Evaluation Of Two Phase Flow Characteristics In A Pipeline: Homogenous Model Approach

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Abstract: The motion of a multi-fluid flow is of interest in the oil and gas industry. The flow characteristics aid or impede production rate. This study analyses two phase fluid flow characteristics consisting of crude oil and natural gas, in straight pipes of the same internal diameter, using homogenous model. Flow values were obtained from a Niger Delta flow station and predetermined experimental flow equations were used to determine the pressure drop in order to comprehend the flow characteristics in the pipeline. An average total pressure loss (ΔP_T) of 0.075 MPa was obtained in the laminar flow category at 0.006228 MPa/m and an average total pressure (ΔP_T) of 27.896 MPa in turbulent flow category at 2.325 MPa/m in a pipe length of 12 metres. Graphs were plotted to show the influence of the calculated flow parameters on the fluid flow. The graphs aided in depicting the flow regimes in the pipeline. These are universally dominant parameters in the oil and gas industry as they significantly impact on the transportation of crude oil from oil wells or reservoirs to the process plants. These results may be used as a baseline and guide to compare realistic measurements in similar flows.

Keywords: Pipeline, Two-phase flow, Homogenous model, Pressure drop, Laminar, Turbulent

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1.0 Introduction

The most commonly employed method of transporting fluid from one point to another is to force the fluid to flow through a piping system. Pipes of circular cross section are most frequently used because that shape offers not only greater structural strength but also greater cross sectional area per unit of wall surface than any other shape (Rajput, 2010). They can also withstand large pressure differences between the inside and the outside without undergoing significant distortion. A large number of flows encountered in nature and technology are a mixture of phases. Physical phases of matter are gas, liquid and solid, but the concept of phase in a multiphase flow system is applied in a broader sense. Multiphase flows play an important role in many natural processes and engineering applications. They occur in a variety of environmental phenomena like rain, fog, snow, avalanches, soil erosion, and landslides, among others. Very critical biological and medical flows like blood flow is a multiphase flow, virtually every processing technology deals with multiphase flows. The flow of multiphase mixtures is a common phenomenon in industrial plants, such as chemical reactors and power generation units. It is considered to be an important phenomenon in the oil and gas industry from the energy point of view. It is often the flow of all materials produced from a reservoir and may consist of hydrocarbon gases (with Carbondioxide-CO_2 and traces of Hydrogen Sulphide-H_2S), hydrocarbon liquid (oil and condensate), water and solids (sand and grit). In order to successfully design and operate any process plant, knowledge of the chemical and physical properties of the materials being processed is fundamental. In many cases, the materials that are being processed do not follow as a single phase such as a gas, liquid or solid. Instead, combinations of two or more of these phases may pre-dominate; gas-liquid, gas-solid, liquid-solid, liquid-liquid and even gas-liquid-solid flows are commonly encountered. Gas-liquid flows frequently ensue in all types of process equipment and they are also prevalent in many oil and gas pipeline systems. Brill & Beggs (1991) stated that more than half of the natural gas gathered in the United States in the early 1970's flowed within two-phase pipelines.

