Turbulence Characteristics Study of the Emulsified Flow

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Abstract: - The presence of emulsions brings numerous undesirable effects to the oil and gas industry; it affects the flow regimes and flow behavior in the pipeline, reduces the quality of crude oil, requires longer retention time in the separation vessels, causes corrosion to the transport system, contaminates catalyst used in the refining process that leads to huge economic losses. The formation of emulsions; dynamic break-up and coalescence of the dispersed droplets tend to diminish the turbulence in the flow. This suggests that turbulence is consumed during the emulsification process. The turbulence characteristics of the water-oil emulsions flow in the pipeline are examined and discussed. The Reynolds stress and turbulence intensity analysis show that turbulence activities and transport influence the formation of emulsions and it is induced from the constriction of pipeline. The largest amount of fluctuating components are observed nearest to the constriction and the turbulence is diminishing as the flow flows further away from the constriction. This research work enables the oil industry to provide a better strategy in treating the emulsification phenomena in the pipeline transportation system.

Key-Words: - constrictions, crude oil, emulsions, Reynolds stress, turbulent intensity, UVP, water cuts

1 Introduction

In the oil and gas industry, emulsification in the pipeline flow is unavoidable as crude oil usually comes together with water from the reservoir. Crude oil must pass through different processes before it is processed and refined into more useful products such as gasoline, petroleum, liquefied petroleum gas, lubricating oil, asphalt, paraffin wax, diesel fuel and bitumen. Throughout all these processes, the agitation, mixing as well as the turbulence energy formed through downhole wellbores, surface chokes, valves, pumps, and pipes will directly lead to the formation of emulsion in the crude oil flow [1].

The formation of emulsions is undesirable in the oil and gas industry because emulsification brings a number of problems; it affects the flow regimes and flow behaviour, reduces the crude oil's quality, occupies a volume in the pipeline, reduces the mass flow rate, requires longer retention time in the separation vessels, causes corrosion to the transport system, contaminates catalyst used in the refining process and increases operating cost. It has been discovered that the presence of emulsions also can affect the friction factor of the flow, as well as the viscosity of the mixture and pressure drop along the pipeline [2-4].

Wong et al. [5] carried out a study on the characteristics of the water-in-oil (W/O) emulsions in order to develop a better understanding on the W/O emulsions. Three parameters, namely, water cuts (WC), Reynolds number and pipeline constrictions were studied. The study on the stability of W/O emulsions of different controlling parameters shows that, with the increase in the water cuts, the stability of the emulsions is increased and with the increase in the Reynolds number, the stability of emulsions is increased. From the study of the stability of W/O emulsions, it is concluded that the stability of the emulsions increases with the increase in the water cuts and Reynolds number.

Dol et al. [6] did an experimental study on the effects of W/O emulsions in the pipeline flow 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. From this study, it is recommended the crude oil be delivered at a higher Reynolds number. 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.

With reference to these findings, it is known that the emulsified flow or formation of emulsions in the pipeline is closely related to turbulence. However, the roles of turbulent flow generated in the pipeline in emulsification process has not yet been understood. Hence, further investigation and additional analysis are needed to confirm the turbulence activities in the emulsified pipeline flow.

Therefore, this paper will discuss the turbulence characteristics of the water-oil emulsions flow in order to have a better understanding on the roles of turbulence in the formation of emulsion in the pipeline flow. The turbulence characteristics of the water-oil emulsions flow in the pipeline are examined and discussed through the analysis of Reynolds stress and turbulence intensity of the flow field. This will then broadly contribute to the transportation of crude, *i.e.* with less emulsions formation, as the energy for the formation of emulsions can be controlled accordingly with the understanding on the roles of turbulence activities in the emulsification process.

This study investigates the influence of the water cuts (WC) ranging from 0 to 40%, 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 Methodology

2.1 Crude oil

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

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.

