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Simulation of Drag Reducing Polymers for Single and Two Phase Flow in Horizontal Pipe

Simulasi Penggunaan *Drag Reducing Polymers* untuk Aliran Fluida Satu Fasa dan Dua Fasa dalam Pipa Horizontal

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Abstract

Drag reducing polymers is one of the drag reducer types that is widely used in industry as an additive to improve fluid flow efficiency in pipes. This study is conducted to analyze the parameters that influence the efficiency of drag reducing polymers through developing equation model, and to observe the phenomenon of drag reduction that occurs in fluid flow through computational fluid dynamic simulation. The data used in this study are obtained from a set of experimental data for a single-phase flow of liquid and three sets of experimental data for annular two phase flow of gas-liquid in horizontal pipe. Each parameter, such as fluid velocity and pipe diameter, is analyzed based on the model equations proposed in this study. Based on the calculation results the final single phase flow equation model is obtained, which gives a value for onset drag reduction of 4.00 with an error up to 18%. Meanwhile, the proposed annular flow equation is suitable only when the condition of fluid film distribution is uniform and symmetrical with the error of around 20%, which is for smaller diameter pipes. The computational fluid dynamic simulation results show change of fluid velocity profiles to be more parabolic. This is because of an increase of the mean fluid velocity of up to 0.43%, as the effect of adding drag reducing polymers.

Keywords: single-phase flow, two-phase flow, annular, horizontal, drag reducing polymers

Abstrak

*Drag reducing polymer*s merupakan salah satu jenis pengurang hambatan yang banyak digunakan industri sebagai aditif untuk meningkatkan efisiensi aliran fluida dalam pipa. Penelitian ini dilakukan untuk menganalisis parameter yang berpengaruh terhadap efisiensi *drag reducing polymers,* yaitu melalui penurunan model persamaan, serta untuk mengobservasi fenomena yang terjadi pada aliran fluida melalui simulasi dinamika fluida komputasi. Data yang digunakan dalam simulasi ini berasal dari satu set data eksperimen untuk aliran fluida satu fasa dalam bentuk cair dan tiga set data eksperimen untuk aliran fluida anular dua fasa gas-cair dalam pipa horizontal. Masing-masing parameter, yaitu kecepatan fluida dan diameter pipa, dianalisis berdasarkan persamaan model yang diajukan di studi ini. Berdasarkan hasil perhitungan diperoleh model akhir persamaan aliran satu fasa dengan nilai untuk faktor *onset drag reduction* sebesar 4,00 dan menghasilkan tingkat kesalahan hingga 18%. Sedangkan persamaan aliran *annular* dua fasa yang diajukan hanya sesuai untuk kondisi distribusi film cairan yang seragam dan simetris dengan tingkat kesalahan sekitar 20%, yaitu pada pipa dengan diameter yang lebih kecil. Hasil simulasi dinamika fluida komputasi menunjukkan perubahan profil kecepatan fluida menjadi lebih parabolik. Hal ini dikarenakan bertambahnya rata-rata kecepatan keluaran fluida hingga 0,43% sebagai efek dari penambahan *drag reducing polymers*.

Kata kunci: aliran satu fasa, aliran dua fasa gas-cair, anular, horizontal, *drag reducing polymers*

1. Introduction

One of the risks in transporting fluid to a very far place is the increase of pressure drop. Pressure drop is a form of loss in fluid transportation that may occur because of low efficiency of the pump, number of fittings in piping, elevations, as well as the friction between the fluids and the pipe itself. High pressure drop causes the throughput of the pipe to be not optimal.

One of the options to handle the pressure drop in a fluid flow is by adding small amount of additive to fluid flow to facilitate turbulency of the flow. This additive is known as drag reducing agents (DRA). In turbulent flow, the fluid is moving in chaotic random motion. The addition of DRA in the flow can slow down the generation of eddies as well as reduce the frequency and the rotation rate of vortex.

The advantages of DRA application in flow systems are enormous. It has the ability to increase the pipeline system capacity as well as to reduce pumping energy, pressure loss, pipe diameter, pipe thickness, heat transfer rates in turbulent mixing, and pipe erosion. (Edomwonyi-Otu *et al.*, 2013). These benefits of DRA lead to its application in various fields, such as in long distance fluid transport with pipeline, domestic heating and cooling, petroleum loading and offloading, pipeline corrosion inhibition, well drilling and hydraulic fracturing operations, water supply, irrigation and hydropower systems as anti-misting agents in jet fuels and tanks, sewage systems and in the transportation of suspensions and slurries, etc.

The chemical agents that reduce the drag effects are particulary divided into five categories: polymers, surfactans, fibres, micro bubbles and compliant coating. In industrial application, polymers as DRA are widely used because of economic reasons as they can reduce the drag effect up to 80% (Abubakar *et al*., 2014). Polymers as DRA are commonly known as Drag Reducing Polymers (DRPs) and it has been found that the addition of very small amount (parts per million) of polymers can significantly reduce pressure drop because of frictional drag (Edomwonyi-Otu *et al*., 2015).

