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# Experimental Study on the Effects of Water-in-oil Emulsions to Wall Shear Stress in the Pipeline Flow

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## ABSTRACT

Study on the emulsion formation mechanically and relate the effect of emulsions to the friction or wall shear stress ( $\tau_w$ ) in the pipeline flow has not yet been explored. So, this study aims to understand the emulsions formation mechanically and to discover the effects of water-in-oil emulsions to the pipeline flow transport by relating the effect of emulsions to the wall shear stress or friction of the pipe. In this study, wall shear stress is compared at water cuts from 0% to 40%, Reynolds number that covers laminar (1100 < Re < 1800) and transitional (2400 < Re < 2800) flow regime, pipeline constrictions that consists of gradual and sudden contraction with a contraction ratio of 0.50 and 0.75, respectively as well as along the pipelines. To carry out the experiments, the Ultrasonic Velocity Profiler and a lab-scale flow rig were used. The results show that the maximum wall shear stress happens at 10% water cuts, higher Reynolds number results in lower wall shear stress, pipeline constriction with contraction ratio of 0.75 results in higher wall shear stress than the contraction ratio of 0.50 and sudden constriction results in higher wall shear stress than the gradual constriction, and wall shear stress increases with the increase in the length of the pipeline downstream the pipeline constriction. In conclusion, pipeline flow with higher Reynolds number and pipeline constriction (which represents the usage of choke valve in the industries) type gradual constriction ratio 0.50 are recommended to be used in the oil and gas industries because this combination results in the lowest wall shear stress.

**Keywords:** Water-in-oil; Emulsions; Wall shear stress; Friction; Emulsification; Pipeline flow.

## 1. INTRODUCTION

Formation of emulsions is an unavoidable phenomenon in oil and gas industries as crude oil will always produce together with water from the reservoir. It has been reported that the most common type of emulsion that is found in oil and gas industries is water-in-oil (W/O) emulsions (Wong *et al*. 2015). However, this emulsification phenomenon is completely unwelcomed in oil and gas industries as it brings countless harmful effects to the industries. The negative effects cause by the presence of emulsions, such as, affects the general flow behavior of the flowing fluid (Pal 1987) (Omer and Pal 2013), affects the transportation of crude oil, lowers the production rate (Dol *et al.* 2016), leads to higher pressure drop (Keleşoğlu *et al*. 2012) (Pal and Rhodes 1989) (Kokal 2005), leads to higher operating cost (Lim *et al*. 2015), as well as causing problems in the downstream refinery system (Lim *et al*. 2015), have been widely reported in the existing literature.

Besides, numerous studies have been conducted to understand the formation of emulsions. However, almost all of these studies on the emulsification are due to the application of an external force such as stirring, shaking, blending and whisking. Also, existing studies on emulsification mainly focused on the use of chemical compounds (Ortega *et al*. 2010) (Zaki *et al*. 2000) (Nghiem *et al*. 1993) (Aguileraa *et al*. 2010) (Bobra 1990) (Bobra 1991) (Ashrafizadeh and Kamran 2010) (Briceno *et al*. 1997) (Pal *et al*. 1992) and batch processes (Binks 1993) (Ahmed *et al*. 1999) (Johnsen and Rønningsen 2003) (Farah *et al.* 2005) (Dan and Jing 2006) (Maia Filho *et al*. 2012) (Broboana and Balan 2007) (Anisa and Nour 2010). To the author's best knowledge, only Nädler and Mewes (1997), Keleşoğlu *et al*. (2012) and Plasencia *et al*.

(2013) had carried out a study on the formation of water-in-oil emulsions solely from flow shear using a lab-scale pipeline. Less attention has been paid to the pipeline flow of W/O emulsions. Therefore, in this study, the formation of W/O emulsions is investigated using a continuous flow loop, where the emulsification process is induced by the flow shear and turbulence effects such as the pipeline constriction disturbance in the flow loop.

The main aim of this paper is to give a contribution to the understanding of the effects of W/O emulsions to the pipeline flow transport by relating the effect of emulsions to the wall shear stress or friction of the pipe. This study investigates the influence of the water cuts ranging from 0 to 40%, Reynolds number which covers laminar (1100 < Re < 1800) and transitional (2400 < Re < 2800) flow regime as well as pipeline constrictions with types of gradual contraction with a contraction ratio of 0.50 (GC 0.50), gradual contraction with a contraction ratio of 0.75 (GC 0.75), sudden contraction with a contraction ratio of 0.50 (SC 0.50) and sudden contraction with a contraction ratio of 0.75 (SC 0.75, to the pipeline flow transport by using a continuous flow loop.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The primary material used in this study was Miri Light Crude (MLC), provided by PETRONAS Miri Crude Oil Terminal (MCOT). This type of crude oil is defined as light crude stock as it has an API gravity of 29.79°. The properties of MLC are as follow: the density at 15°C is 0.8768 g/cm$^3$, the kinematic viscosity at 25°C is 4.785 cSt, the asphaltenes content is 0.43 wt% and the BS&W is 0.05 vol%.

The next material used in this study was filtered water. Filtered water was obtained by filtering the tap water from local municipal water supply. The purpose of using filtered water is to remove the unwanted rust and sediment particles present in the tap water.