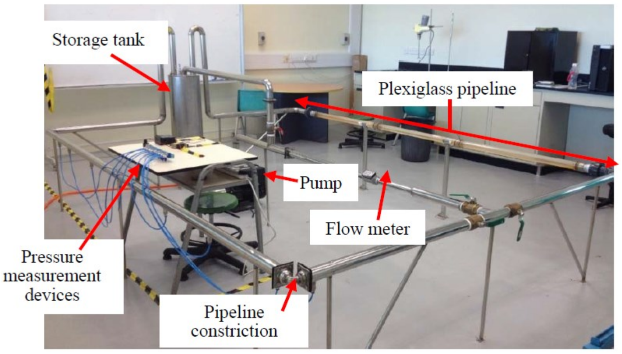

Fig. 1. Actual photo of the flow rig.

2.3 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 [6]. 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.

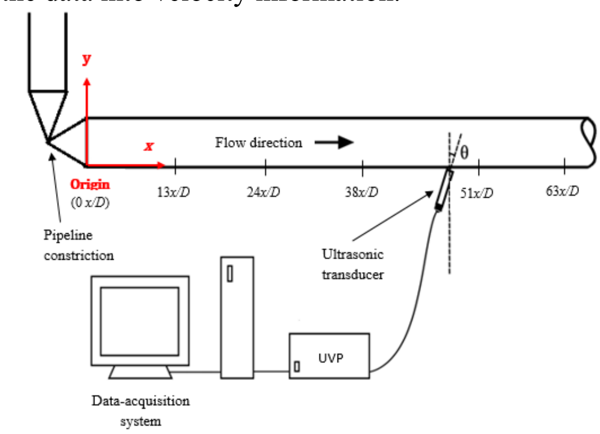

Fig. 2. Schematic diagram of the experimental setup for velocity measurement.

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 location 13 *x/D* to 63 *x/D* (as shown in Fig. 2). To obtain the streamwise velocity gradient ($\frac{\partial U}{\partial X}$), the velocity 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*).

2.4 Reynolds stress

Reynolds stress is one of the important characteristics in the study of turbulence activities. It is the shear generated in the fluctuating component of the flow and as has been known, shear is one of the important sources in producing turbulence. With reference to the Turbulent Kinetic Energy Budget, the Reynolds stress ($\overline{u_i u_j}$) term appears at the "loss to turbulence" term of mean kinetic energy equation and shear production term of turbulent kinetic energy equation. This shows the significant contribution of Reynolds stress to the transfer and production of turbulent energy in the flow. The Reynolds stress analysis in this study will bring to an understanding on the transport of momentum due to the velocity fluctuation in the flow as a result of the pipeline constriction effect and also the W/O emulsions effects. The Reynolds stress in this study is presented in its normalized form. It is normalized by the averaged streamwise velocity of the flow, giving the normalized Reynolds stress - the $\frac{\overline{u'u'}}{U^2}$.

2.5 Turbulent intensity

Turbulence intensity analysis is used for the study of the turbulence characteristics of emulsified flow because it is a measure used for characterizing the turbulence level in term of percentage. In other words, turbulence intensity allows one to examine the turbulence level in the flow statistically. In this study, turbulence intensity is used to examine the fluctuations of the streamwise velocity component. A larger turbulence intensity indicates a higher turbulence level and vice versa. In the present work, the turbulence intensity is calculated using

$$\text{Turbulence intensity} = \frac{u'}{\overline{U}} \qquad (1)$$

where u' stands for root-mean-square of turbulent velocity fluctuation and $\overline{U}$ stands for the averaged streamwise mean velocity.

In this section, the turbulence intensity along the pipeline (increase in the pipe length) after the pipeline constriction and the turbulence intensity with respect to different water cuts are compared and discussed. The purpose is to understand the correlation in between the turbulence level of the flow with the emulsification behaviour as well as to confirm the proclamation made in the previous findings of [6] – an increase in water cuts leads to drag-reduction effect as a result of turbulence diminishing by the presence of emulsions, thereby resulted in the decrease of wall shear stress, τ_w.

3 Results and Discussions

3.1 Reynolds stress comparisons along the pipeline

Figure 3 (a) and (b) to Fig. 7 (a) and (b) present the normalized Reynolds stress ($\frac{\overline{u'u'}}{U^2}$) from the pipeline constriction type GC 0.50 at the pipeline location of 13 *x/D* and 63 *x/D* respectively, for 0 to 40% WC. The $\frac{\overline{u'u'}}{U^2}$ profiles for pipeline constrictions of GC 0.75, SC 0.50 and SC 0.75 show about the same profiles.

