SUDAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

INVESTIGATION OF OIL WATER CONCURRENT FLOW IN HORIZONTAL PIPELINES

تقصي الإنسياب المتزامن للزيت و الماء في خطوط الأنابيب الأفقية

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN MECHANICAL ENGINEERING (POWER)

By

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قرآن كريم

أَلَمْ تَرَ أَنَّ اللَّهَ يُزْجِي سَحَابًا ثُمَّ يُؤَلِّفُ بَيْنَهُ ثُمَّ يَجْعَلُهُ رُكَامًا
فَتَرَى الْوَدْقَ يَخْرُجُ مِنْ خِلَالِهِ وَيُنَزِّلُ مِنَ السَّمَاءِ مِن
جِبَالٍ فِيهَا مِن بَرَدٍ فَيُصِيبُ بِهِ مَن يَشَاءُ وَيَصْرِفُهُ عَن مَّن
يَشَاءُ ۖ يَكَادُ سَنَا بَرْقِهِ يَذْهَبُ بِالْأَبْصَارِ (43)

صدق الله العظيم

النور 43

DEDICATION

To my mother, the source of passion and encouragement

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Firstly, I would humbly acknowledge the patronage of Allah without which it would never be possible to accomplish this work in this form.

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ABSTRACT

Pressure loss in an oil water concurrent flow in pipelines represents a big challenge in the design and operation of crude oil pipelines. Pumping capacity and pipeline operation cost is directly affected by the pressure gradient along the pipeline. This loss is influenced by different parameters such as the line size; water cut (concentration), oil viscosity, etc. These losses have attracted number of researchers who investigated the flow type from different aspects, mostly at small scale (laboratory).

However in this work, the oil water flow in horizontal pipeline is investigated at the full scale pipeline dimensions (152.4mm diameter and 50 km long) and actual fluid properties using the capabilities of the OLGA software. The actual operational parameters records used to build and validate the computational model.

The objective the study is to investigate the factors influencing the pressure loss along the pipeline and how their influence. Impact of different parameters in the flow pressure drop along the pipeline is evaluated and compared against the previous studies and published literature.

It is found that pressure drop in an oil water concurrent flow in horizontal pipeline is increasing with increase of flow rate, reducing of water content and reducing of pipe diameter while the inlet temperature has limited effect on improving flow ability to limited distance with no effect on the overall pressure gradient.

ملخص الدراسة

يمثل فقدان الضغط عند الإنسياب المتزامن للماء و الزيت في خطوط الأنابيب الأفقية تحدياً كبيراً في تصميم و تشغيل الأنابيب كما تتأثر قدرة الضخ و تكلفة تشغيل خطوط الأنابيب بصورة مباشرة بمعدل فقدان الضغط خلال الأنبوب. و يتأثر الفقد بعدة عوامل مثل حجم الأنبوب، نسبة الماء في المائع، لزوجة الزيت ، الخ. ... هذه الفقودات أثارت إهتمام عدد من الباحثين الذين بحثوا هذا النوع من الإنسياب من عدة أوجه (في نماذج صغيرة (المعمل)).

في هذا البحث جرى إستقصاء إنسياب الماء و الزيت في الأنابيب الأفقية بالحجم الكامل(انبوب بقطر152.4mmو طول 50km) و الخصائص الحقيقية للخام بإستخدام برنامج الحاسوب(OLGA). أستخدمت متغيرات التشغيل من سجلات التشغيل لبناء و إختبار النموذج الحاسوبي.

الهدف من الدراسة هو إستقصاء العوامل المؤثرة على فقدان الضغط خلال الأنابيب و كيفية التأثير على متغيرات التشغيل.

أستخدم تطبيق (OLGA) الحاسوبي لإجراء البحث لمعرفة تأثير مختلف المتغيرات في إنخفاض ضغط الإنسياب خلال خط الأنابيب و تم تقييمه و مقارنته بالدراسات السابقة و المنشورة.

وجد أن إنخفاض الضغط في الإنسياب المتزامن للماء و الزيت في الأنابيب الأفقية يزيد بزيادة معدل الإنسياب و نقصان نسبة الماء في المائع و نقصان قطر الأنبوب ، بينما يكون تأثير درجة الحرارة محدودًا في تحسين الإنسياب لمسافة محدودة و لا تؤثر كثيرًا في إنخفاض الضغط الكلي.

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LIST OF SYMBOLS

Symbols	Description
ST	Stratified flow
ST & MI	Stratified and mixing interface flow
$D_{o/w}$	Dispersed oil in water flow pattern
$D_{w/o}$	Dispersed water in oil flow pattern
ρ_w	Water density
ρ_o	Oil density
ρ_m	Mixture density
μ_o	Oil viscosity
μ_w	Water viscosity
μ_m	Mixture viscosity
α	Water hold up

GLOSSARY

Water cut:	Volumetric percentage of the water in the mixture
Water fraction:	Same as above
Water holdup:	The fraction of cross-sectional area occupied by the water
Superficial velocity:	The mean velocity, which the phase would travel at if it occupied the whole of the channel cross section.
In situ property:	Local property at certain moment
Flow pattern:	A description of the geometrical distribution of a multiphase fluid moving through a pipe
Pour point:	Minimum temperature at which the fluid can flow

ABBREVIATIONS

CFD	Computational fluid dynamics
SW	stratified wavy
SWD	stratified wavy drops
SMW	stratified mixed water layer
SMO	stratified mixed oil layer
VOF	Volume of fluid model
API	American petroleum institute
S. G	Specific gravity
PIG:	Pipeline integrity gauge
BLPD	Barrel liquid per day
FR	Flow rate

Chapter I

INTRODUCTION

CHAPTER I

INTRODUCTION

1.1 PREFACE:

Interest in studying the liquid-liquid flows has increased in the second half of the last century [Grassi B. et al, 2008] however the driving mechanism of the two liquids flow are not yet clearly obtained and it is approved from the conducted studies that such knowledge can not be simply borrowed from gas liquid field for which a larger literature is currently acquired by extensive researchers work. [Grassi B.et al, 2008,].

Different experimental works are conducted by researcher to improve the understanding of the two liquids flows starting from the late 1950s when the first documented experimental study was reported [Russell et al, 1959] Number of experiment were conducted by Russell in a 1 inch pipe of 8 meter length from which he could observed and therefore suggest the first classification of the liquid – liquid flow patterns. These early investigations proved that gas liquid two phase models are not capable to predict liquid- liquid two phase flow behavior. Moreover, most of the available published literature is related to relatively small diameter and laboratory scale systems.