### 2.2 Experimental set-up and procedures

### 2.2.1 Experimental flow rig

The experimental flow rig made for the use of this study is presented in Fig. 1. The flow rig is a closed-circuit loop which consists of a 55 liters storage tank, a positive displacement pump, a digital flow meter, a pressure measurement device, and two 90° bend pipeline constrictions. The 90° bend pipeline constriction is served to replicate the usage of choke valves in the oil and gas industry, which causes the formation of emulsions. The flow rig is constructed using the 2" stainless-steel (SS) pipes with an inner diameter of 48 mm and a wall thickness of 2 mm. The test segment AB is made of plexiglass with an inner diameter of 44 mm and wall thickness of 1 mm. Figure 2 shows the actual photo of the lab-scale flow rig used for this study.

The pump is a positive displacement pump, model TQ 1500 manufactured by Walrus Pump Co (Walrus). The specifications of the selected pump are as follow:

- Power – 2 HP
- Cycle – 60 Hz
- Maximum height – 134 ft
- Maximum flow rate – 250 L/min
- Maximum pump pressure – 58 psi
- Maximum inlet pressure – 48 psi
- Maximum discharge head – 32 m

This pump was selected mainly because the maximum discharge pressure of the pump is able to overcome the total pressure loss in the flow loop. Also, this type of pump is designed for pumping non-aggressive water and solid particles free water, which is suitable for this research.

The flow meter is a 1" turbine flow meter, model GPI® A100 digital type flow meter. The specifications of the selected flow meter are as follow:

- Accuracy – ± 1.5 %
- Repeatability – ± 0.2 %
- Flow range – 10 L/min to 190 L/min
- Temperature limit – −40 °C to 121 °C
- Maximum pressure it can withstand – 300 psi
- Maximum pressure drops across the flow meter – 5 psi

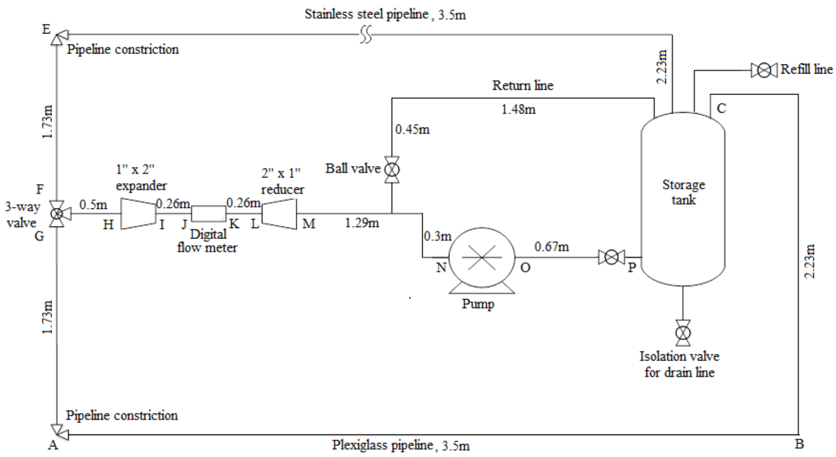



**Fig. 1. Flow sheet of the flow rig.**

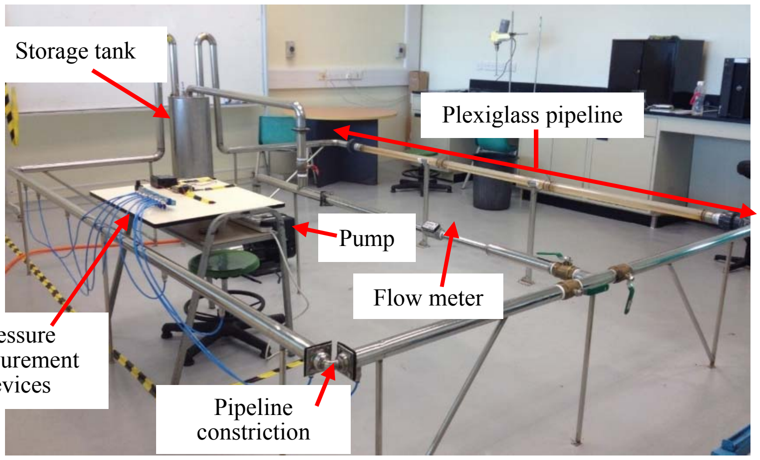



**Fig. 2. Actual photo of the flow rig.**

This flow meter was selected mainly because its measurable flow range meet the requirements for this research study and it is suitable for use in crude oil service.

### 2.2.2 Velocity Measurement

In this study, velocity profile of the flowing fluid in the pipeline is captured by using UVP (ultrasonic velocity profiler). The working principle of UVP system is it uses pulsed ultrasonic Doppler Effect together with the echography relationship, as shown in Fig. 3. The ultrasonic (US) transducer transmits short US pulses into the flowing fluid and when the pulses hit on the minuscule particles in the flowing fluid, it will reflect to the transducer. From there, the system processes the data into velocity information.

