the water volumetric content was further increased to 40%. However, for the case of the lowest flow rate of 20 L/min, no emulsion droplets were formed at 20% water content due to insufficient turbulence or dispersion energy. Thus, it can be seen that in this case, there was no pressure drop difference between pure crude oil and 20% water volumetric content.

At water volumetric content of 40%, the maximum peak pressure drop was observed for flow rates of 100 L/min and 80 L/min. This peak pressure drop indicates maximum stable water-in-oil emulsion droplets, and the system had reached the phase inversion point, agreeing with the research by Keleşoğlu *et al* [8]. Further addition of water content resulted in phase inversion, with the formation of oil-in-water emulsions, water-in-oil emulsions and multiple emulsions.

However, samples with lower rates of 20 L/min to 60 L/min were only able to attain the maximum peak pressure drop at the water volumetric content of 60%. This suggests that the lower flow rate has a later phase inversion point, in addition to less stable emulsion droplets. This can be related to the reduced interactions and less coalescence between emulsion droplets at lower velocity.

At water volumetric content of 60% and beyond, all samples had experienced phase inversion, from water-in-oil emulsions to oil-in-water emulsions. After the phase inversion, the flow pressure drop started to descend, due to the presence of unstable emulsions, irregular size distribution of emulsion droplets, non-aggregated emulsions with less dense packing, and water as the continuous phase. This observation supports the earlier findings on the drag-reducing characteristics of unstable emulsion [6 and 7]. The pressure drop decreased to the final value of the pressure drop of pure water, which was around 0.01 – 0.02 barg.

Comparing the flow rates, sample with a flow rate of 100 L/min had the most significant change in pressure drop. At water volumetric content of 40%, it reached the maximum peak pressure drop with a value of 0.17 barg. The pressure drop had increased 142.86% from the pressure drop value of pure crude oil. Meanwhile, sample with a flow rate of 20 L/min had the least change in pressure drop. At a water content of 60%, it reached the maximum peak pressure drop with a value of 0.05 barg. The pressure drop only increased 25% from the pressure drop value of pure crude oil. This observation strengthens the hypothesis of the effect of emulsions on pressure drop. Sample with a flow rate of 20 L/min had the least amount of emulsions, due to its low velocity, low turbulence and the correspondingly low dispersion energy to form the emulsion [27].

3.2 Dissipation energy

The results strengthen the view that higher shear rate (higher flow rate or velocity) would give more dissipation energy to disperse the water phase into the continuous oil phase as emulsion droplets [6]. Higher dissipation energy, which comes from the higher shear rate, is needed to surmount the pressure gradient between the convex and concave sides of an oil-in-water droplet's interface, before the droplet can be formed stably and sustained [27]. Apart from forming more emulsion droplets, the droplets were also more stable when formed at higher flow rate. The interactions of asphaltenes are believed to play an important part at the interfacial films of these multiple emulsions, but unfortunately, this particular area is not fully understood yet.

The pressure drop data discussed earlier can be further analyzed to calculate the friction factor. The equation for Fanning friction factor, *f*, is given as:

$$f = \frac{\Delta PD}{2L\rho V^2}$$

where ΔP stands for pressure drop, D stands for internal diameter of the pipe, L stands for the length of the measured pressure drop, ρ stand for density, and V stands for velocity. Table 4 shows the calculation for the friction factor. It has been mentioned earlier that the dissipation energy is used to disperse the emulsion droplets and higher dissipation energy facilitates the formation of more stable emulsion droplets.

Table 4: Friction factor values

Water Content	**Density**	**Friction Factor for 100 L/m**	**Friction Factor for 80 L/m**	**Friction Factor for 60 L/m**	**Friction Factor for 40 L/m**	**Friction Factor for 20 L/m**
0%	876.80	0.18	0.24	0.42	0.63	2.52
20%	901.44	0.27	0.34	0.55	0.77	2.45
40%	926.08	0.41	0.52	0.73	1.04	2.98
60%	950.72	0.33	0.44	0.84	1.45	2.91
80%	975.36	0.18	0.18	0.25	0.43	1.13
100%	1000.00	0.04	0.03	0.06	0.14	0.55

The dissipation energy profile shares trend similarity with the pressure drop profile (compare Figure 3 and Figure 4). This highlights the significant relationship between dissipation energy, formation of emulsions and the corresponding flow pressure drop. The highest dissipation energy resulted in maximum emulsification and maximum pressure drop.

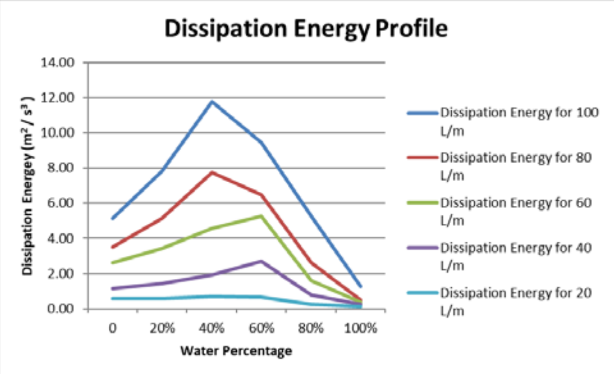

Figure 4: Dissipation energy profile

The energy dissipation can be re-written as:

$$\varepsilon = \frac{\Delta PV}{L\rho}$$

and it can be deduced that the dissipation energy is directly proportional to the pressure drop and velocity.

5 Conclusion

This research has met the stated objectives to study the formation of emulsions in a continuous flow loop, to determine the phase inversion, to investigate the relationship between emulsions formation and pressure drop, as well as the effect from dissipation energy.

Higher flow rate, and correspondingly higher kinetic energy, facilitates the formation of more stable emulsion droplets. At lower flow rate, there are more emulsions droplets which destabilize and settle out. Stable emulsions increase the flow viscosity, resulting in greater pressure drop. Also, this research presents a new idea that phase inversion is affected by flow rate, where higher flow rate brings the emulsions system to an earlier phase inversion. This can be caused by the more frequent coalescence of the emulsion droplets at higher flow rate.

Phase inversion can be determined as the point with a maximum pressure drop, as the water volumetric content increases in water-in-oil emulsions system. Further addition of water triggers the phase inversion from water-in-oil emulsions to oil-in-water emulsions. After the phase inversion, the pressure drop starts to decrease, until it reaches the pressure drop of pure water. Although multiple emulsions are present, the pressure drop still decreases because of the presence of unstable emulsions, irregular size distribution of emulsion droplets, non-aggregated emulsions with less dense packing, and water as the continuous phase.

Apart from flow pressure drop profile, the analysis of pressure drop data allows dissipation energy profile to be drawn. Dissipation energy profile shows the amount of energy in forming emulsions. Higher presence of emulsions requires more dissipation energy, and results in more pressure drop. The dissipation energy is directly proportional to the pressure drop and velocity.

The flow pressure drop profile is a good production optimization tool for the upstream oil industry. Oil-producing platforms aim to produce at an optimum flow rate and discharge pressure, *i.e.* the highest possible flow rate that can be achieved without causing pressure limitation to the export pumps. With the flow pressure drop profile, the maximum pressure drop for a pipeline can be estimated more accurately, and the effect of emulsions on the flow pressure drop can be better understood. Although pipeline emulsions flow is an inevitable occurrence in the oil production industry, but the formation of emulsions can be controlled by manipulating the flow rate or water content, apart from reliable mitigation methods such as demulsifier chemical treatment and heat treatment. It is recommended to deliver the crude at high flow rate, but without exceeding the limitation of the export pump's discharge pressure by reducing the formation of stable emulsions.

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