The current work intends to investigate the oil water two phase flow in 6 inch pipeline at full field scale to identify how the pressure drop is influenced by different factors in order to improve the pipeline operation.

1.2 OBJECTIVES:

The objectives of this work is summarized in following three objectives:

- To study the concurrent flow of oil and water (two phase fluid flow) in horizontal pipelines and the factors affecting the pressure gradient along the pipeline.
- To investigate the influence of each flow parameters such as pressure, viscosity, temperature, mixture composition.
- To propose potential opportunities for the flow improvement that can help facilitating the flow and improving operation economics.

1.3 PROBLEM STATEMENT AND RESEARCH QUESTION:

Normally the oil produced from oil field is normally associated with water and hence they need to be transported simultaneously via pipelines between the processing facilities and to the export terminals.

While flowing through long pipelines, oil-water mixture flow takes different flow regimes that changes due to changes in the operation conditions and probably pipeline geometry. Resistance to flow varies along the pipeline due changes in crude oil characteristics, mixture composition. Moreover, ambient condition can also have its impact on the flow ability.

Currently chemicals injection is widely used to improve flow ability through pipeline. However this chemical are costly and thus it affects the operational cost. Moreover, the associated safety and environmentally risk in handling such chemicals cannot be ignored.

Good understanding of the oil water mixture flow behavior will enable the operating companies to optimize the design and operation of the transportation pipelines and hence minimize the operational problems and cost.

This research tends to study this type of flow and identify what are the parameters that having significant effect on the pressure drop and how is their effects.

1.4 SIGNIFICANCE

This research will help better understanding of the liquid-liquid systems flow and therefore help developing flow assurance plans. Further it will help minimizing chemical consumption and hence safety concerns.

Moreover, improving the flow characteristic will obviously save the investment being made in the bigger pumps and power consumed for pump operation. Nevertheless, this shall enhance pipeline integrity by reducing the pipeline operating pressure and minimizing safety risks associated with chemicals and contaminated water disposal.

1.5 RESEARCH METHODOLOGY

1.5.1 Overview of approach

The study is based on the observation and operation of actual field pipeline of 50 km long operating in Sudan. The geometry of the pipeline and specification of the flowing fluids are used to build and validate a model using computer software which is later used to study the impact of variations of different parameters.

1.5.2 Data Collection

The pipeline is located in Canar oil field in the south west of Sudan and extends to 50 km long with 6 inches diameter. It used to transfer stabilized clean water oil mixture. Operating parameters such as suction and discharge pressures, temperatures, flow rates and water cut (concentration) is being recorded on hourly basis using calibrated instruments. This data have been recorded for a long period and utilized to build and validate the simulation model.

1.5.3 Data Analysis

The collected data have been averaged to get the daily values and screened to omit the very odd values. Then the computational model is designed based on physical specifications and initial are fine-tuned and validated with available data.

1.5.4 Interpretation

Validated and fine-tuned model is utilized to manipulate the operation parameters to investigate the impact of each parameter on the flow characteristics with special attention to the pressure drop along the pipeline as intended by the study.

Chapter II

LITERATURE REVIEW

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

Fluid flow is said to be multiphase flow when two or three fluids of different specifications flows simultaneously, or a similar fluid flows at two different states of matter in the same time in a conduit (e.g. water and steam) and they have an interface which is influenced by the flow of the two fluids . As such, the multiphase flow can be of liquid-liquid (e.g. oil-water) or liquid-gas (e.g. water-steam), liquid-solid (e.g. slurry) or other combination of any two or three types of fluids. The multiphase flow can basically be characterized by the interaction between the different components and its impact on the flow characteristics.

In fact, most of the flows in the nature as well as in many of industrial applications and day to day life are of the multiphase types, such as:

- The blood and body fluids represent two fluid flow systems (blood component and oxygen distribution via blood).
- Rainfall and river streams represent multiphase flow streams as well (water flow through air representing liquid gas two phase flow).
- Moreover, steam and water flow in boilers, as well as refrigerant flow in refrigeration cycles is another systems of multiphase flows (liquid gas flow).
- Flow of the mixture of the atomized fuel and air in the combustion chambers represents another multiphase flow system.

- In addition, oil well production and crude oil processing and transportation includes different multiphase flow systems.
- Slurry

The wide range over which the multi fluids or multiphase flow application is spread and the complexity associated with it made it crucial to study the characteristics of this type of flow. However, with the recent developments in computer sciences, it becomes possible to use the numerical methods to simulate such complications.

2.2 FLOW PATTERNS (REGIMES):

Based on different parameters such as velocity of the flow, conduit geometry and specifications (roughness and inclination) and flowing fluids properties (viscosity, density, surface tension, etc.). [Roberto Ibarraa et al, 2014].

Difference between the two fluid densities has a great influence on the flow. Large density ratios cause the two phases to travel at different velocity as can be observed in gas liquid two phase flows. However in liquid-liquid flows the density ratios are not that high and sometimes it tend to be nearly the same and thus it has no significant impact on the flow. Whereas the viscosities can vary from 0.3 to 10,000 [Valle, A., 2000] and thus it prevails in such flows.

Three different forces are actually presents in the liquid-liquid flow in pipelines. Those are the viscous and gravitational forces which tends to eliminate the perturbation and maintain smooth interface, and the inertia force which maintains continuous fluid and prevent slugging, and interfacial forces which minimizes the interfacial energy. Variation of these forces is causing the flow pattern to vary.

Despite the extensive work made by researchers on oil water flow, still there is no much consensus on how to classify the oil water flow regimes [WeiWang et al, 2013]. This, can be because of the difference in the tools and experimental condition at which the flow regime are observed. Tools used in identifying flow regimes includes conductivity measurement, Gamma densitometer and high frequency impedance probes [A.A. Al-Moosawy et al 2008], while other workers rely on the visual observation such as [13. Antonio C. et al, 2004] or CFD applications as what [Mohammed A. Al-Yaari, 2011 , 12. Akter, F. and Deb, 2017] have done.