Application of DRPs that provides economic impact was first carried out on the 1300 km Trans-Alaska pipeline, with 10 ppm of oil-soluble polymer which helps to increase the throughput significantly up to 200000 bbl/day as the result of 50% reduction of pressure drop (Edomwonyi-Otu *et al.*, 2013). This bigger capacity was achieved without adding two pumping stations as suggested in the initial scenario. Since then, DRA have been used in many petroleum product pipelines, such as in the Bass Strait in Australia, Mumbai Offshore, Iraq-Turkey oil pipeline and in Oseberg Field in the North Sea amongst others (Abdulbari *et al*., 2014).

Some studies conclude that the effectiveness of DRA performance is affected by many factors, such as oil viscosity, pipe diameter, gas and liquid velocities, oil composition, water cut, pipe inclination, DRA concentration, type of DRA and shear degradation of the DRA (Al-Amri *et al*., 2014). Thus, there are various objects to be learned about the DRPs and the complex phenomenon of drag reduction in fluid flow.

Generally, simulation studies that develop prediction model of DRA effectiveness and the drag reduction mechanism in the flow after injecting DRA are very scarce in literature. Some of the few researchers who have made contributions to this area include Al-Kayiem and Khan (2016), Karami and Mowla (2013), and Strelnikova and Michkova (2013). In this study, the focus is on simulation study to develop model of drag reduction in single phase water flow experimented by Vancko (1997) and two-phase gas liquid annular flow experimented by Vancko (1997); Al-Sarkhi and Hanratty (2001a, b); and Fernandes *et al.* (2004). The parameters such as phase velocities and pipe diameters are varied in two-phase annular flow.

Annular flow is one of the patterns in two phase gas liquid flow; it occurs when the system is having very high gas phase velocity in contrast to very low liquid phase velocity. This flow can be found in the system of natural gas and condensate. Some experiments related to the use of DRPs in the annular flow have shown a significant reduction in pressure drop and changes in flow patterns. In this study the phenomenon of velocity profile and flow pattern alteration are observed through computational fluid dynamic (CFD) simulations, respectively in single and two phase flow. The model and simulation are expected to help describe and understand the phenomenon of drag reduction in fluid flow better.

2. Methodology

In this study there were two mathematical models; each developed for single-phase flow and two-phase gas-liquid annular flow with the effect of drag reduction affecting pressure gradient and friction calculation, alongside some computational fluid dynamic (CFD) simulation trials to show the behavior of fluid flow. Some of the general assumptions being used were:

1. Flow was under isothermal condition
2. Flow inside a circular, horizontal pipe, with no fittings and elevation.

While more specific assumption for two-phase annular flow model were:

1. Two-phase annular flows had liquid film thickness distributed uniformly
2. There was entrainment in gas core, with droplet deposition rate equal to atomization and there was no slip between the entrained fraction and gas flow.

2.1. Pressure Gradient

The principal of pressure gradient on steady conditions is the application of mass conversion and momentum, and can be influenced by three main factors as written in Equation 1 (Karami and Mowla, 2013).

$$\frac{dP}{dL} = \frac{\rho\ u\ du}{dL} + \ \rho\ \sin\theta^{o} + \frac{2\ f\ \rho\ u^{2}}{D} \qquad (1)$$

The first term of the righthand side of equation represents velocity changes; the second term represents elevation changes; and the last term represents the existence of friction or shear stress in the pipe wall respectively. In this study, Equation 1 will be simplified by assuming that there is no velocity changes and the pipe is a long horizontal pipe without difference in elevation. Therefore the friction loss parameter can be expressed on the form of Fanning friction factor in Equation 2.

$$\frac{dP}{dL} = \frac{2\ f\ \rho\ u^{2}}{D} \qquad (2)$$

DRPs application on a fluid flow will reduce total pressure drop, particularly affecting the frictional factor of total pressure drop. The effectiveness of DRPs can be denoted in a percentage of drag reduction presented in Equation 3 and 4.

$$DR\% = \left(1-\frac{\Delta P_{DRPs}}{\Delta P}\right)\times 100 \qquad (3)$$

$$DR\% = \left(1-\frac{f_{DRPs}}{f}\right)\times 100 \qquad (4)$$

The subscript of DRPs indicates pressure drop and friction factors affected by DRPs. In the following section, equations and models of fluid flow are developed for pressure gradient and friction factor with drag reduction.