To carry out the experiments, the US transducer was placed on the transducer holder with an incidence angle of $10°$ at the measurement location, starting from measurement

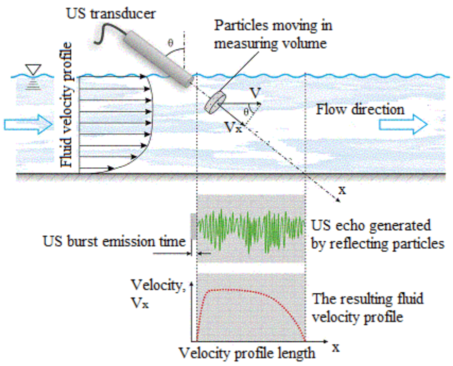



**Fig. 3. Working principles of UVP monitor** *(Metflow 2000)*

location 13 *x/D* to 63 *x/D* (as shown in Fig. 4). To obtain the streamwise velocity gradient ($\partial U/\partial X$), thevelocity of the flowing fluid was measured across the direction y, which is perpendicular to the direction of the flowing fluid in the pipeline (direction x). In order to obtain the velocity perpendicular to the pipe wall, Eq. (1) (Geisler 2001) is used:

$$v = \frac{v_x}{\cos\alpha} \qquad (1)$$

where, $v$ denotes velocity of particle (m/s), $v_x$ denotes velocity component along transducer axis (m/s), and $\alpha$ denotes Doppler angle.

It is important to note that the Doppler angle is not the same as the incident angle. As the incident angles is 10 degrees, the Doppler angle is 80 degrees. By substituting Doppler angle and the velocity measured along the transducer axis using the UVP probe, the velocity perpendicular to the pipe wall can be achieved.

Same steps were repeated for other variables, according to the variables matrix presented in Table 1. In this study, the effects of water cuts, types of constriction and Reynolds number to the wall shear stress in pipeline flow were examined.

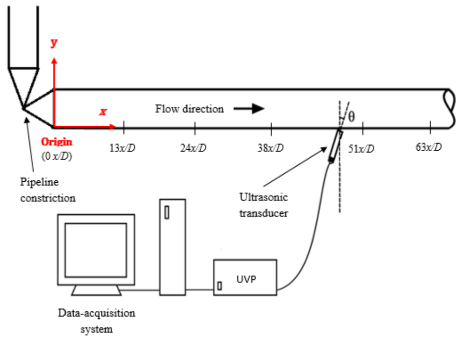



**Fig. 4. Schematic diagram of the experimental setup for velocity measurement.**

### 2.2.3 Wall Shear Stress Analysis

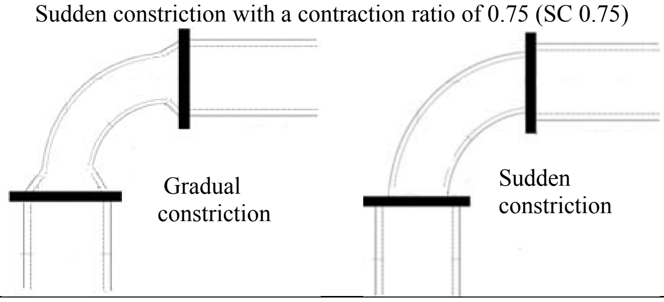
In the present work, wall shear stress ($\tau_w$) is determined from Eq. (2).

$$\tau_w = \mu \frac{\partial U}{\partial X} \qquad (2)$$

Where, $\mu$ is the dynamic viscosity of the flowing fluid and $\partial U / \partial X$ is the shear rate of the flowing fluid in the main flow.

In the following discussion, the results are discussed based on the analyzed $\tau_w$ as it signifies not only

**Table 1 Variables matrix of the study**

| Controlled parameter | Studied range |
|---|---|
| Water cuts (WC) | 0 – 40 % |
| Types of constriction | Gradual constriction with a contraction ratio of 0.50 (GC 0.50)<br>Gradual constriction with a contraction ratio of 0.75 (GC 0.75)<br>Sudden constriction with a contraction ratio of 0.50 (SC 0.50)<br>Sudden constriction with a contraction ratio of 0.75 (SC 0.75)<br> |
| Reynolds number | 1100 < *Re* < 1800 (laminar inlet flow regime)<br>2400 < *Re* < 2800 (transitional inlet flow regime) |

the shear stress at the wall of the pipeline, but also denotes as the direct measure of the shear produced by the main flow as well. The $\tau_w$ presents in the subsequent study is normalized to obtain dimensionless $\tau_w$ results for comparison. It is normalized by the diameter of the constriction (D), dynamic viscosity of the flowing fluid ($\mu$) and average inlet velocity ($U$), as shown below:

$$\text{Normalized } \tau_w = \frac{\tau_w D}{\mu U} \tag{3}$$

## 2.3 Uncertainty Analysis

The errors are made up of bias errors (fixed or systematic errors) and precision error (random errors).

### 2.3.1 UVP – Velocity Measurement Accuracy

This velocity resolution of $\pm$ 0.4% is accounted for the bias error for the velocity measurement. Meanwhile, the precision error of the velocity measurement for each of the cases is different since different parameters (eg. Reynolds number, input water fractions, type and ratio of pipe constriction) are used in this study. The highest precision error investigated among all the cases is determined to be $\pm$ 4.75%. From there, the highest overall uncertainty among all the experiments is calculated to be $\pm$ 4.77% at a 95% confidence level.

### 2.3.2 Shear Stress, $\tau$

The total error on the shear stress was estimated to be in between 1.54% to 4.11%. The errors for shear stress in each of the studied cases (at different water cuts) are summarized in Table 2.

## 3. RESULTS AND DISCUSSION

### 3.1 Effect of Water Cuts

For laminar inlet flow, as presented in Fig. 5, the $\tau_w$ increases as the water cuts increase from 0% to 10% and then decreases with the further increase in the water cuts from 10% to 40%. For transitional inlet flow, it is observed that the $\tau_w$ increases with the increase in water cuts from 5% to 10% and then it decreases with further increase in the water cuts, as presented in Fig. 6. The results show that for both the laminar and transitional inlet flow, the change in the trend of $\tau_w$ with respect to water cuts happens at 10% WC.