2.0 Review of previous studies

Choi et al (2003), obtained data of flow regimes, void fraction, and frictional pressure drop in normal gravity, microgravity and hyper-gravity (2g) aboard a MU-300 aircraft. They concluded that the gravity dependency on flow regimes was more clearly seen as a gas and liquid flow rates decrease. The effect of gravity on two phase flow was insignificant for the turbulent flow regions. Curtis and Coffield (1999) investigated two phase flow pressure drop of high quality steam. Two phase pressure drop across a straight test pipe was experimentally determined for Reynolds number (Re) steam flow of a flow quality of 0.995 to 1.0. The testing described was been performed in order to reduce uncertainties associated with the effects of two phase flow on pressure drop. The two phase pressure drop data obtained in this test enhanced development of a correlation between friction factor, Reynolds number and flow quality. Fore et al (1997) presented measurements on both fluid flow and heat transfer for two phase slug flows in microgravity; they used air and two liquids (water and 50% aqueous glycerine solution) to obtain a range of liquid Reynolds numbers from 1000 to 20,000 in a 25.4mm inner diameter tube. They showed based on a comparison of microgravity to normal gravity correlations that the heat transfer coefficients are smaller in reduced gravity than in normal gravity under the same flow conditions. They summarised that smaller liquid phase turbulence levels in the gas and liquid can explain this difference. Hannah et al (2012), through their research in computational fluid dynamics analysis of two phase fluid flow in a packed Bed reactor which included the use of CFD in simulating an experiment on multiphase flow to compare results on flow regime and pressure drop. Their results included discussion of the programs capabilities for conducting analysis and comparison of simulated flow parameters against experimentally determined values. James and Silberman (1958) conducted a study on two phase flow in horizontal pipes with special reference to bubbly mixtures. It was found that the friction factor of what is approximately equal or slightly greater than the friction factor for liquid flowing alone in the mean velocity of the liquid while their size is inversely proportional to the square root of the pipe diameter. Kamp et al (2009) developed a mechanistic model for bubble coalescence in turbulent flow. Their model can be used to predict pressure drop in pipes. Their data was validated by data obtained in a reduced gravity aircraft. They concluded that in the absence of gravity, collisions between bubbles are smaller than the length scale of turbulence are primarily due to turbulence. Manmatha et al (2012) used computational fluid dynamics (CFD) modelling to evaluate the pressure drop caused by two phase flow of oil/water emulsions through sudden contractions. They obtained that the loss coefficients for the emulsions are found to be independent of the concentrations and type of emulsions. The numerical results were validated against experimental data and were found to be in good agreement. Wang et al (2004) presented data on the interfacial friction factor and relative interfacial roughness on the gas-liquid interface of an air-water annular flow in a tube with inner diameter of 9.525mm2. Their results show that while the roughness in microgravity is less than half of that in normal gravity, the friction factor was only about 10% smaller in microgravity than that in normal gravity. The goal of this study is to obtain the pressure loss in a straight pipe of two phase flow using a homogenous model and show the influence of the pressure drop on the fluid flow. The flow station is operational in Nigeria's Niger Delta region and readings were collected from flow measurements during the study.

3.0 Materials and Methods

3.1 Materials

The data of flow measurements collected from the flow station in its raw form are tabulated below

Table 3.1 *Values from Oil Field*

Time Interval (s)	Upstream Pressure (PSI)	Temperature (^{o}C)	Oil Rate (BBLS)	Gas Rate m^3/d	Oil Gravity	Gas Gravity	Oil Temperature (^{o}C)	Choke /64"	BSW %
300	1476.758	36.65779	60.73164	3747832.416	0.805	0.732	29.29671	16	0
600	1558.606	36.51199	65.88369	6642417.166	0.805	0.732	29.46829	16	0
900	1626.157	36.35392	72.24052	7668777.600	0.805	0.732	29.60159	16	0
1200	1685.792	36.25266	76.21214	7842880.903	0.805	0.732	29.72569	16	0
1500	1737.953	36.13910	82.68974	7226676.608	0.805	0.732	29.76706	16	0
1800	1778.395	36.04242	89.22033	8006824.618	0.805	0.732	29.76401	16	0
2100	1816.027	35.81993	93.39465	8249701.684	0.805	0.732	29.64754	16	0
2400	1853.611	35.77543	100.97332	8211006.942	0.805	0.732	29.48667	16	0

Values tabulated in Table 4.1 above were converted to standard data units to be used for this evaluation and the converted values are tabulated in Table 3.2.

Table 3.2 *Converted Oil Field values*

Time interval (s)	Gas Rate		Oil Rate		
	m^3/d	m^3/s	$Bbls$	m^3	m^3/s
300	3747832.416	43.377	60.73164	9.65558	0.0322
600	6642417.166	76.88	65.88369	10.47469	0.0349
900	7668777.600	88.759	72.24052	11.48534	0.0383
1200	7842880.903	90.774	76.21214	12.11678	0.0404
1500	7226676.608	83.642	82.68974	13.14664	0.0438
1800	8006824.618	92.672	89.22033	14.18492	0.0473
2100	8249701.684	95.483	93.39465	14.84859	0.0495
2400	8211006.942	95.035	100.97332	16.05340	0.0535

3.2 Methods

3.2.1 Homogenous Model

In the two phase homogenous flow model, it is assumed that both phases are well mixed and flow at the same velocity. In a pipe flowing upward in an inclined angle θ, the pressure loss is affected by friction loss, acceleration and body force (gravitation). These losses can be said to be non-linear and depends on each other. For example, the gravitation pressure loss reduces the pressure and thus the density must change and hence, acceleration must occur.

$$Total\ Pressure\ Loss = \frac{dP}{dx} = \frac{dP}{dx}\downarrow_f + \frac{dP}{dx}\downarrow_a + \frac{dP}{dx}\downarrow_g$$

The two phase flow characteristics evaluation were carried using fluid flow fundamental principles. The following equations were applied in finding the fluid flow parameters. The following equations were adopted from texts in due order.