2.2. Drag Reduction in Single-Phase Flow

Several models of drag reduction in single phase fluid flow have been developed in the past on the basis of Prandtl-Karman equation. By using Prandtl-Karman plot to depict drag reduction on Newtonian fluids, it can be related to other variables through Equation 5.

$$f^{-1/2} = (4{,}0+\Delta)\log\left[Ref^{(1/2)}\right] - (0{,}4) - \Delta\log\left[Ref^{(1/2)}\right]^{*} \qquad (5)$$

$Re\,f^{(1/2)*}$ is the value of $Re\,f^{(1/2)}$ on critical wall shear stress at which the drag reduction phenomenon by polymer begins, or also known as on set drag reduction point. Final model of Equation 5. with defined $\log\left[Ref^{(1/2)}\right]^{*}$ as an onset drag reduction value is written below as Equation 6.

$$f^{-1/2} = (4{,}0+\Delta)\log\left[Ref^{(1/2)}\right] - (0{,}4) - 4\Delta \qquad (6)$$

Karami and Mowla (2013) propose a general model for drag reduction in single-phase non-Newtonian crude oil flow. They develop an onset drag reduction constant as well as an equation for slope increment factor (here denoted as Δ) depending on operating condition variables such drag reducer concentration and properties, temperature of working fluid, as well as pipe diameter and roughness. The properties of DRPs in this study are reffered to Hassanean (2016) and Karami and Mowla (2013).

For single phase flow with drag reduction, Vancko's experimental data is used in this study for determining the *'on set drag reduction'* constant value. The data are water flow inside 10 cm diameter horizontal circular pipe, the fluid velocities and drag reducer concentrations varied by 0.6 – 0.9 m/s and 5, 10, and 25 ppm respectively. Processing basic equations of lines generated from Prandtl-Karman Plot provides the data of slope increments which are used to calculate the average value of onset drag reduction. The injection of DRPs is limited to a certain level, as injecting higher concentration of the DRPs can cause negative effect because it increases the pressure gradient (Al-Yaari *et al.*, 2013). The final model from Equation 6 for Vancko's data is validated then presented in Result and Discussion Section.

Using the same data, CFD simulation is then carried out to observe the fluid flow phenomenon with drag reduction effects. Previous studies claim that DRPs change the velocities profile of a fluid, where flat-profile turbulence flow can be shifted to be more parabolic. Listed below in Table 1 are data from Vancko's experiment as input for the simulation. Computational fluid dynamic simulations are performed using COMSOL Multiphysics under turbulent flow condition. For single phase liquid flow, the parameter which is used as the input that gives different value for condition with and without DRPs is the roughness of wall or surface. This parameter is found by applying Karman-Nikuradse Equation as presented by Equation 7.

Table 1. Variations of friction factor without and with 5 ppm DRPs – Vancko (1997)

ppm	u_s (m/s)	Re	dP/dx (Pa/m)	F
0	0.704	87924.94	128	0.012970
	0.788	98415.98	156	0.012616
	0.852	106409.16	178	0.012314
5	0.704	87924.94	70	0.007093
	0.788	98415.98	84	0.006793
	0.852	106409.16	93	0.006434

Turbulence model parameters in COMSOL Multiphysics use the assumption of smooth wall represented by parameter "B". Consequently, the value of B parameter for smooth wall need to be adjusted according to this study. Parameter ΔB is used as a recompense for the rough pipe. The value of ΔB is defined by Equation 8.

$$\Delta B=\frac{1}{\kappa}.\ln(1+0{,}3h_{esg}^{+}) \quad (8)$$

Parameter κ is defined at the value of 0.41 for turbulence flow. Parameter h_{esg}^{+} is dimensionless sand grain roughness height and defined by Equation 9.

$$h_{esg}^{+}=\frac{h_s\,u_f}{v} \quad (9)$$

Flow geometry for this single phase flow simulation is described in Figure 1. This model has considered the fully developed flow region. The velocity profile of the flows are plotted at the fully developed flow region (around 3 meters from the inlet) and analyzed.

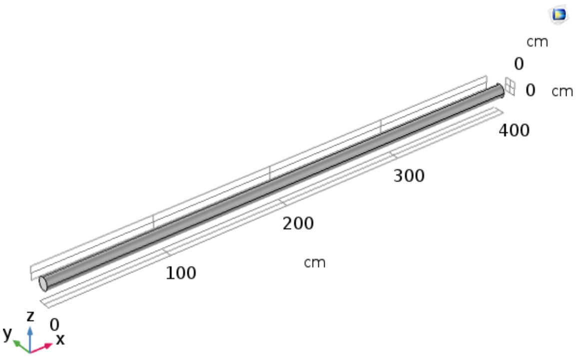

Figure 1. Geometry of single phase flow simulation for horizontal pipe (id = 10 cm)

For momentum balance simulation, the basic equation is presented by Equation 10.

$$\rho(u.\nabla)u=\nabla.[-pI+(\mu+\mu_T)(\nabla u+(\nabla u)^T]+F \quad (10)$$

in which ρ is fluid density, μ is fluid viscosity, u is fluid velocity, and F is external force.

2.3. Drag Reduction in Two-Phase Annular Flow

The mechanism of pressure drop in a multiphase flow is more complicated and requires deeper understanding of 3 things; the flow behavior of each phase, the interaction between the phases, and the effect of each phase on each other. One of the gas-liquid two-phase flow patterns taken into account is the annular horizontal flow. This pattern occurs when the gas phase flows with much greater velocity than the liquid; making it flows at the center of the pipe while the liquid is flowing around the gas – creating a liquid film that is usually thicker at the bottom, and some entrainment. Some of the basic parameters accounted in developing the model for annular flow are interfacial shear stress, entrainment on gas core, and liquid film thickness.