Al-Moosawy [A.A. Al-Moosawy et al, 2008] classified four main flow regimes that can observed in liquid-liquid flow which are stratified, large slugs, dispersed and annular flow regimes.
In horizontal liquid – liquid flow there are up to 3 main types, Segregated Flow, Intermittent Flow and Distributive Flow. Different flow patterns can be defined as follows and illustrated in fig (1.1) below:

- Segregated Flow: in which each fluid flow separately and can be divided up into Stratified, Wavy and Annular Flow.
- Intermittent Flow where batches of one fluid is flowing and separated by the second fluid and can be divided up in to Plug and Slug Flow.
- Distributive or dispersed Flow where droplets of one fluid are entrained in the other fluid.

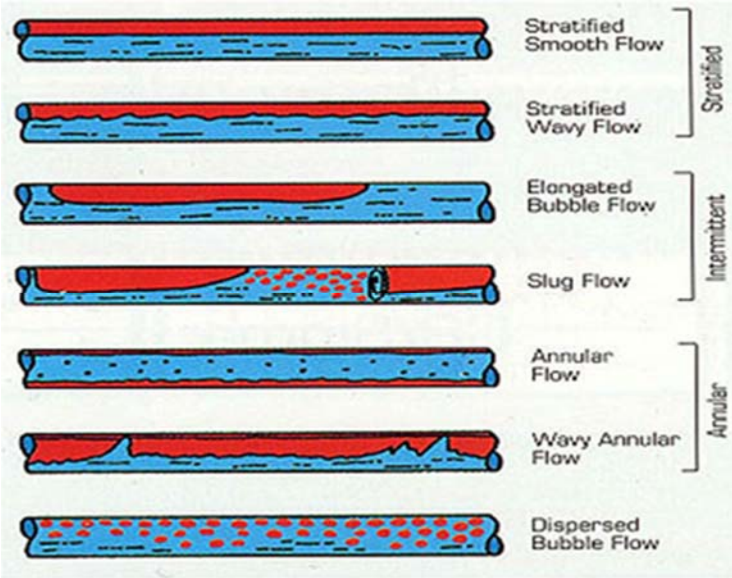


Fig (2.1) Main flow regimes in horizontal liquid-liquid flow

2.3 FLOW PATTERN (REGIME) MAP

Flow pattern map can is produced by plotting two different parameter such as superficial velocities or water or oil fraction in a chart where the observed flow pattern is displayed. It is normally plotted for specific flow and can be based on the superficial velocities of the oil and water as that of [Vielma et al., 2007] which illustrated in fig (1.2) or can be based on the mixture velocity and the water fraction as that of [Mohammed A. Al-Yaari, 2011] which illustrated in fig (1.3) . This flow regime maps show the transition between the different flow regimes.

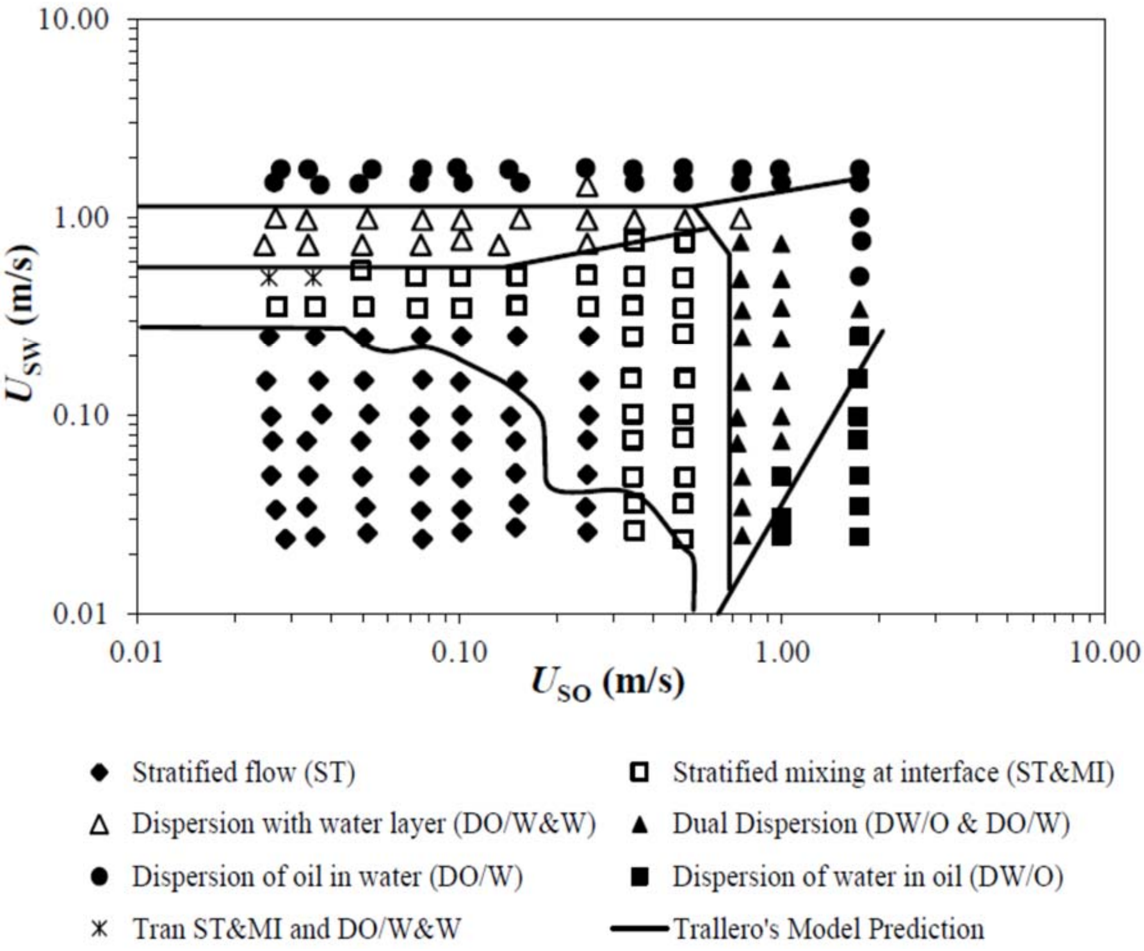


Fig (2.2): Flow pattern map for oil-water horizontal 2-in. pipe. Comparison with Trallero (1995) transition boundaries model [Vielma et al., 2007]