Area of pipe is equal to $\pi D^2/4$ 3.1

Total Mass Flow Rate is equal to

$$\dot{m} = \dot{m}_G + \dot{m}_L \qquad 3.2$$

where $\dot{m} = total\ mass\ flow\ rate$

$\dot{m}_G = mass\ flow\ rate\ of\ gas = \frac{\rho_{gas}}{\rho_{air}} = specific\ gravity$

$\dot{m}_L = mass\ flow\ rate\ of\ liquid = \frac{\rho_{liquid}}{\rho_{water}} = specific\ gravity$

$\dot{m} = \rho * q$ ρ is density and q is volume flow rate/sec

Total Mass Flux is equal to $G = \frac{\dot{m}}{A}$ 3.3

Where $G = total\ mass\ flux$

$\dot{m} = total\ mass\ flow\ rate$

$A = Area\ of\ Pipe$

Mass velocity doesn't exist in reality. Hence, it is emphasized that this mass velocity is the actual velocity (Genick B. (2013)).

Total Volumetric Flow Rate is equal to

$$Q = Q_G + Q_L \qquad 3.4$$

where $Q_G = Gas\ Volumetric\ Flow\ rate$

$Q_L = liquid\ Volumetric\ Flow\ Rate$

Liquid with very high bulk modulus (constant or almost constant density). The volumetric flow rate can be considered as constant (Genick B. (2013)).

Quality or Dryness Fraction is equal to $x = \frac{\dot{m}_G}{\dot{m}}$ 3.5

where $x = Quality\ or\ Dryness\ Fraction$

$\dot{m} = total\ mass\ flow\ rate$

$\dot{m}_G = mass\ flow\ rate\ of\ gas$

The dryness fraction and wetness fraction remain constant along the pipe length as long as the gas and liquid masses remain constant.

Void Fraction measured by using either an optical means or by an indirect approach, such, electrical capacitance of a conducting liquid phase. The homogenous void fraction α_m is determined from the Quality x and given as

$$\alpha_m = \frac{1}{1+\left[\frac{U_G}{U_L}\left(\frac{1-x}{x}\right)\frac{\rho_G}{\rho_L}\right]} \qquad 3.6$$

Where $\frac{U_G}{U_L}$ $is\ the\ slip\ ratio\ (velocity\ ratio, S)$

$\frac{\rho_G}{\rho_L} = density\ ratio\ of\ gas\ and\ liquid$

And this is equal to 1.0 for a homogenous flow.

This fraction may vary along the pipe length if the gas density is not constant along the pipe length so does the liquid fraction (Awad et al (2008)).

Liquid Hold-Up could also be referred to as liquid fraction which is expressed as

$$L_H = 1 - \alpha \qquad 3.7$$

Actual **Velocities** are dependent upon the phases because in the actual cross section, the phase flows are independent on each other. Thus, a superficial velocity is commonly determined in which one phase occupies more space and move at a higher velocity that the other phase throughout the length of the pipe. Since we are evaluating the flow characteristics using a homogenous model, the average velocity of both phases is sought. The summation of the **Gas Superficial Velocity** **(**$U_{SG} = \frac{G_G}{\rho_G} = Q_G$) and **Liquid Superficial Velocity** **(**$U_{SL} = \frac{G_L}{\rho_L} = Q_L$) gives the **Average Velocity** as **(**$U_m = U_{SL} + U_{SL}$). 3.8

Homogenous Density can be calculated by using

$$\rho_m = \frac{1}{\frac{X}{\rho_g}+\frac{(1-x)}{\rho_L}} \qquad 3.9$$

The flow **Viscosity** adopted from (Dukler, A. E. (1964), introduced this homogenous two phase viscosity definition μ_m based on the averaged value of kinematic viscosity.