Research on two-phase gas-liquid flow with DRPs show a good result for pressure drop reductions as well as changes in flow pattern. Some of horizontal annular flow with drag reducer experiments investigated in this study are from Vancko (1997), Al-Sarkhi and Hanratty (2001a, b), and Fernandes *et al.* (2004). Each experiment data specification is listed in Table 2. For the interfacial based on these data, a model calculation for two-phase annular flow pressure gradient with and without DRPs is developed. Fernandes *et al.* (2004) propose a model for drag reduction phenomena in Equation 11.

$$\frac{dP}{dL}=-\frac{4}{D}\tau_i-\frac{4}{D}\,E_r(\,u_{sG}-u_i) \quad (11)$$

Interfacial shear stress as the friction component of the pressure gradient in Equation (10) can be written as follows in Equation 12.

$$\tau_i = \frac{1}{2}\, f_G\left(1+\gamma\,\frac{\delta_{FL}}{D}\right)\,\rho_G\,(u_{sG}-u_i)^2 \qquad (12)$$

where Y= 24 $(\rho_L/\rho_G)^{1/3}$ is a dimensionless value acting as roughness from liquid film, and higher Y means rougher liquid film acting upon the gas flow.

The entrainment rate is defined in Equation 13.

$$E_r = u_{sG}\sqrt{\rho_L\,\rho_G}\;\frac{k_E\,\mu_L}{4}\,\left(Re_{sFL}-Re_{sFLC}\right) \qquad (13)$$

The proposed model by Fernandes *et al.* (2004) for drag reduction phenomena in annular flow is through alteration of parameter γ and k_E in Equation 14 and 15.

$$\frac{\gamma}{\gamma_{DRPs}} = R_\gamma \geq 1 \qquad (14)$$

$$\frac{k}{k_{DRPs}} = R_k \geq 1 \qquad (15)$$

It is stated that R_γ and R_k are determined to match their experimental data.

In this study, some components are modified to offer different approach and calculation from the main assumption, for example, the liquid film of annular flow is uniformly distributed using the same governing pressure gradient in Equation 11.

2.4. Interfacial Shear Stress

Interfacial shear stress (τ_i) for two-phase gas-liquid flow is written in Equation 16.

$$\tau_i = \frac{f_i\rho_G}{2}(u_G-u_i)^2 \qquad (16)$$

Interfacial friction factor is calculated iteratively with algorithm described in Equation 17-19.

1. Calculation of friction number (Fn), with (f_G) as an initial value (Equation 17).
2. Calculation of frictional relative roughness (k/D), (Equation 18).
3. Calculation of interfacial friction factor f_i (Equation 19).

Repeatedly calculate Equation 17-19 until the desired convergence is achieved.

$$Fn = \frac{f_i\left(\frac{u_{sG}}{\sqrt{g\,D}}\right)\left(\frac{\sigma}{\mu_L\sqrt{g\,D}}\right)^{0.04}\left(\frac{\rho_L\,g\,D^2}{\sigma}\right)^{0.22}}{(0.05+f_i)(1-H_L)^{1.5}} \qquad (17)$$

$$\frac{k}{D} = 0.5145\,H_L s_i^{-1.5}\;\times\{\tanh[0.05762(Fn-33.74)]+0.945\} \qquad (18)$$

$$f_i = 0.0625\Big/\left[\log_{10}\left(\frac{15}{Re_G}+\frac{k/D}{3.715}\right)\right]^2 \qquad (19)$$

Table 2. Data for simulation of DRPs in two-phase gas-liquid annular flow

	Fluid	iD (cm)	u_{sG} (m/s)	u_{sL} (m/s)
Vancko (1997)	CO_2-LVTOil	10	7	0.08, 0.15, 0.25
			9	0.08, 0.15, 0.25
			11	0.08, 0.15, 0.25
Al-Sarkhi and Hanratty (2001a)	Air-Water	9.53	30	0.034, 0.080, 0.147
			36	0.035, 0.083, 0.147
			43	0.04, 0.08, 0.147
Al-Sarkhi and Hanratty (2001b)	Air-Water	2.54	24	0.062, 0.104, 0.125
			34	0.062, 0.104, 0.125
			41	0.062, 0.104, 0.125
Fernandes *et al* (2004)	NG-Condensate	1.9	10.4	0.016, 0.083, 0.22
			16.6	0.016, 0.1, 0.22
			21.3	0.016, 0.083, 0.196

2.5. Liquid Film Thickness

Liquid film thickness can be estimated by using Equation 20.

$$d=\frac{1}{2}D\ [1-(1-H_L)^{1/2}] \quad (20)$$

Interfacial velocity (u_i) is estimated from the average wave velocity with respect of liquid phase velocity profile as described by Equation 21.