**Table 2 Uncertainty estimation for shear stress**

| Variable | Water cuts | Bias Limit $W_i$ | Precision Limit $P_i$ | Overall uncertainty $U_i$ |
|---|---|---|---|---|
| Shear stress ($\boldsymbol{Pa}$) | 0% | $\pm$ 0.57 % | $\pm$ 1.47 % | $\pm$ 1.58 % |
| | 5% | $\pm$ 0.57 % | $\pm$ 1.43 % | $\pm$ 1.54 % |
| | 10% | $\pm$ 0.57 % | $\pm$ 2.30 % | $\pm$ 2.37 % |
| | 15% | $\pm$ 0.57 % | $\pm$ 3.52 % | $\pm$ 3.57 % |
| | 20% | $\pm$ 0.57 % | $\pm$ 3.27 % | $\pm$ 3.32 % |
| | 25% | $\pm$ 0.57 % | $\pm$ 3.34 % | $\pm$ 3.39 % |
| | 30% | $\pm$ 0.57 % | $\pm$ 4.07 % | $\pm$ 4.11 % |
| | 35% | $\pm$ 0.57 % | $\pm$ 2.61 % | $\pm$ 2.67 % |
| | 40% | $\pm$ 0.57 % | $\pm$ 2.84 % | $\pm$ 2.90 % |

The increase in $\tau_w$ with the increase in water cuts is believed to be due to different shear as a result of different amount of emulsions present in the flow. With higher water cuts, the amount of emulsions (number of water droplets per unit volume) formed is higher as well. When the dispersed water droplets per unit volume is higher, the collisions between the dispersed water droplets happen more frequently as compared to that of the lower droplets per unit volume. When one dispersed water droplet collides or hits with another dispersed water droplet in the flow, they will exert shear on one another. The same goes for the collisions between the emulsions with the fluid particles (the continuous phase fluid) around them. With the presence of more emulsions, the collision rate is increased, which leads to an increase in the shear. Consequently, the wall shear is affected. Wall shear will be larger when there are more emulsions because the collision rate of the emulsions increases with the amount of emulsions. Following the above discussion, the higher the amount of emulsions, the higher is the collision frequency and hence the higher is the shear rate. Therefore, the larger the wall shear stress with the increase in the water cuts.

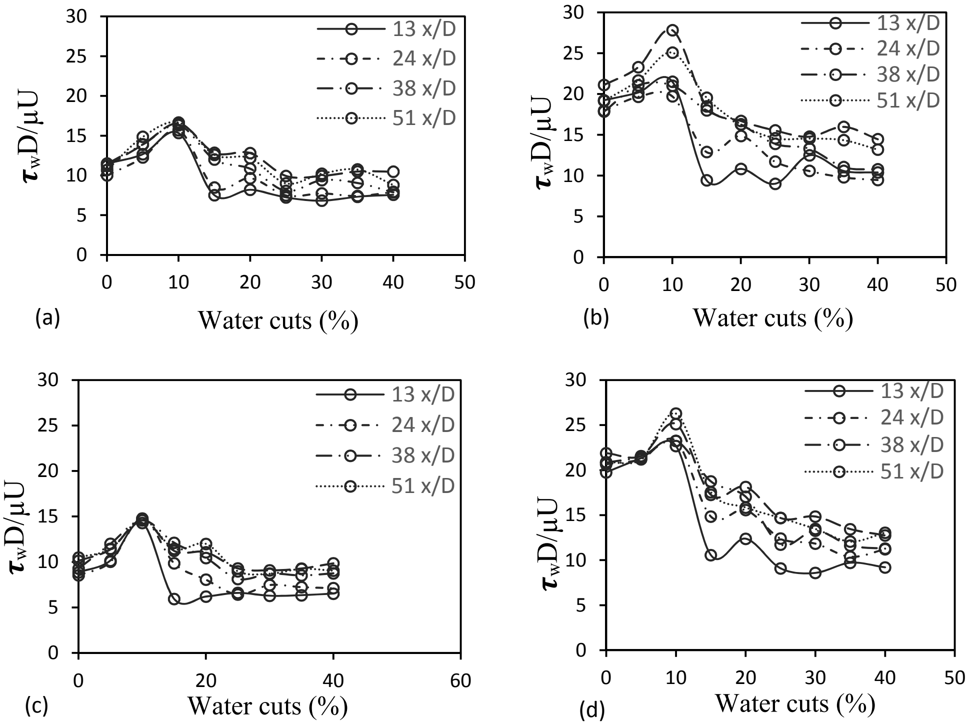



**Fig. 5. Normalized $\tau_w$ versus water cuts for pipeline constriction (a) GC 0.50 (b) GC 0.75 (c) SC 0.50 and (d) SC 0.75 (Laminar flow inlet).**