$$\mu_m = \rho_m \left[x\left(\frac{\mu_G}{\rho_g}\right) + (1-x)\left(\frac{\mu_L}{\rho_L}\right)\right] \qquad 3.10$$

Reynolds Number expression available for a two phase liquid-gas flow is of an empirical mixture as a function of mass quality (x) (Genick B. (2013)) and expressed as

$$Re_m = \frac{Gd}{\mu_{tp}} \qquad 3.11$$

where $\mu_{tp} = x\mu_G + (1-x)\mu_L$

Friction Pressure Loss is calculated using

$$-\frac{dP}{dx}\downarrow_f = \frac{4\tau_w}{D} \qquad 3.12$$

The wall shear stress can be estimated by

$$\tau_w = f\frac{\rho_m U_{m^2}}{2} \qquad 3.13$$

The friction factor is measured for a single phase flow where the average velocity is directly related to the wall shear stress. This is because there is no available experimental data for the relationship of the averaged velocity of the two (or more) phases and wall shear stress (Genick B. (2013)). The friction factor was not measured for the "averaged" viscosity of the two phase flow. Hence, the friction factor is obtained by using the correlation

$$f = C\left(\frac{\rho_m U_m D}{\mu_m}\right)^{-n} \qquad 3.14$$

Where C and n are constants which depend on the flow regimes (turbulent or laminar)

For laminar flow, C=16 and n=1 & for turbulent flow, C=0.079 and n=0.25

Gravity Pressure Loss is given as $\frac{dP}{dx}\downarrow_g = g\rho_m \sin\theta\, h$ 3.15

The density change during the flow can be represented as a function of density. The density in the equation above is the density without the “movement” (the “static” density).

Acceleration Pressure Loss can be estimated by

$$\frac{dP}{dx}\downarrow_a = \dot{m}\frac{dU_m}{dx} \qquad 3.16$$

The acceleration pressure loss (can be positive or negative) results from change of density and the change of cross section. The equation becomes

$$\frac{dP}{dx}\downarrow_a = \dot{m}\frac{d}{dx}\left(\frac{\dot{m}}{A\rho_m}\right) \qquad 3.17$$

Total Pressure Loss between points can be calculated through integration

$$\Delta P_T = \Delta P_f + \Delta P_a + \Delta P_g \qquad 3.18$$

where ΔP_f *is friction pressure loss*

ΔP_a *is acceleration pressure loss*

ΔP_g *is gravitational pressure loss*

4.0 Result and Analysis

Table 4.3 *Table showing results for mass flow rate, mass flux, flow densities and volumetric flow rates for both phases of fluid flow*

Time interval (s)	$\dot{m}\,(\frac{kg}{s})$	$\dot{m}_G(\frac{kg}{s})$	$\dot{m}_L\,(\frac{kg}{s})$	$\rho_g(\frac{kg}{m^3})$	$\rho_L(\frac{kg}{m^3})$	$G_G(\frac{kg}{m^2s})$	$G_L(\frac{kg}{m^2s})$	$G(\frac{kg}{m^2s})$	$Q_G(\frac{m}{s})$	$Q_L(\frac{m}{s})$
300	64.181	38.26	25.921	0.88206	805	8390.351	5684.43	14074.78	9512.223	7.061
600	95.908	67.813	28.095	0.88206	805	14871.27	6161.184	21032.46	16859.71	7.654
900	109.123	78.291	30.832	0.88206	805	17169.08	6761.404	23930.48	19464.75	8.399
1200	112.59	80.068	32.522	0.88206	805	17558.71	7132.018	24690.79	19906.48	8.86
1500	109.036	73.777	35.259	0.88206	805	16179.17	7732.237	23911.4	18342.48	9.605
1800	119.819	81.742	39.077	0.88206	805	17925.88	8350.219	26276.1	20322.74	10.373
2100	124.07	84.222	39.848	0.88206	805	18469.74	8738.596	27208.33	20939.32	10.855
2400	126.895	83.827	43.068	0.88206	805	18383.11	9444.737	27827.85	20841.12	11.733

Table 4.4 *Table showing results for dryness fraction, wetness fraction, void fraction, liquid hold-up, flow velocities, and viscosity for both phases of fluid flow*