$$u_i=1.8\frac{u_{sL}}{H_L},\ \text{for } Re_L\leq 2100 \quad \text{or} \quad u_i=\frac{u_{sL}}{H_L},\ \text{for } Re_L\geq 2100 \quad (21)$$

2.6. Entrainment on Gas Core

Calculation of entrainment rate (E_r) is performed by using Liu and Bai's (2017) model for calculating the 'generalization of droplet entrainment rate'. The model to calculate the entrainment rate is presented by Equation 22 and 23.

$$E_r=4{,}347\times 10^{-6}\times \rho_L Re_L^{0{,}584}\times \left(\frac{\rho_L}{\rho_G}\right)^{0{,}0561}\left(\frac{\tau_i\ d}{\sigma}\right)^{1{,}045}\left(\frac{D_{hydraulic}}{\sqrt{\sigma/(g(\rho_L-\rho_G))}}\right)^{-0{,}291} \quad (22)$$

for air-water experiment, with pressure range of 0.12 MPa $\leq P \leq$ 0.76 MPa.

$$E_r=1{,}357\times 10^{-8}\times \rho_L Re_L^{0{,}646}\times \left(\frac{\rho_L}{\rho_G}\right)^{0{,}487}\left(\frac{\tau_i\ d}{\sigma}\right)^{0{,}391}\left(\frac{D_{hydraulic}}{\sqrt{\sigma/(g(\rho_L-\rho_G))}}\right)^{0{,}157} \quad (23)$$

for steam-water experiment, with pressure range of 3 MPa $\leq P \leq$ 9 MPa.

2.7. Drag Reduction Effect

The model proposed in this study for annular flow with DRPs is a modification of Equation 18 multiplied by $\mathcal{X}$ as an effect of drag reduction on the friction factor of the flow.

$$\tau_i=\frac{\mathcal{X}\ f_i\ \rho_G}{2}(u_{sG}-u_i)^2 \quad (24)$$

This $\mathcal{X}$ value is designed to relate to the value of experiment %DR, where $\mathcal{X}\approx(1-\%DR)$. The prediction of $\mathcal{X}$ is related to liquid phase and gas phase velocities and liquid holdup from the corresponding flow.

Modification in interfacial shear stress (τ_i) – as being affected by $\mathcal{X}$ value, will also affect the entrainment rate (E_r) as it is having τ_i in the calculation, as mentioned in Equation 22 and 23. The model for two-phase annular flow above is then validated with the experimental data. The model for $\mathcal{X}$ is shown in the Equation 25 in the discussion section.

3. Results and Discussion

3.1. Single-Phase Flow

Equation 6 is validated by Vancko's data (Vancko, 1997) for single-phase Newtonian water flow, which results in 13-18% range of errors between the calculation and the proposed model, as presented in Figure 2.

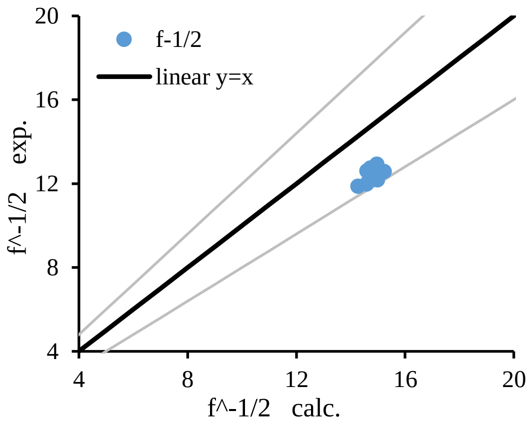

Figure 2. Comparison of model calculation results with experimental data for single phase flow

The CFD simulations for single phase flow with and without DRPs are conducted by varying the 'roughness' parameter. Change in velocity profile is observed, as shown in the Figure 3. Plotting the velocity magnitude on 2D graph, here are the changes measured 3 m from the inlet of the flow.

As described in Figure 3, each of the superficial velocities from the experiment is plotted and compared for flow without DRPs (line with asterisks) and flow with-DRPs (dotter line with circles). From the plot it can be seen that the flows with-DRPs are showing more parabolic profiles. Turbulent flow have a characteristic of a '*flat*' velocity profile as the distribution of momentum, mass, and energy transfer perpendicular to the wall is very chaotic resulting in '*mixing*' effect thus reducing the efficiency of the energy to flowing the fluid forward. Having more parabolic profile shows better distribution within layers of the fluid, and indicates a better efficiency of the flow.