From these figures, it is determined that the $\frac{\overline{u'u'}}{U^2}$ peak region at the location 13 *x/D* downstream the pipeline constriction is larger than that at 63 *x/D*. As shown in Fig. 3 (a) to Fig. 7 (a), the $\frac{\overline{u'u'}}{U^2}$ peak region for 0%, 10%, 20%, 30% and 40% WC covers about 0.35, 0.20, 0.45, 0.40 and 0.25 of the pipe radius (*y/R*) at the pipeline location of 13 *x/D*. As the fluid flows further downstream to location 63 *x/D* of the pipeline (increase in the pipe length), the results show that the $\frac{\overline{u'u'}}{U^2}$ peak region for 0 %, 10%, 20%, 30% and 40% WC reduces to 0.25, 0.15, 0.30, 0.10 and 0.10 *y/R*, respectively (as shown in Fig. 3 (b) to Fig. 7 (b)). This indicates that nearest to the pipeline constriction, the transport of momentum in the pipe that governs by the fluctuating components cover a larger cross-sectional area of the pipe since the $\frac{\overline{u'u'}}{U^2}$ peak region is larger. Further downstream the pipeline, the fluctuating components governs a smaller cross-sectional area of the pipe governs for the momentum transport. Only the flow near to the pipeline wall (*y/R* = 0) shows a significant momentum transport by the fluctuating component. This indicates that further downstream, the transport of flow is mostly governed by the main flow. With reference to these observations, it is understood that the fluctuating components are most energetic at the location nearest to the constriction of the pipeline (13 *x/D*) and weaken with the increase in the pipe length. This suggests that the pipeline constriction is the source of turbulence production, where the largest amount of fluctuating components are observed there.

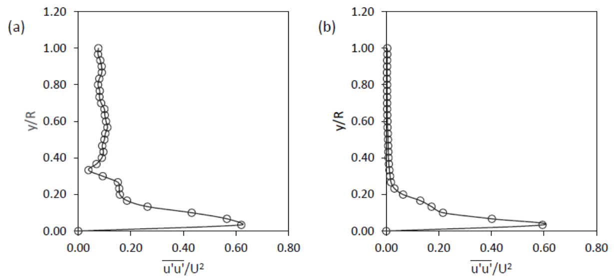

Fig. 3. The $\overline{u'u'}/U^2$ profile at location (a) 13 *x/D* and (b) 63 *x/D* for pure crude after the pipeline constriction type GC 0.50.

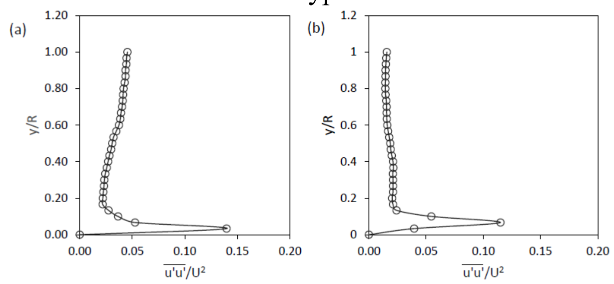

Fig. 4. The $\overline{u'u'}/U^2$ profile at location (a) 13 *x/D* and (b) 63 *x/D* for 10% WC after the pipeline constriction type GC 0.50.

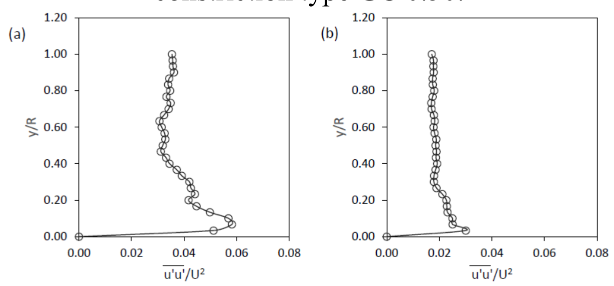

Fig. 5. The $\overline{u'u'}/U^2$ profile at location (a) 13 *x/D* and (b) 63 *x/D* for 20% WC after the pipeline constriction type GC 0.50.