Time Interval (s)	$Q(\frac{m}{s})$	x	$1-x$	α_m	L_H	U_{SG} $(\frac{m}{s})$	U_{SL} $(\frac{m}{s})$	U$_m$ (m/s)	ρ_m $(\frac{kg}{m^3})$	μ_m $(\frac{kg}{ms})$
300	9519.284	0.5961	0.4039	0.9993	0.0007	9512.223	7.061	9519.284	1.4857	0.001203
600	16867.36	0.7071	0.2929	0.99955	0.000457	16859.71	7.654	16867.36	1.2469	0.000777
900	19473.15	0.7175	0.2825	0.99957	0.000431	19464.75	8.399	19473.15	1.2288	0.000744
1200	19915.34	0.7111	0.2889	0.99956	0.000445	19906.48	8.86	19915.34	1.2399	0.000749
1500	18352.08	0.6766	0.3234	0.99948	0.000524	18342.48	9.605	18352.08	1.303	0.000878
1800	20333.11	0.6822	0.3178	0.99949	0.00051	20322.74	10.373	20333.11	1.2923	0.000859
2100	20950.18	0.6788	0.3212	0.99948	0.000518	20939.32	10.855	20950.18	1.2988	0.000871
2400	20852.85	0.6606	0.3393	0.99943	0.000563	20841	11.732	20852.85	1.3345	0.000935

Table 4.5 *Table showing results for Reynold's number, Friction Factor and Wall Shear Stress for both phases of fluid flow*

Time Interval (s)	v_G $(\frac{m^2}{s})$	v_L $(\frac{m^2}{s})$	Re$_m$	U_{tp} $(\frac{kg}{ms})$	*f*	τ_w $(\frac{N}{m^2})$
300	0.000129	0.0018137	1819	0.589762	0.000017861	1202.278
600	0.000129	0.0018137	3747	0.427715	0.000007753	1375
900	0.000129	0.0018137	4420	0.412532	0.001996	465144.3
1200	0.000129	0.0018137	4460	0.412875	0.001985	487988.9
1500	0.000129	0.0018137	3858	0.472241	0.000007713	1692.451
1800	0.000129	0.0018137	4315	0.464066	0.002022	540116.2
2100	0.000129	0.0018137	4420	0.46903	0.002011	573216.9
2400	0.000129	0.0018137	4280	0.495453	0.002036	590720.5

Table 4.6 *Table showing results for the flow regime, friction pressure loss, gravity pressure loss and total pressure loss for both phases of fluid flow*

Time Interval (s)	Flow regime	ΔP_f $(\frac{N}{m^2})$	ΔP_G $(\frac{N}{m^2})$	ΔP_{total} $(\frac{N}{m^2})$	ΔP_{total} (MPa)
300	Laminar	63111.71	27.36	63139.71	0.06314
600	Laminar	72185.81	22.962	72208.77	0.07221
900	Turbulent	24417025	22.629	24417047	24.417
1200	turbulent	25616213	22.83	25616236	25.616
1500	Laminar	88842.56	23.995	88866.55	0.08887
1800	Turbulent	28352556	23.798	28352580	28.353
2100	turbulent	30090129	23.918	30090152	30.09
2400	turbulent	31008950	24.575	31008975	31.01