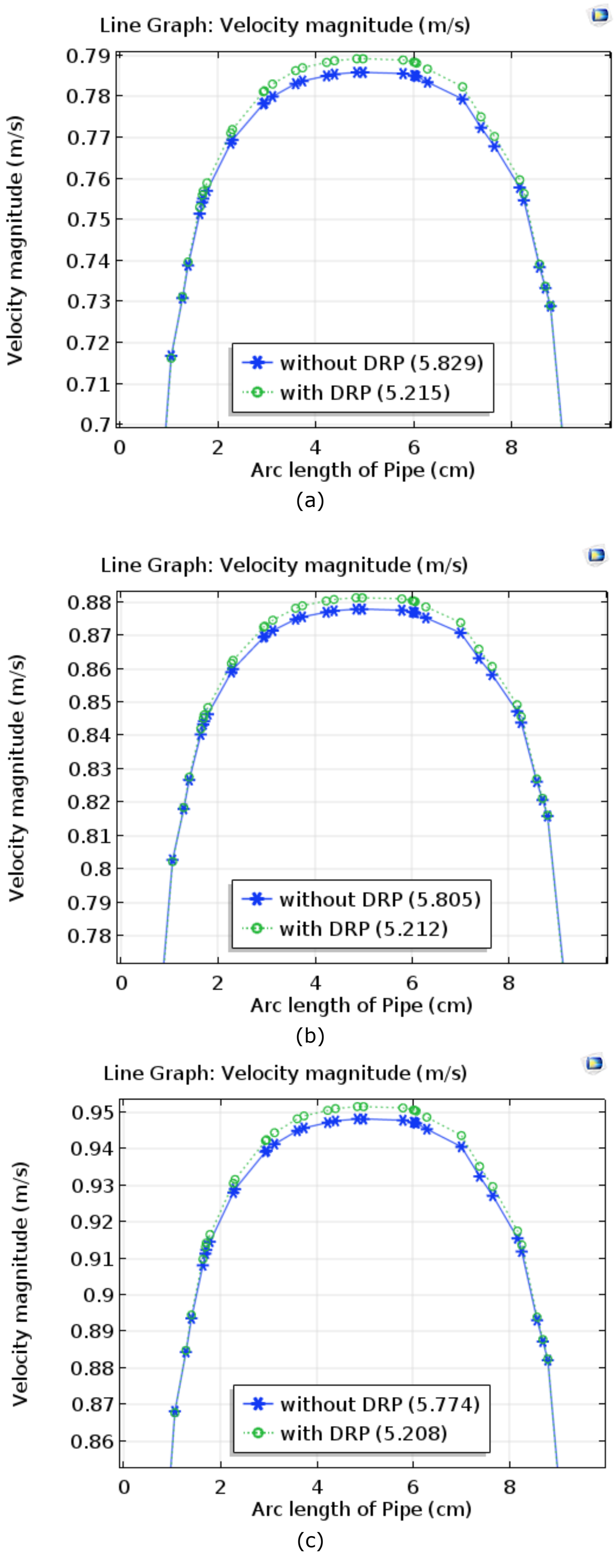

Figure 3. Velocity profile at 300cm from the inlet, for flow with and without DRPs (a) $\boldsymbol{u_s}$ = 0.704 m/s, (b) $\boldsymbol{u_s}$ = 0.788 m/s, (c) $\boldsymbol{u_s}$= 0.852 m/s

This is related to the fact that there is an increase in average velocity magnitude. The superficial velocities (u_s) simulated here are reffered to velocities in Table 1. The increase for each superficial velocity is: 0.43% for u_s = 0.704 m/s, 0.39% for u_s = 0.788 m/s, and 0.35% for u_s = 0.852 m/s.

3.2. Two-Phase Annular Flow

Figure 4-7 show the validation between the results for calculation model versus the experimental data for iD 1.9 cm (Fernandes *et al.*, 2004), iD 2.54 cm (Al-Sarkhi and Hanratty, 2001b), iD 9.53 cm (Al-Sarkhi and Hanratty, 2001a), and iD 10 cm (Vancko, 1997). It can be seen that the range of error in calculation for one group of data increases greatly with the diameter size.

One of the governing assumptions in this study that holds an important role in modeling the pressure gradient of two-phase annular flow is the uniformity of liquid film distribution in the flow, as mentioned in the previous section. However, this assumption visibly is only suitable for the data with smaller pipe diameter: iD=1.9 cm (Fernandes *et al.*, 2004) and iD=2.54cm (Al-Sarkhi and Hanratty, 2001b). The difficulty in estimating the asymmetrical distribution of liquid film becomes a challenge in applying the proposed model for cases with larger diameter pipe under the given flow condition. This problem arises because when the model is applied to larger pipe diameter with larger asymmetrical distribution of liquid film, the calculation is over specified for interfacial friction and pressure gradient.

The analysis for the high errors is that at larger pipe diameter, the liquid film is mainly distributed at the bottom of the pipe causing very thin film on the top. At this condition, the shear stress and the entrainment rate would have smaller value in comparison with the calculated one. Thus, it makes the model overspecifies the pressure gradient and causes high number of errors. This can be seen in Figure 4-7. Range of errors from the calculation model for two-phase annular flow without-DRPs in Figure 4-7 reaches up to 0.77% – 15.65% for Fernandes data (Fernandes *et al.*, 2004), 0.4% – 20.32% for Al-Sarkhi and Hanratty data (Al-Sarkhi and Hanratty, 2001b), 20.76% – 60.87% for Al-Sarkhi and Hanratty data (Al-Sarkhi and Hanratty, 2001a), and for Vancko data (Vancko, 1997) the error reaches up to 173.64%.