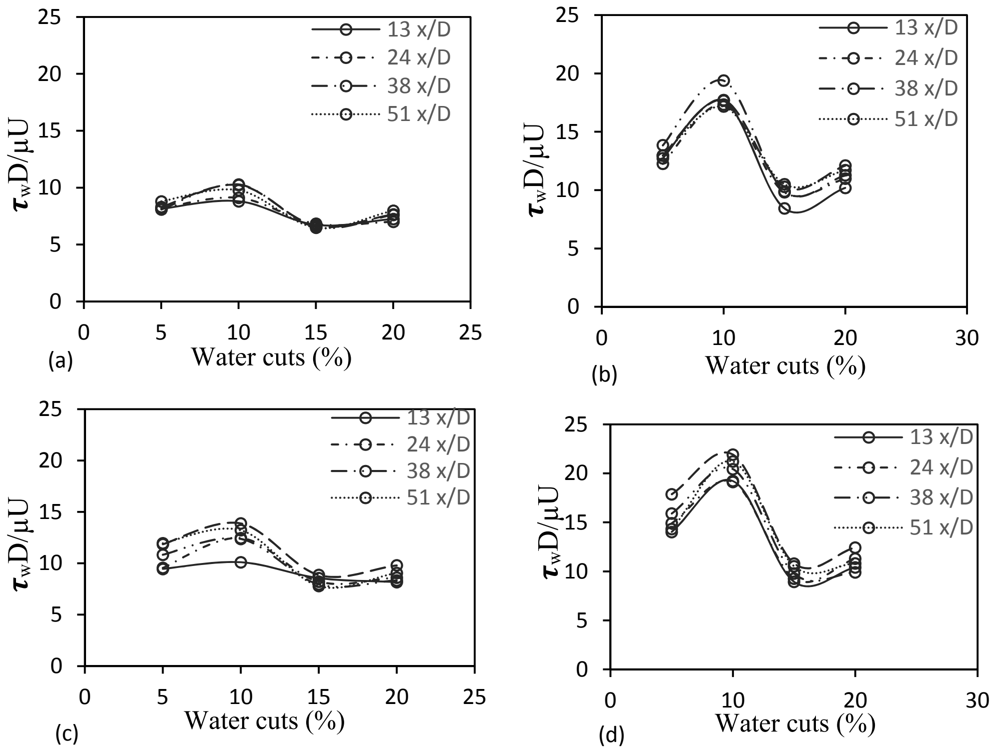



**Fig. 6. Normalized $\tau_w$ versus water cuts for pipeline constriction (a) GC 0.50 (b) GC 0.75 (c) SC 0.50 and (d) SC 0.75 (Transitional flow inlet).**

However, beyond 10% WC, the results show that the $\tau_w$ decreases with the increase in the water cuts for both the laminar inlet flow and transitional inlet flow. This is due to the drag reduction effect as a result of the presence of significant amounts of W/O emulsions in the flow. Drag reduction phenomenon caused by W/O emulsions has been reported elsewhere (Omer 2009) (Haegh and Ellingsen 1977). The drag reduction phenomenon is believed to be caused by the suppression of turbulence as a result of dynamic break-up and coalescence of the dispersed droplets in the flow. The obtained results suggest that as the water cuts reaches beyond 10%, the amount of dispersed water droplets (emulsions) in the flow is sufficient to cause a significant effect on the turbulence suppression. As the water cuts increases, the amount of emulsions formed similarly increases. As a result of that, there are more dispersed water droplets to interact and suppress the turbulent eddies created at the pipeline constriction and this resulted in a higher degree of turbulence suppression. With the increase in the turbulence suppression, the drag reduction is more profound as well. Therefore, the $\tau_w$ decreases as the water cuts increase beyond 10%.

### 3.2 Effect of Reynolds Number

Figure 7 show that the $\tau_w$ is lower in the transitional inlet flow (higher Reynolds number) as compared to laminar inlet flow (lower Reynolds number). This finding is observed in all types of pipeline constrictions and water cuts under examination.

Transitional inlet flow results in lower $\tau_w$ than the laminar inlet flow is owing to the difference in the amount of energy in the flowing fluid. At a higher flow rate, there is more energy in the flow. As a result of that, emulsions are dispersed into smaller droplets as more energy is used for the dispersion of emulsions. In order to discover the role of energy in the emulsification behaviour in the respective flow regime (laminar and transitional inlet flow), the dissipation energy is examined. Previous studies (Johnsen and Rønningsen 2003) (Abiev and Vasilev 2016) (Walsh 2016) have indicated the use of dissipation energy as the source of energy for the emulsification process. The dissipation energy rate is calculated using Eq. (4) (Walsh 2016).

$$\varepsilon = 2f\frac{U^3}{D} \qquad (4)$$

Figure 8 compares the dissipation energy rate calculated for both the laminar and transitional flow inlet with respect to water cuts downstream the pipeline constriction. From Fig. 8, it is shown the dissipation energy rate of transitional inlet flow (higher flow rate) is higher than that of the laminar inlet flow (lower flow rate). Higher dissipation energy rate indicates that at higher flow rate, there is a higher rate of interaction in between the dissipation eddies and the water droplets. Since energy is dissipated through turbulent eddies, during the dissipation action, the turbulent eddies interact with the water and shear them into smaller droplets. Previous study (Walsh 2016) has stated that small-scale eddies in the flow are responsible for the dispersion of emulsions into finer droplets. At higher flow rate, there are more turbulence eddies created at the constriction owing to the more turbulent flow as a result of higher flow rate. As a direct consequence of that, there is more interaction (shearing) in between the emulsions and the turbulence eddies during the dissipation action. Consequently, the emulsions are broken into finer droplets in the higher flow rate.