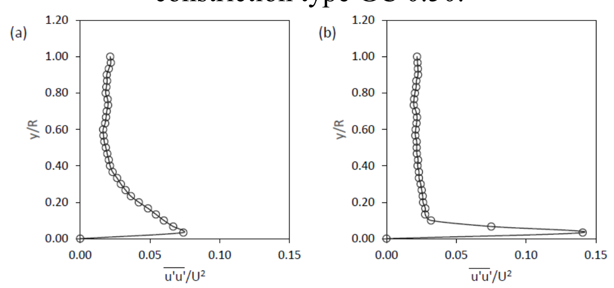

Fig. 6. The $\overline{u'u'}/U^2$ profile at location (a) 13 *x/D* and (b) 63 *x/D* for 30% WC after the pipeline constriction type GC 0.50.

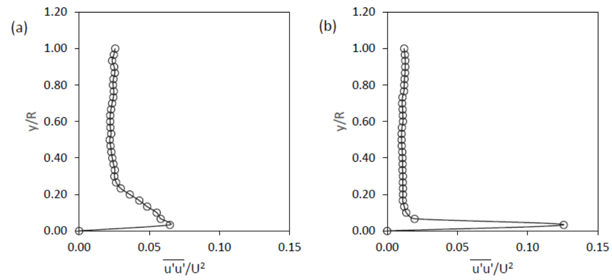

Fig. 7. The $\overline{u'u'}/U^2$ profile at location (a) 13 *x/D* and (b) 63 *x/D* for 40% WC after the pipeline constriction type GC 0.50.

The $\frac{\overline{u'u'}}{U^2}$ results also show that as the water cuts increases, the momentum transfer due to velocity fluctuation components is reduced. Likewise, the fluctuating components become less energetic as the water cuts increases. It has been extensively reported that turbulence suppression is one of the main factors that leads to the decrease in Reynolds stress [7 and 8]. Lower Reynolds stress indicates that there is less momentum transfer. This is because fluctuating velocity components in the turbulent flow induces lesser kinetic energy. Since the results show that the $\frac{\overline{u'u'}}{U^2}$ decreases with the increase in water cuts, it is logical to suggest that the presence of emulsions is able to suppress the velocity fluctuation in the flow. Since turbulence is due to the fluctuation of the velocity component in the flow and emulsions are capable of suppressing the fluctuation, therefore increase in the water cuts (increase in emulsions) will directly lead to the diminishing of turbulence.

3.2 Turbulent intensity comparisons along the pipeline

Figure 8 (a) and (b) to Fig. 15 (a) and (b) present the distribution of streamwise turbulence intensity ($\frac{u'}{\overline{U}}$) from the pipeline constriction type GC 0.50 at pipeline location of 13 *x/D* and 63 *x/D*, for 0 to 40% WC respectively. The streamwise $\frac{u'}{\overline{U}}$ profiles for pipeline constrictions of GC 0.75, SC 0.50 and SC 0.75 show similar profiles.

From Fig. 8 to Fig. 15, it is observed that the streamwise $\frac{u'}{\overline{U}}$ peak region (fluctuation region) at pipeline location 13 *x/D* downstream the constriction is larger than that at the 63 *x/D* downstream constriction. For pure crude, it is determined that the streamwise $\frac{u'}{\overline{U}}$ peak region reduces from 0.35 to 0.25 of the pipe radius (*y/R*) as the flow flows from 13 *x/D* to 63 *x/D*. For emulsified flow with 10%, 15%, 20%, 25%, 30%, 35% and 40% WC, the results show that the $\frac{u'}{\overline{U}}$ peak region reduces from 0.20 to 0.15 *y/R*, 0.35

to 0.25 *y/R*, 0.40 to 0.25 *y/R*, 0.40 to 0.10 *y/R*, 0.40 to 0.10 *y/R*, 0.40 to 0.05 *y/R* and 0.30 to 0.10 *y/R*, respectively.