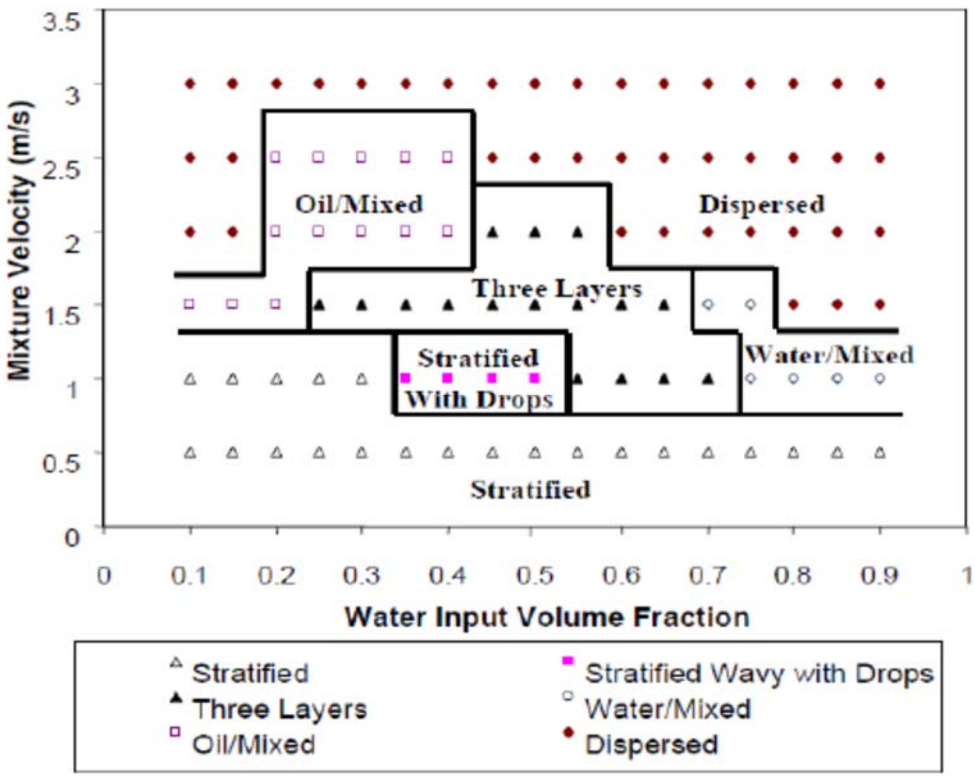


Fig (2.3): Flow pattern map of oil water flow (adapted from Mohammed A. Al-Yaari, 2011)

These patterns are predicted by using flow regime maps as shown below. From the flow regime transition map it can be seen that multiphase flow attends different flow regimes. These flow regimes are dependent on the difference in rate and velocity flow, gas and liquid. Simulation models that solve the full Navier Stokes equations for three phase flow can indicate which flow regime is present at any time in the pipe.

As can be seen the flow regime varies along the line with superficial velocities of the oil and water. This is because the pressure drop along the line and impacts on the equilibrium between the phases and the amount of oil, water change, which again impacts on the actual velocity along the pipe and the flow regime.

2.4 MEASUREMENTS IN MULTIPHASE FLOWS

Different measurement tools and instruments are used to identify liquid-liquid flow characterizes such as the flow rates, liquid hold up, flow patterns, wettability, interface, etc.

Some of tools used for estimating liquid holdup includes conductivity sensing probes, impedance probes and quick closing valves. Flow image visualization is obtained by using transparent pipes along with high speed cameras or complete Particle Image Velocimetry (PIV) system. In some other cases, flow pattern is predicted by combinations of instruments reading and other empirical correlations. Other tools may include pressure and temperature gauges and transmitters, flow meters, etc. some of these tools are illustrated in fig (1.4) below.

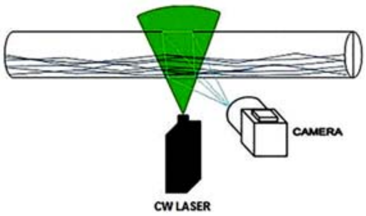
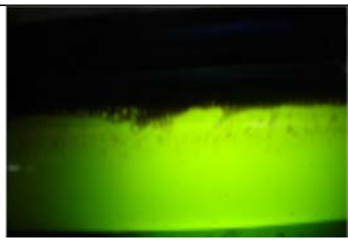
Visualization tools		
	High speed camera, video camera and Particle Image Velocimetry (PIV)	Flow patterns image captured by high speed camera
Measuring tools (pressures, flow rate, temperatures, etc.)		
	Gamma densitometer (density and concentration)	Flow meters
Data acquisition tools (PLCs, computer, data cards, etc.)		
	Computers	Data aqcuisition card and PLC

Fig (2.4): Some of the measurement tools used in multiphase flow investigations systems

2.5 PREVIOUS STUDIES

The flow of liquid-liquid mixture in micro channel has mostly being studied from mixing performance aspect as noted by [Ben-Ran Fu, 2013] and the pressure drop in such flow has rarely been investigated. Thus, he investigated the pressure drop in liquid-liquid mixture of (sulfuric acid (H2SO4) and sodium bicarbonate (NaHCO3)) and water in rectangular silicon-based micro channels with uniform and varying cross-sectional areas as determined experimentally and numerically.

He followed the conventional way in multi-fluid experiments by feeding the two fluids separately and made them mixed before the test section. The sulfuric acid and sodium bicarbonate can chemically interact together and produce CO2 bubble (H^+ $+HCO_3$ $\rightarrow$ O_2 $+H_2O$) if they get sufficient time or have high concentration. To avoid such complications the author considered solution of concentration low enough and flow rate high enough to prevent such chemical interaction. He run the experiment for different concentrations.

The researcher has set the test rig to have to two uniform shape pipes to feed the individual fluid to the test section which is conversion divergence shaped. Further, pressure differential transducer was used to measure the pressure drops. Flow simulation is carried using commercial software (CFD-ACE+). Grid independence assured with different numbers of cells. Moreover, fixed atmospheric pressure assumed at the outlet and steady inlet flow rate and no slip condition at all channel walls.

Finally he made the theoretical analysis for the pressure drop based on Hagen–Poiseuille equation. He reach a good agreement the experimental result and CFD findings as shown in fig (2.1).