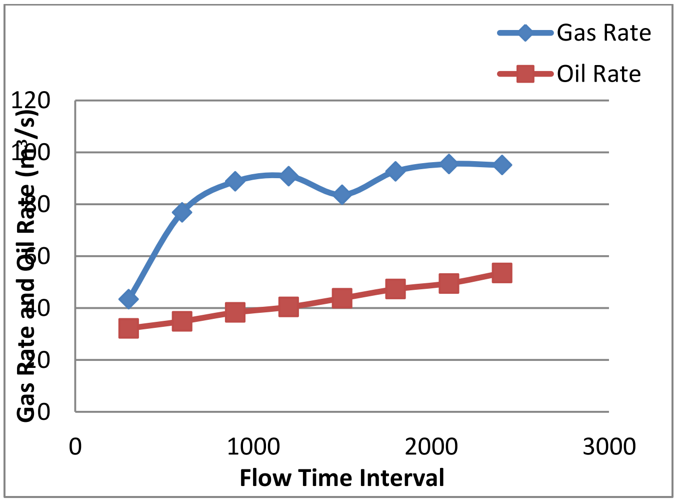

Fig. 4.1 *Plot of Gas Flow Rate and Oil Flow Rate against Flow Time Interval*

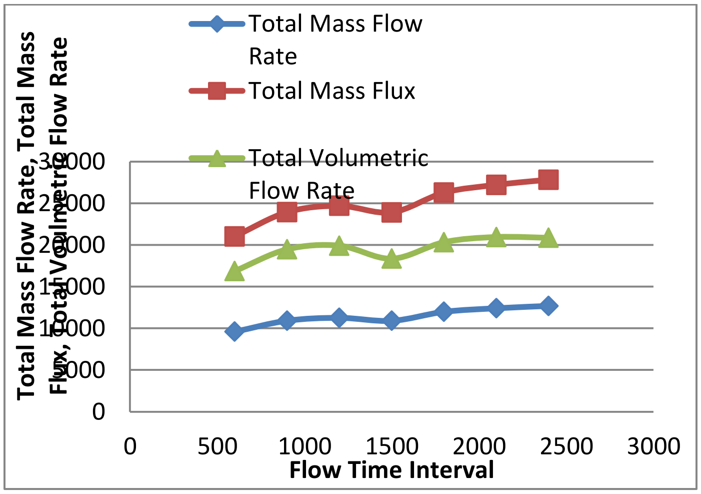

Fig. 4.2 *Plot of Total Mass Flow Rate, Total Mass Flux and Total Volumetric Flow Rate against Flow Time Interval*

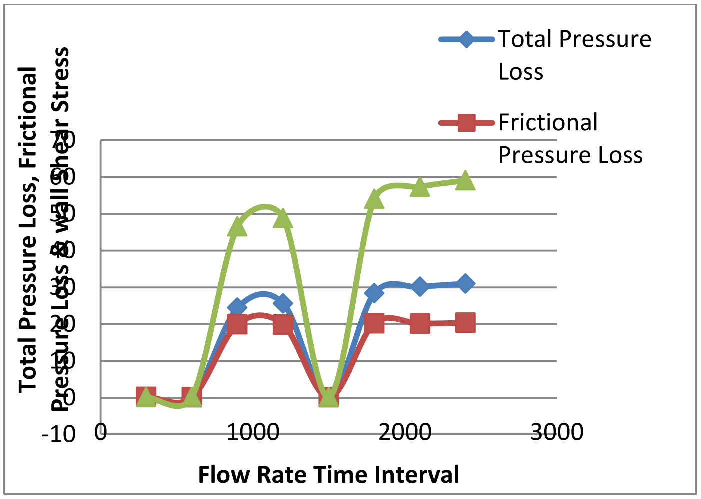

Fig. 4.3 *Plot of Total Pressure Loss, Frictional Pressure Loss and Wall Shear Stress against Flow Time Interval*

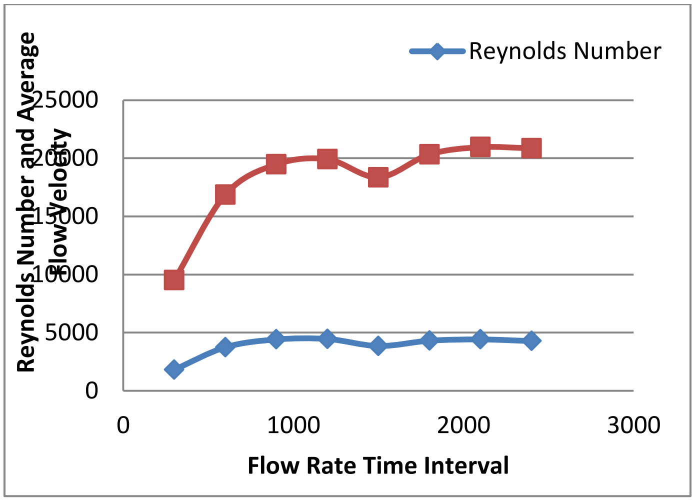

Fig. 4.4 *Plot of Reynolds Number and Average Flow Velocity against Flow Time Interval*