Decrease in droplets size with the increase in dissipation energy also has been reported elsewhere (Gomaa *et al*. 2014). Study had revealed that the emulsion friction factor was reduced due to the reduction in the average dispersed phase droplet size of the emulsion (Al-Yaari *et al*. 2014) (Gong 2010). This indicates that friction factor is directly correlated to the dispersed droplet size.

From the above discussion, it is clear that higher flow rate results in dispersed droplets of finer size as compared to the one from lower flow rate owing to the higher dissipation energy rate. With finer dispersed droplets size, the friction factor is lower, which eventually results in lower $\tau_w$. This explains the lower $\tau_w$ in transitional inlet flow (higher flow rate) as compared to the laminar inlet flow (lower flow rate).

Figure 9 compares the $\tau_w$ results from different types of pipeline constrictions for laminar inlet flow ($1100 < Re < 1800$) and transitional inlet flow ($2400 < Re < 2800$). The result shows that the effect of the geometry of constriction, which are gradual contraction and sudden contraction on $\tau_w$, is less significant. However, it is observed that sudden contraction gives slightly higher $\tau_w$. On the other hand, the effect of contraction ratio, which are contraction ratios of 0.50 and 0.75, shows a noteworthy influence on the $\tau_w$. Flowing fluid through the pipeline constriction with a contraction ratio of 0.75 is shown to exhibit higher $\tau_w$ as compared to the one of contraction ratio of 0.50. Fluid flowing through a pipeline constriction of smaller diameter (contraction ratio 0.50) results in higher $\tau_w$ is due to higher shear rate in the pipeline constriction with smaller diameter. Al-Yaari *et. al.* (2014) stated that given the same Reynolds number, the shear rate in a pipe with half a diameter of another pipe is four times higher than the pipe with bigger size. As a result of higher shear in the constriction of smaller diameter, the water dispersed droplets are broken into smaller size owing to higher shearing rate. With the presence of smaller dispersed water droplets produced from the pipeline constriction of smaller diameter, the friction factor is lower. Hence, this resulted in the lower $\tau_w$ in the pipeline with contraction ratio of 0.50.

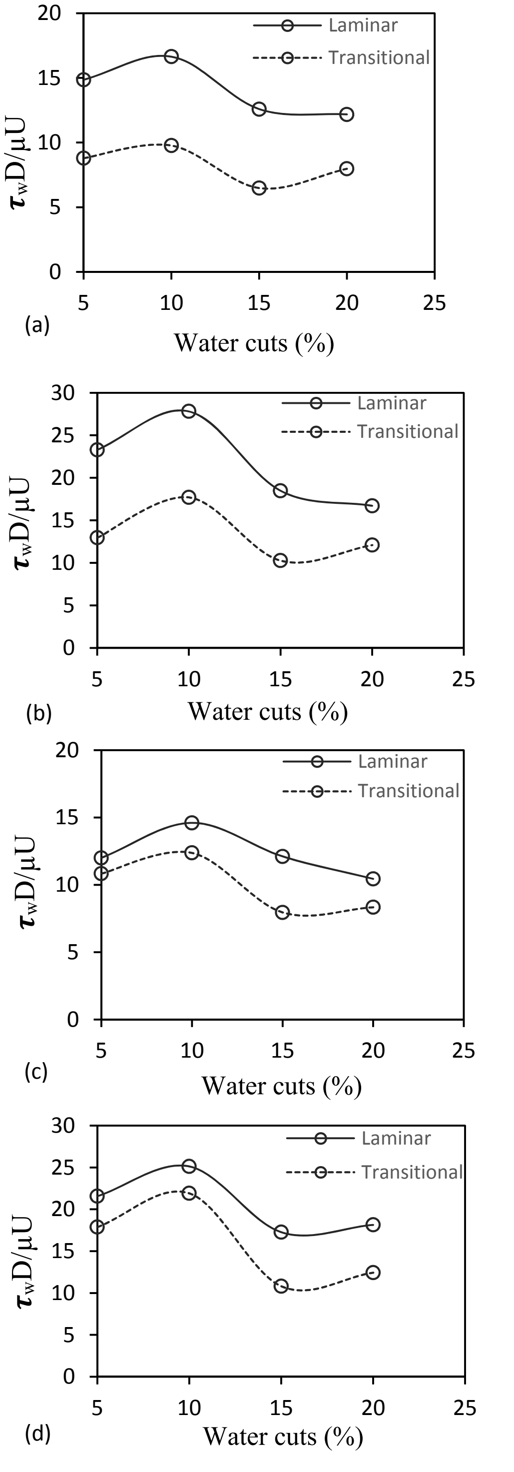



**Fig. 7. Normalized $\tau_w$ versus water cuts at different flow regime for pipeline constriction (a) GC 0.50 (b) GC 0.75 (c) SC 0.50 and (d) SC 0.75.**

### 3.3 Effect of Types of Pipeline Constriction

As mentioned above, pipeline with the sudden contraction shows higher $\tau_w$ than the gradual pipeline contraction. The sudden constriction pipeline is expected to have a higher energy loss than the gradual constriction pipeline. Higher energy loss to the flow indicates that more energy is available for the formation of emulsions. As a result of that, more emulsions are formed through the sudden constriction pipeline as compared to the gradual constriction pipeline. Collision among