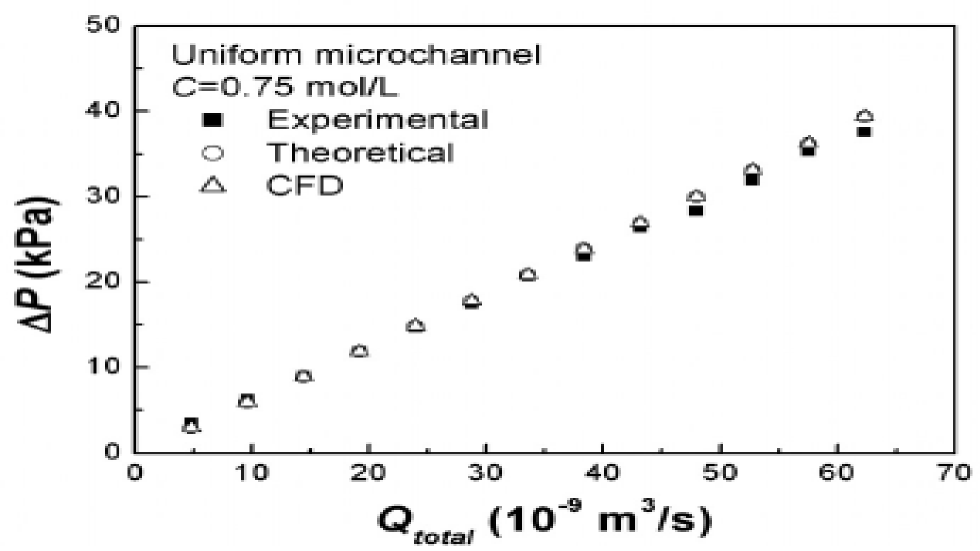


Fig (2.5). Comparisons of total pressure drops among experimental, theoretical, and CFD simulation results in uniform micro channel [Ben-Ran Fu, 2013]

For the uniform micro channel, the velocity profile evolved from a two-peak velocity profile at the intersection between the front channels and main channel (x/L = 0) into a fully developed velocity profile for x/L = 0.03. It revealed very good matching with the analytical fully developed velocity profile. For converging and diverging sections, the velocity profiles continued to develop from two-peak distributions into parabolic velocity profiles in the axial distributions due to the changes in the channels' cross sections. The theoretical analysis of velocity profile at x/l =0.6 for the converging part and x/l=0.4 diverging part agreed with analytical solution assuming uniform cross section at those specific points.

However while the pressure in the main channel of the uniform cross section distributed linearly, the pressure distribution dropped rapidly near the converging part exit and decreased rapidly in the diverging part and slowly near the outlet. Therefore further drop may enable bubble flow in divergent micro channel. He also found that pressure drop increased proportionally with the flow rate and mixture concentration as illustrated in figure (2.2).

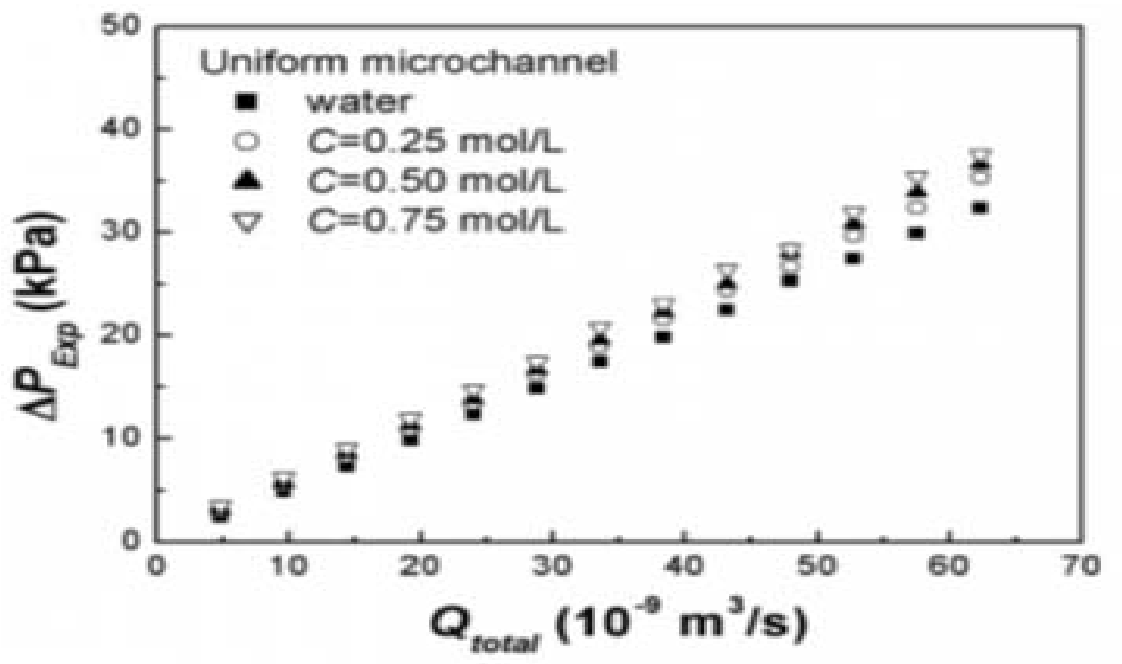


Fig (2.6): pressure drop in uniform micro channel Vs. flow rate at different concentrations [Ben-Ran Fu, 2013]

Another efforts made by [Wei Wang et al , 2013] to investigate the oil water two phase flow system in order to formulate a systematic way for the prediction of flow patterns transition across different oil phase viscosities. The authors discussed the models of flow patterns transition and developed model for the analysis which they used to investigate the flow through 1, 2 and 3 inches pipes with the viscosity ratio of oil to water is 29.6 and interface tension of 0.036 N/m. Accordingly they claimed that stratified flow pattern dominated with the increase of the pipe diameter while dispersed pattern prevailing with narrower diameters. This is basically because the gravity effect tends to delay interface disturbance and bring the flow pattern to stabilization. However, in small diameter pipes, the turbulent energy and energy dissipation rate are high enough to overcome the gravity effect.

Moreover, for the same pipe dimensions and mixture composition, it is found that higher flow velocities is required to maintain oil in water dispersed flow than what required to maintain water in oil dispersed flow pattern.

In order to investigate the viscosity effect, different viscosities, same pipe diameter and fixed interface tension are used (10, 50, and 80mPa·s, 2 inch diameter and 0.036 N/m). The prediction yields that increase of viscosity reduces tendency for stratified flow pattern and increases tendency for water in oil dispersed flow pattern while it has poor influence in tendency for oil in water dispersed pattern. Further, increase of viscosity promotes the viscous instability and reduce the superficial velocity needed to maintain the stratified flow pattern.