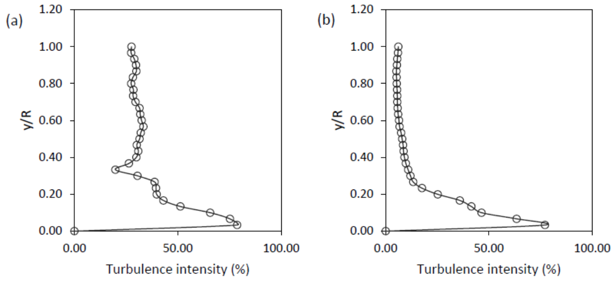

Fig. 8. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 0% WC after the pipeline constriction type GC 0.50.

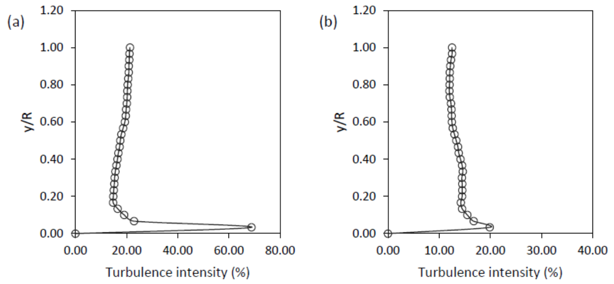

Fig. 9. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 10% WC after the pipeline constriction type GC 0.50.

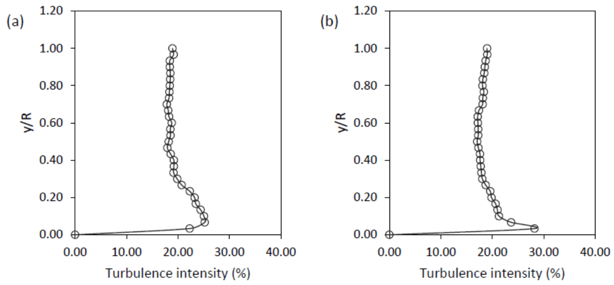

Fig. 10. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 15% WC after the pipeline constriction type GC 0.50.

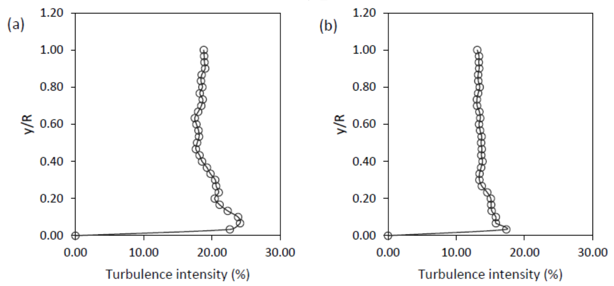

Fig. 11. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 20% WC after the pipeline constriction type GC 0.50.

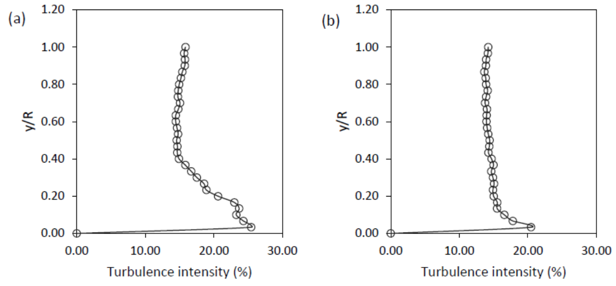

Fig. 12. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 25% WC after the pipeline constriction type GC 0.50.

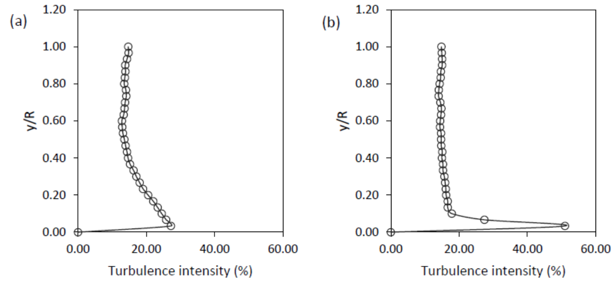

Fig. 13. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 30% WC after the pipeline constriction type GC 0.50.