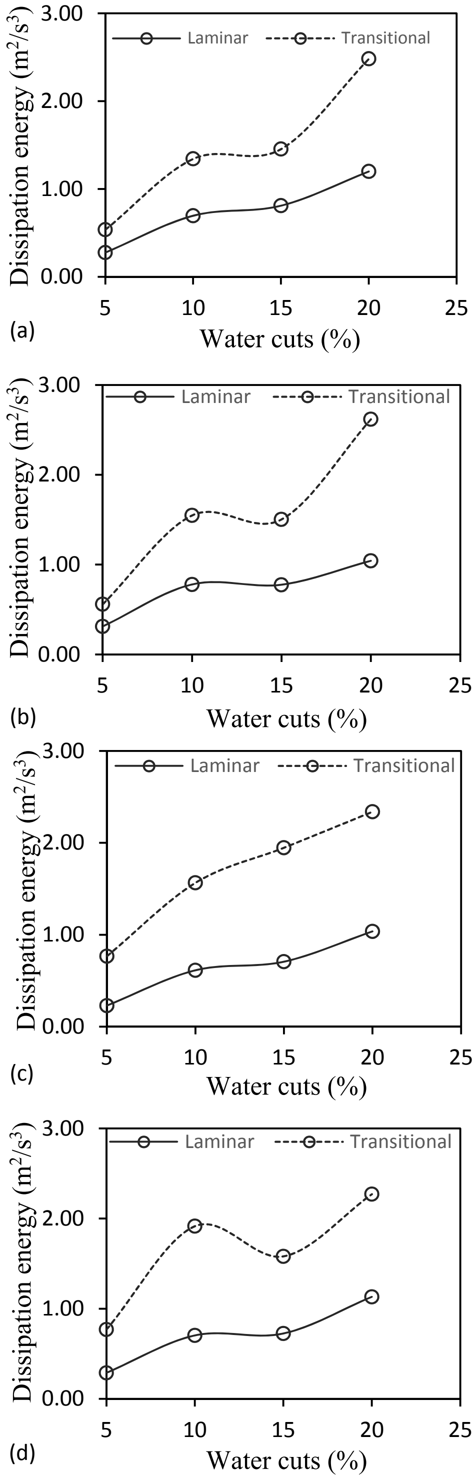



**Fig. 8. Dissipation energy as a function of water cuts at different flow regime for pipeline constriction (a) GC 0.50 (b) GC 0.75 (c) SC 0.50 and (d) SC 0.75.**

droplets as well as with the pipeline wall will exert shear on one another. Thus, with the presence of more emulsions in sudden constriction pipeline, the collision rate is increased, leading to an increase in the shear (increase in the friction) and resulting in a higher $\tau_w$.

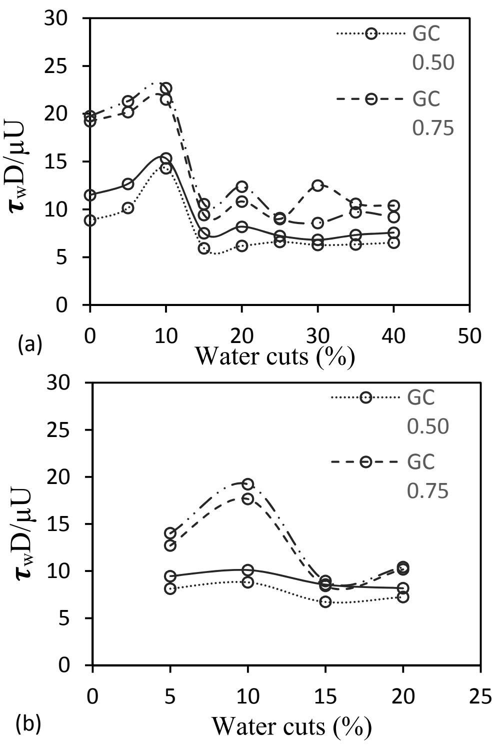



**Fig. 9. $\tau_w$ subject to various type pipeline constrictions for (a) laminar flow inlet and (b) transitional flow inlet.**

### 3.4 Changes of wall shear stress along the pipeline

Figure 10 depicts the changes of $\tau_w$ along the pipeline (increase in the length of the pipeline) after the pipeline constriction for laminar inlet flow (1100 < *Re* < 1800) and transitional inlet flow (2400 < *Re* < 2800). The measurement locations after the pipeline constriction were at 13 *x/D*, 24 *x/D*, 38 *x/D*, 51 *x/D* and 63 *x/D* along the horizontal pipeline. The results demonstrate that $\tau_w$ increases with the increase in the pipe length after the pipeline constriction, for both laminar and transitional inlet flow.

The increase in $\tau_w$ with the increase in the pipe length downstream the pipeline constriction is due to the increase in the average dispersed water droplets (emulsions) size. In this study, the pipeline constriction acts as the dispersing zone for the emulsification process, where water is dispersed into small dispersed water droplets forming the W/O emulsions. It has been stated that the emulsions are at its finest size right after the dispersing zone (Karbstein and Schubert 1995). This means that the emulsions formed right after the pipeline constriction are at its smallest size as the pipeline constriction is the dispersing zone in this study.

According to Jafari *et. al.* (2008), the newly formed emulsions are thermodynamically unstable and the interface of emulsions is not completely covered by emulsifier molecules, where these conditions lead to re-coalescence of the dispersed droplets. Tjaberinga *et. al.* (1993) stated that the coalescence possibility is very low in the dispersing zone of an emulsification equipment as a result of longer continuous phase liquid drainage time in the contact region between the two colliding droplets (film drainage) than with the contact time between these droplets upon collision. Coalescence may occur as the dispersed droplets leave the dispersing zone due to the increase in contact time (Karbstein and Schubert 1995).