He concluded that the impact of gravity, viscosity and interfacial tension in the stabilization of oil water separated flow (stratified) is significant. Moreover, the impact of shear stress in viscous oils is very clear and can be characterized by ignoring the velocity of the viscous phase (oil).

Oil water flows patterns in horizontal pipes have been studied by [Mohammed A. Al-Yaari, 2011], who used the CFD capabilities by using the commercial software Fluent 6.2 to solve the governing equations for the stratified oil water flow in horizontal pipes based on finite volume method. The author had examined different available models for flow pattern investigation and conducted mesh independency study.

Further, he conducted experimental work to investigate the flow patterns. He changed the mixture input velocities and water fraction in the input mixture, and thus he noted the following patterns of flow: stratified wavy(SW) flow, stratified wavy drops(SWD), stratified mixed water layer(SMW), stratified mixed oil layer(SMO), three layers of flow and dispersed flow pattern.

He found that volume of fluid (VOF) with RNG-ϵ is the optimum model to simulate the oil water stratified flow patterns.

He concluded that although it was possible to predict the noticeable separated oil layer and the wavy interface, but it couldn't be the same for the separated water layer.

Dry crude oil is studied by [Mysara, 2014] who studied the rheological behavior of the Nile blend crude oil across wide range of temperature using the viscometer HAAKE VT 150 which revealed that the crude assumed none newtonian solidification and Newtonian behavior. These different models were applied to simulate the pressure loss between different pumps stations under specified operation conditions as well as predicting the restarting pressure after frequent shut downs.
The author carried out his study in two stages. Firstly, a sample of the crude oil (Nile Blend) has been tested at the laboratory to get the viscosity over arrange of temperature that simulate the actual line operating temperatures. Secondly he employed published analytical models to calculate the pressure gradient along the pipeline and the yield pressure the required to overcome for startup after shutdown, he found that when the crude is preheated to 60°C, it starts solidified at 29°C. He used this point to differentiate between the Newtonian and no Newtonian properties. When temperature is 12 degrees above solidification point, the crude assumes Newtonian behavior. The author developed different equations to describe the rheological behavior of the crude oil:

$$\mu(T) = 1 * 10^{-4.508}$$

$$k(T) = 6 * 10^{9} e^{-0.4606}$$

$$n(T) = 0.0022\, T^2 - 0.92T + 1.1109$$

And below the solidification point the yield stress is found to be:

$\tau_y(T) = 236.27 - 5.6371\, T$

Which can be used to calculate the pipeline startup pressure requirement when substituted in:

$$\Delta P_y = \frac{4\, \tau_y\, (T)\Delta l}{D}$$

The author concluded that, the Nile blend crude oil has a temperature dependent rheological behavior. It assumes Newtonian behavior till it reaches 40°C while it assumes non Newtonian behavior if the temperature dropped below that.

Moreover the pressure drop increase rapidly when throughput increased to higher than 300 kg/sec and thus precautions must be taken if it is required to go beyond that limit.

Pressure drop in two phase flow has attracted [W. Adrugi et al, 2016] who investigated the pressure drop of liquid-liquid stream in narrow pipes analytically and experimentally. They described the pressure drop by a theoretical function of slug function and capillary number. Low Reynolds flow number had been considered for the experimental work. Water and low viscosity silicone oils at different flow rate were used for the experiments. The set up was made to provide a changeable length of slug. The experiment was found to agree with analytical model of Taylor flow in small scale pipes. The resulted pressure drop is compared with a single flow pressure drop and concluded that pressure drop in two phase flow is quite higher when compared to pressure drop in single phase flow it was justified to be because of the effect of interfacial effect on liquid slug.

The authors in [Kumara et al, 2009] have investigated the oil-water flow in horizontal and slightly inclined. They carried out experiments in flow loop of 15 meter long pipe of 28 millimeter radius. Exxsol D60 oil of 790 kg/m^3 density and viscosity of 1.64 mPa s is used along with water of 996 kg/m^3 density and 1.00 mPa s viscosity are used as working fluids. The pipe orientation is made to be (+/- 5 degrees) from horizontal. Variable inlet velocity water cuts are also practiced and then the time averaged distributions of oil and water phase across the cross section is measured using a single-beam gamma densitometer. Measurements of the pressure drop along the test section were also recoded. Flow pattern and transitions between different patterns were determined by analysis of the densometer reading of phase's distributions and by visual observations. The authors observed that separated flow pattern dominated during lower inlet mixture velocities while the dispersed flow patterns dominated at high inlet velocities.

For inclined pipe orientations, the dispersed flow regime observed during lower inlet velocities. The experimental findings were compared with those of a flow pattern dependent prediction model that uses the area average steady state two fluid model found to be able to predict the pressure profile of dispersed flow at higher water cut for stratified flow, and homogeneous model for dispersed flow. The two fluid model was found to be able to predict the pressure drop and water holdup for stratified flow while the homogeneous flow model could not predict the pressure drop for the dispersed flow pattern at high water cuts. Both models over predicted the pressure drop for dual continuous flow.

Crude oil viscosity reducing is investigated by [Dehaghani and Badizad, 2016] when the worker tried to reduce the viscosity of heavy crude oil by dilution approach. They mixed different industrial solvents and gas condensates with two samples of Iranian heavy crude oils at different temperatures and they observed

reduction in the viscosity when dilutes the samples with toluene and heptane. However, they observed that the effect became less significant at higher concentrations of diluent. This is interpreted as a result of forming hydrogen bonds, adding methanol to heavy crude oil resulted in higher viscosity. Addition of methanol increased the viscosity, while addition of condensate resulted in reduced viscosity. Different models of predicting mixture viscosity were also investigated and found that of Lederer is the most successful in predicting viscosity of such mixture.

Further they concluded that temperature factor has the most significant impact on reducing the viscosity of heavy oil.

The researchers in [Lawrence et al, 2010] had modified a two fluid model based on experimental observation of the interface configurations in separated flows. A 14 millimeter internal diameter acrylic pipe is used to test the water and oil flows at superficial velocities ranging srom 0.05 m/s to 0.62 m/s for oil and from 0.02 m/s to 0.51 m/s for water.