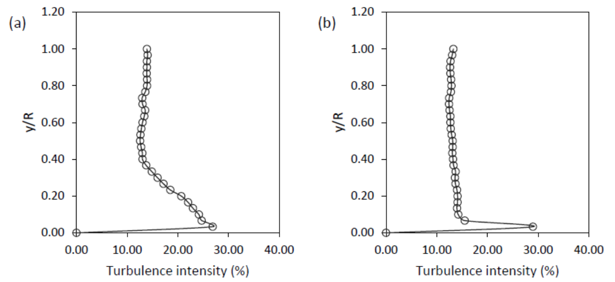

Fig. 14. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 35% WC after the pipeline constriction type GC 0.50.

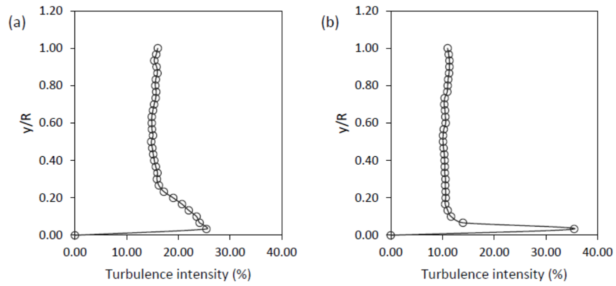

Fig. 15. Streamwise $u'/\overline{U}$ distribution at (a) 13 *x/D* (b) 63 *x/D* for 40% WC after the pipeline constriction type GC 0.50.

The reduction in the streamwise $\frac{u'}{\overline{U}}$ fluctuation region as the flow flows further downstream indicates that the turbulence in the flow is diminished. Since the damping of streamwise $\frac{u'}{\bar{U}}$ is observed in both the pure crude and emulsified flow, the result in this section is unable to prove that turbulence in the flow is consumed for the formation of emulsions. However, the results do suggest that turbulence is induced at the constriction of the pipeline. This is because the results show that the streamwise $\frac{u'}{\bar{U}}$ fluctuation region is larger at 13 *x/D*, where this location is the nearest to the constriction of the pipeline.

The results also show that the maximum streamwise turbulence intensity decreases with the increase in the water cuts from 0% to 40%. With the increase in water cuts from 0% to 40%, the maximum streamwise turbulence intensity decreases from 100% to about 25% only. The decrease in the maximum streamwise turbulence intensities with the increase in water cuts indicates that the turbulence level in the flow with higher water cuts is lower. This is because at higher water cuts, the amounts of emulsions formed are higher as well. As a result of that, the frequency of emulsion-emulsion collision is increased due to the increase in the compactness of the emulsions in the flow.

This is supported by [9] whose report has stated that the intensive exchange of momentum between the particles during the particle-particle collisions will lead to the proximity of their velocities, resulting in the decrease of the velocity fluctuation. This means that an increase in the water cuts (amount of emulsions) will lead to the decrease in the velocity fluctuation owing to more exchange of momentum between the emulsions. Thus, the turbulence level in the flow reduces with the increase in the input of water cuts, as presented by the results shown here. The results suggest that the presence of emulsions diminishes the turbulence in the flow. As a result of diminishing in turbulence, drag in the flow is reduced, leading to a drag the reduction effect with the increase in the water cuts. This has confirmed the discussion in [6] that the drag reduction phenomenon is caused by the diminishing in turbulence due to the presence of emulsions.

5 Conclusion

In order to confirm the postulation made in the previous findings that turbulence is diminished with the increase in the water cuts (increase in the amount of emulsions), this chapter has investigated the turbulence characteristics statistically. The normalized Reynolds stress ($\frac{\overline{u'w'}}{U^2}$) and the streamwise turbulence intensity ($\frac{u'}{\bar{U}}$) are analyzed. The results presented here provide an insight into the roles or contribution of turbulence in the emulsification process. Through the examination on the $\frac{\overline{u'w'}}{U^2}$ and $\frac{u'}{\bar{U}}$, it has been demonstrated that the turbulence is the source for the formation of emulsions and turbulence is induced from the constriction of pipeline.

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