Since the newly formed emulsions are thermodynamically unstable tending to re-coalesce and re-coalesce probability is based on the contact time and as well as the film drainage time, the dispersed water droplets leaving the pipeline constriction (dispersing zone in this study) most likely will re-coalesce. This is because with the increase in the length of the pipeline after the constriction, the contact time of the dispersed water droplets is increased upon collision among the droplets. With the increase in the contact time of dispersed water droplets during collision, they are re-coalesced as one and formed a larger droplet due to the contact time exceeding the liquid drainage time. In other words, increase of contact time between the droplets that collide with one another allowing the droplets to have sufficient time to break the thin film that is separating them and thereafter resulting in the re-coalescence of the collided droplets. Thus, with the increase in the pipe length after the pipeline constriction (dispersing zone), which is from 13 *x/D* to 63 *x/D*, the contact time of the dispersed droplets increased. This leads to re-coalescence of the dispersed droplets along the way down the pipeline. As a result of that, the average dispersed droplets size increases with the increase in the pipe length.

The total surface area of dispersed water droplets (emulsions) is a function of the diameter of the dispersed droplets (Karbstein and Schubert 1995). With the increase in the average dispersed droplets size, the total surface area of dispersed water droplets is decreased. The decrease of the total surface area of dispersed water droplets with the same amount of input energy (same shear force) will lead to an increase in the shear stress. Therefore, $\tau_w$ increases as the fluid flows from 13 *x/D* to 63 *x/D* in the pipeline.

## 4. CONCLUSION

A few major findings are determined from this study. First, for water cuts of 0 to 40% (laminar inlet flow) and 5 to 20% (transitional inlet flow), the maximum $\tau_w$ is found to be at 10% water cuts for both the laminar and transitional flow. Beyond 10%

water cuts, the emulsions exhibit drag-reducing behaviour. Next, for the study on the effect of Reynolds number, it is determined that the higher Reynolds number results in lower $\tau_w$. Furthermore, for the effect of pipeline constriction, it is determined that pipeline constriction with contraction ratio of 0.75 results in higher $\tau_w$ than the contraction ratio of 0.50 and sudden constriction results in higher $\tau_w$ than the gradual constriction for both the laminar and transitional inlet flow. Lastly, the $\tau_w$ is determined to have increased with the increase in the length of the pipeline downstream the pipeline constriction, for both laminar and transitional inlet flow.

In conclusion, the results obtained from this research study enable the oil industry to provide a better strategy in treating the emulsification phenomena in the pipeline transportation system. From this study, it is recommended that the crude oil be delivered at a higher Reynolds number. Pipeline constrictions used in this study, which serves to replicate the usage of choke valves in the oil and gas industry, have shown that gradual constriction with contraction ratio of 0.50 (GC 0.50) is the best amongst the four different types of constrictions used for comparison. Higher Reynolds number and pipeline constriction type GC 0.50 are suggested to be used because they result in the lowest wall shear stress. Lower wall shear stress is desirable because lower wall shear stress indicates lower friction in the flow and therefore pressure drop in the flow can be reduced. This helps in minimizing the energy losses during the transportation of crude in the pipeline.

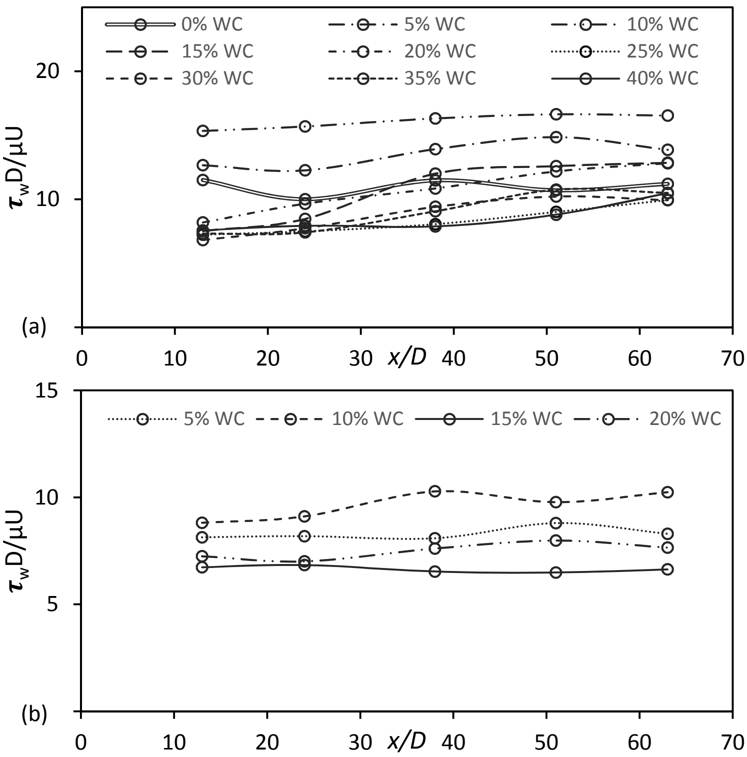



**Fig. 10. Changes of $\tau_w$ along the downstream of pipeline constriction for laminar flow inlet and (b) transitional flow inlet.**

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