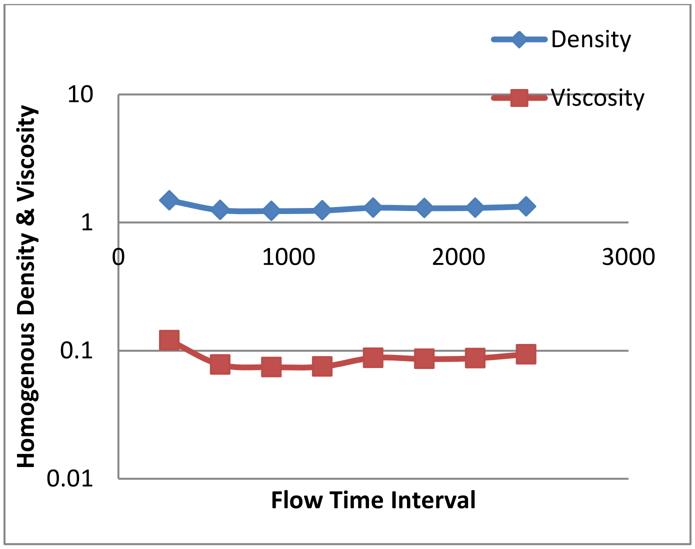

Fig. 4.5 *Plot of Fluid Density and Viscosity against Flow Time Interval*

The solution of this study reveals the flow profile or pattern of the two phase flow by understanding the flow parameters and flow regimes which are depicted by Fig. 4.1 to fig. 4.5. Fig. 4.1 reveals that the pipe flow is in two phases-the gaseous phase and the liquid phase coming from the well. The Oil rate exhibited a steady rise in its flow and this was the same for the gas rate but a lot higher than the Oil rate. The Gas steadily increased until it started descending after a time interval of 1200seconds. This decline ends at 1500seconds and it ascends to its maximum ad remains there. This decline and ascension of the Gas Rate is attributed to the pressure drop within the pipeline. The steady rise of the oil flow was aided by the gas flow making the oil and gas properly mixed to be viewed as a two phase flow. The results from equations 3.2, 3.3 and 3.4 are plotted on Fig. 4.2. The plots (total mass flow rate, total mass flux and total volumetric flow rate) were made against the flow time interval. These flow parameters showed similar pattern and are affected by pressure drop in the pipeline at the same time interval. They are also affected by the flow velocity and bulk modulus. Fig. 4.3 is the plot for total pressure loss, frictional pressure loss and wall shear stress against the flow interval. The plot shows the same plot profile for all flow parameters. The plot also revealed very low pipeline pressure at the beginning of fluid flow. The fluid flow subsequent increase began at 600seconds and then a pressure drop at 1500seconds. It rose again to its maximum point and remained there. Fig. 4.4 is a plot of the flow's Reynolds Number and Average flow Velocity against flow time interval. Both flow properties exhibited similar flow pattern as the Gas flow rate, total mass flow rate, total mass flux, total volumetric flow rate, etc. the same pressure drop affected both flow properties at the same time interval. Fig. 4.5 is a comparison plot of the homogenous density and viscosity of the pipeline flow. The homogenous density decreased as the fluid flow progressed and also, did the flow viscosity.

5.0 Conclusion

Engineers encounter two-phase flow mostly in well tubing and in flow pipelines. The flow may be vertical, inclined or horizontal and methods must be available to satisfy the three basic issues (energy, integrity and delivery) and they require proper understanding of the requirements of multiphase flows. For instance, pressure and temperature drops must be well predicted to maintain the required energy flow in the pipeline systems. In refining industries, flow stations and petrochemical industries, these losses have to be calculated accurately to determine where booster pumps have to be placed when pumping crude oil or other fluids in pipes to distances thousands of kilometres away. Energy input to the gas or liquid is needed to make it flow through the pipe. This energy input is needed because there is frictional energy loss (also called frictional head loss or frictional pressure drop) due to the friction between the fluid and the pipe wall and internal friction within the fluid. In pipe flow substantial energy is lost due to frictional resistances. One of the most common problems in fluid mechanics is the estimation of this pressure loss and knowing the flow regimes the flow transcends through. Calculating pressure losses is necessary for determining the appropriate pump size. Knowledge of the magnitude of frictional losses is of great importance because it determines the power requirements of the pump forcing the fluid through the pipe. An average total pressure loss (ΔP_T) of 0.075 MPa was obtained in the laminar flow category at 0.006228 MPa/m and an average total pressure (ΔP_T) of 27.896 MPa in turbulent flow category at 2.325 MPa/m in a pipe length of 12 metres. The homogeneous model during this research proved to be an important tool in calculating pressure drop and in describing the flow characteristics of a particular pipeline flow so that production can be maximized.

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