The calculation model for two-phase annular flow with-DRPs, which uses $\mathcal{X}$ as a factor, related to the drag reduction (%DR) of the flow is shown in the Equation 24, and Equation 25 below is the $\mathcal{X}$ as the drag reduction factor related to superficial velocities of gas and liquid as well as liquid holdup of a system.

$$\mathcal{X} = 0{,}62\left(\frac{u_{sL}}{u_{sG}}\right)^{H_L} \qquad (25)$$

Since only calculation for smaller diameter pipes seems valid and in accordance with the experiments, it is also concluded that Equation 24 produces better result for the same data sets. Error of the calculation for these two data sets are 8 – 26% for Fernandes data (Fernandes, 2004), and 1 – 12% for Al-Sarkhi and Hanratty data (Al-Sarkhi and Hanratty, 2001b), as seen in Figure 5.

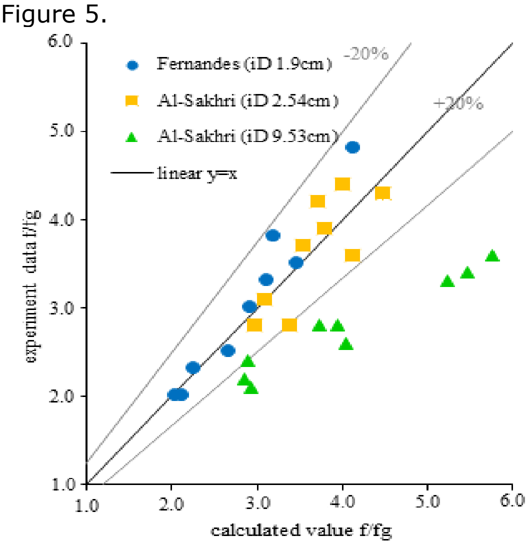

Figure 4. Comparison of calculated f/fg versus the experimental data of annular two-phase model without DRPs

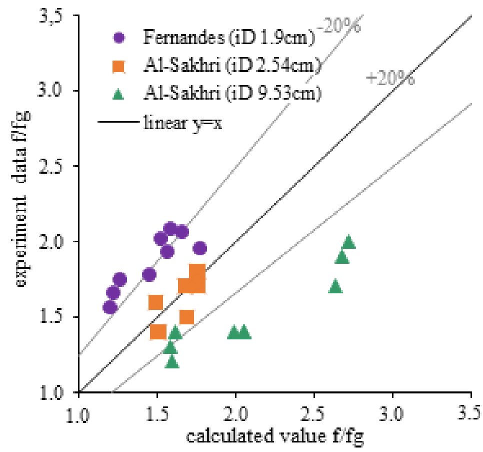

Figure 5. Comparison of calculated f/fg versus the experimental data of annular two-phase model with DRPs

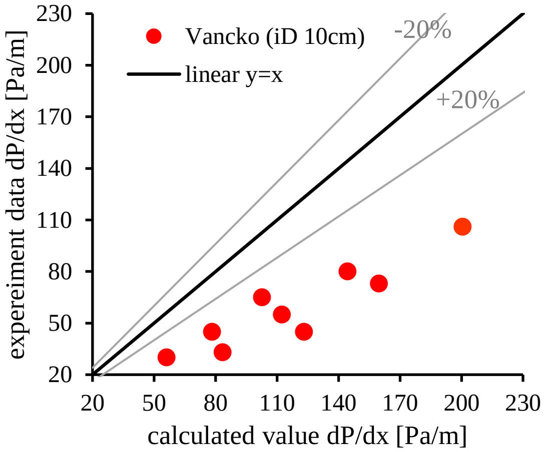

Figure 6. Comparison of calculated dP/dx versus the experimental data of annular two-phase model without DRPs

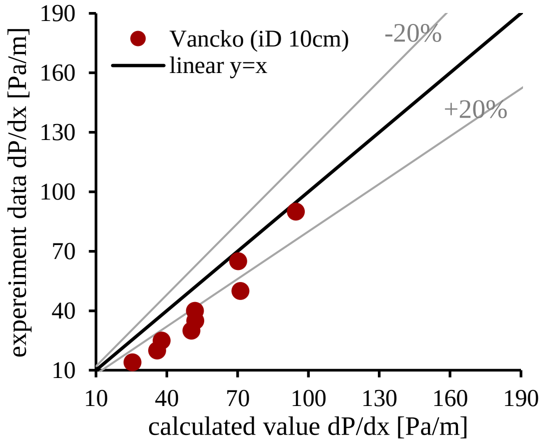

Figure 7. Comparison of calculated dP/dx versus the experimental data of annular two-phase model with DRPs

In this study, the contribution of velocities on drag reduction phenomena is observed. Based on the experimental results, at the constant gas velocity, the higher the liquid velocity the higher drag reduction effect attained. Based on the calculation, this might be because of the fact that more liquid is in the flow and the DRPs – which is injected in the form of solution, will have more significance in liquid fluid. The same correlation is also adopted in the $\mathcal{X}$ model, where the liquid velocity and liquid holdup are taken under consideration, in which their higher values will cause bigger drag reduction. The result of higher drag reduction with the increase in the velocity mixture is also concluded by Abubakar et.al. (2016) for oil-water flow with DRPs and are carried out in horizontal and upward-inclined acrylic, based on their previous works concerning DRPs performance (Abubakar et.al., 2015 a,b). However, there is a limitation of the significance of drag reduction increase at high mixture velocities.