Usage of the conductance probe enabled the researcher to obtain the interface heights which are obtained at the pipe center and near the pipe walls indicating that the interface had a concave shape in all cases under investigation. The authors developed a correlation between the two heights to be used in the two fluid model. Further the average wave amplitude was calculated from the time series of the probe signal at pipes center and had been used as an equivalent roughness in the mode of interfacial stress. The obtained roughness and interface shape along with the interfacial shear stress correlations from the literature are used in the two fluid model. Findings proved that the two fluid model predictions of pressure drop and interface high had improved by inclusion of the equivalent roughness and interface curvature along the superficial velocities under investigation. The

authors concluded that modified model performed well compared to two fluid model with other correlation of shear stress, especially for predicting pressure drop.

The flow of heavy crude oil with water in the horizontal pipes has been experimentally investigated in [Wei Wang et al, 2011]. The workers used a flow loop of 25.4 mm (1inch) stainless steel pipe of 50 m overall length. Operating fluid used is crude oil (of 628.1 mPa s viscosity and 10.33 mN/m interfacial tension) and water. They took pressure drop reading and sampling along with the visual observation to identify the flow patterns and patterns transition.

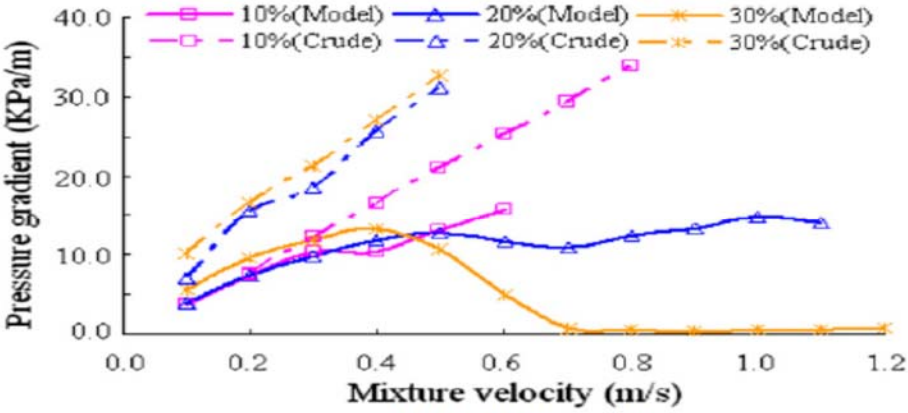
Worker conducted the experiments at 60 ºC in the crude storage and the pipeline, they used electrical heating and water circulation as well as insulation to maintain this temperature. Crude oil for the experiment is collected from an oil field and dehydrated before feeding to the system while the water phase was filtrated of the separated water. Both, crude oil and water were then fed to storage and properly mixed to compose a homogenous oil water mixture before being fed to the flow loop.

According to their work, they found that water in oil emulsion observed all through the condition studied. And this emulsion prevailed particularly at low mixture velocities and low water fraction. When mixture velocity or water fraction increase, water tends to separate. They also noticed annular flow where water in oil emulsion flow in the core surrounded by a water layer, during the high mixture velocity and water fraction.

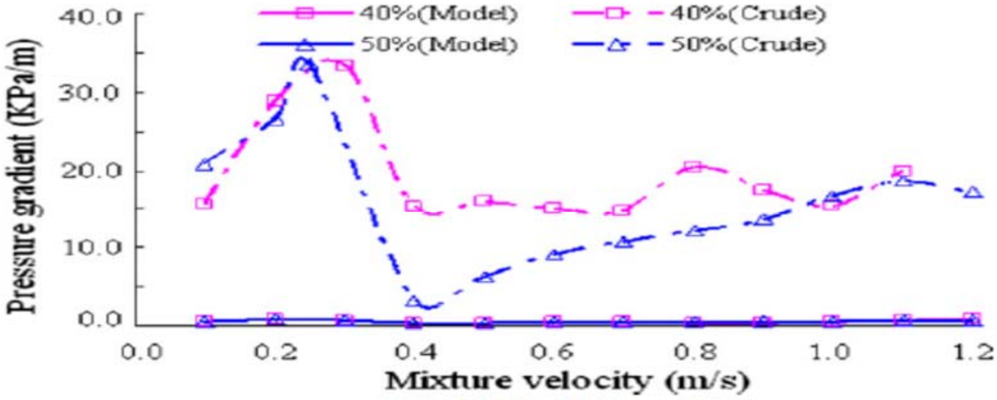
Same experiment was conducted using model oil of similar properties and results were compared to that of the crude oil. Behavior similarity is observed at low

water fractions. However, at high water cuts, an oil in water dispersed flow patterns is noticed in model oil system unlike the crude oil flow system.

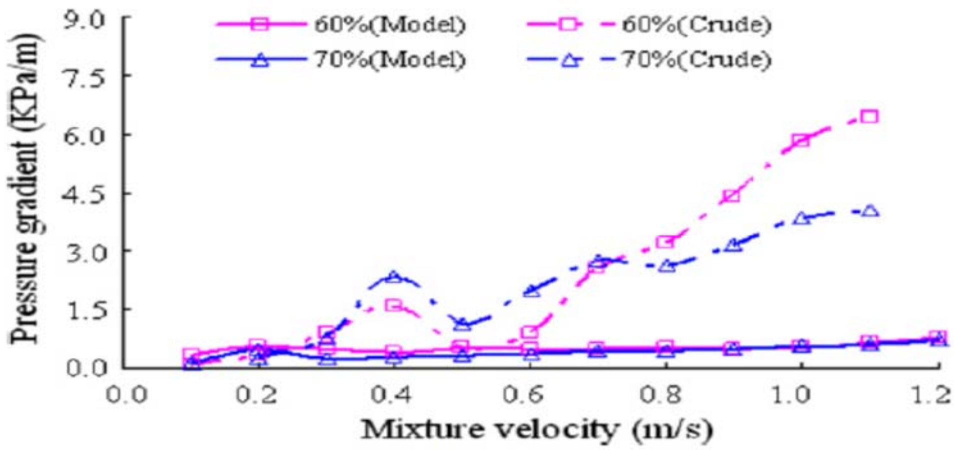
As illustrated in fig (2.3), in both cases the pressure drop decreased upon water separation. However, the pressure gradient in crude oil system is generally higher than that of the model oil. The authors claimed that the difference is caused by the natural surfactant naturally found in the crude oil such as asphalting that tends to accumulate on the interface and enhance the stability of the emulsion.