Regardless of the result, the idea behind surface tension reduction for flow with-DRPs is that the small polymer chain disturbs bonds and forces work on the fluid surface and lowers the surface tension, which then leads to the tendency of the fluid to spread easily. Thus, in annular flow, the top liquid film will fall down more easily; when accumulated over time the flow will show a more stratified behavior – liquid on the bottom of the pipe while gas flowing on top,- as supposed to the annular ones.

Figure 8 is the result CFD for annular flow, y axis shows the fluid volume fraction as gas (air) equal to 1 and liquid (water) equal to 0. By changing surface tension, the curve can be estimated so that liquid phase would be shifted to one side and the flow would show a stratified behavior. Through the plot, there is no difference in flow pattern for different surface tension values. This becomes the work in the future to show and prove a possible parameter behind the change in flow pattern of annular flow with the addition of DRPs.

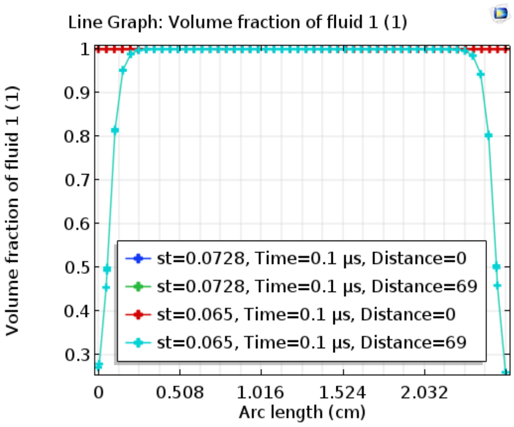

Figure 8. Plots of the fluid volume fraction of a gas (= 1) and liquid (= 0) phase from annular flow simulation, at 69 cm from the inlet

4. Conclusion

Two drag reduction models are developed; one is drag reduction in single phase flow with onset drag reduction parameter $\log\left[Ref^{(1/2)}\right]^{*}=4{,}0$ for Vancko data. The prediction of friction factors reaches up to 18% deviation. Further, model for pressure gradient in two-phase flow is very dependent on how the assumption of liquid film uniformity distribution suits the experimental condition, such as fluids velocities and pipe diameter.

Based on four sets of data, the smaller diameter shows a good fit with 0.77% – 15.65% and 0.4% – 20.32% error for Fernandes data (Fernandes *et al.*, 2004) and Al-Sarkhi and Hanratty data (Al-Sarkhi and Hanratty, 2001b) respectively for the flow without DRPs. Drag reduction factor used in annular flow with-DRPs calculation, $\mathcal{X}$, which is related to liquid and gas phase velocities as well as the liquid hold-up, produces error around 8 – 26% and 1 – 12% for Fernandes data (Fernandes *et al.*, 2004) and Al-Sarkhi and Hanratty data (Al-Sarkhi and Hanratty, 2001b) respectively. From the $\mathcal{X}$ factor, it can be understood that the higher the liquid velocities, the higher the liquid holdup, and the lower $\mathcal{X}$ will be calculating higher drag reduction effect as it will reduce the overall pressured drop calculation, as mentioned in the previous section, about the mechanism of fluids velocities influence over drag reduction phenomena.

From the simulations of drag reduction in flow pattern alteration, the single phase simulation shows a good conformity to the experimental and theoretical statement in which the drag reduction changes the profile of fluid velocity.

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Nomenclature

Re	Reynolds Number	
μ	Viscosity	kg/m.s
ρ	Density	kg/m^3
D	Pipe Diameter	m
L	Pipe Length	m
Z	Elevation	m
u	Velocity	m/s^2
P	Pressure	$kg/m.s^2$
V	Volume	m^3
m	Mass	Kg
g	Gravity	m/s^2
σ	Surface Tension	N/m
T	Temperature	^oC
τ	Shear Stress	$kg/m.s^2$
f	Friction Factor	-
H_L	*Holdup*	-
ε	Pipe Roughness	L
Er	Entrainment Rate	$kg/m^2.s$
k_E	parameter of entrainment rate in gas core	-
d	Liquid Film Thickness	m
S	Phase Perimeter	m
s	Dimensionless Interfacial Perimenter	
Δ	Slope increment P-K plot	-
χ	Factor of Drag Reduction	-
%DR	Drag Reduction	-

Subscript

G	Gas phase
L	Liquid phase
FL	Liquid film
FC	Critical Liquid Film
s	Superficial