(a) WF=10% – 30%



(b) WF=40% – 50%



(c) WF=60% – 70%

Fig (2.7) a/b/c: Pressure gradient against mixture velocity of heavy crude oil (60 °C) & model oil (30 °C)–water flow at different water fractions

Flows of Free water-crude oil mixtures in pipelines is investigated by [Melissa et al, 2000]. They used two pipelines for this investigation including a 60 meter

long pipeline of 52.7 mm internal diameter and another flowing loop of 100 meter long and 105.3 mm internal diameters. Both lines were horizontal and insulated.

Tests were conducted at different water fractions and temperatures. They achieved water assisted flow at water fraction of 0.1. They used this fraction and temperature of 38 ^{o}C for the test in the bigger pipe of 105 mm and vary the superficial velocity of the mixtures from 0.3 m/s and 0.77 m/se and from 0.5 m/s to 1.2 m/s for the 53 mm pipeline.

Further, the tests were stopped for the whole night and operation started again and pressure drop recorded during the restart process.
From the finding they obtained it is clear that pressure gradient increase with the increase of the flow rate as well as the viscosity (inversely proportional with the temperature), as indicated in fig (2.4) and (2.5).

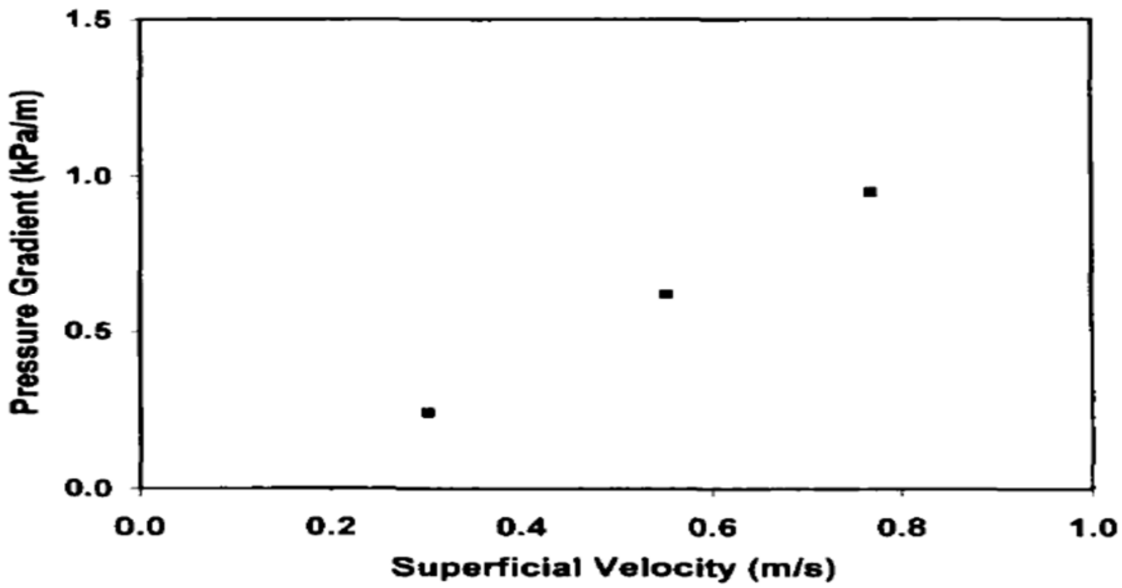


Figure (2.8): Effect of superficial velocity on the Pressure gradient as adopted from [Melissa et al, 2000]

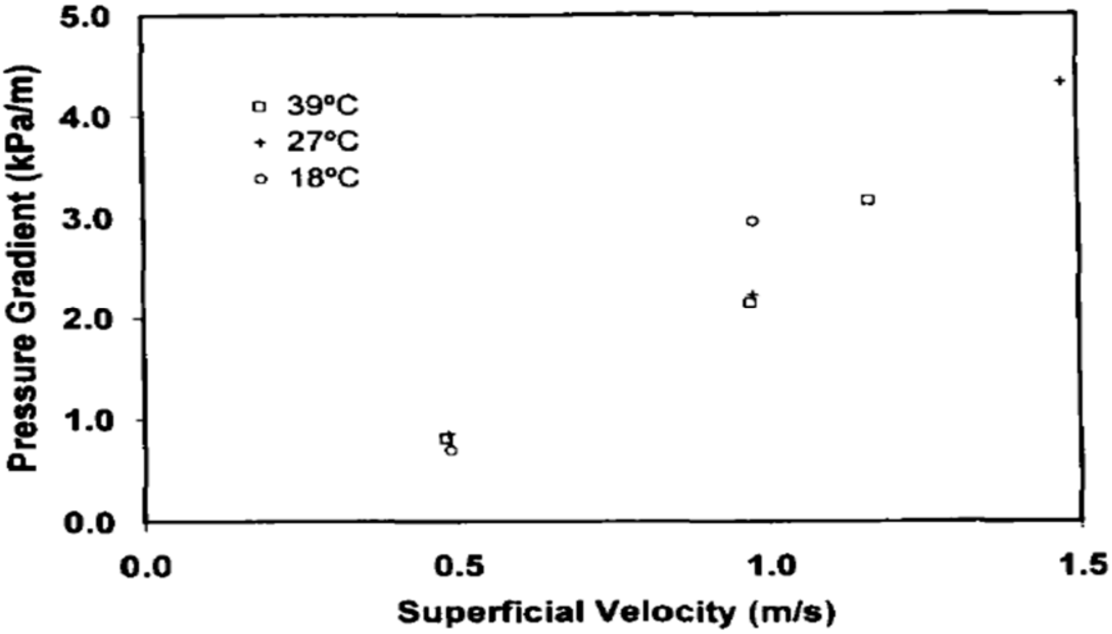


Fig (2.9): Oil viscosity effect (temperature) on pressure gradient [Melissa et al, 2000]

From the presented studies it can be noted that most of the studies are based experimental works at small scale and none of them is based on actual operational data or full scale system, which will require accurate correlation to scale up the finding to the actual field problem.

The current work combines the CFD capabilities and actual operation historical records to investigate the crude oil and water flows in the horizontal pipelines with special focus on the pressure drop at the full scale pipeline of 6 inches diameter and 5000 meter length. The actual physical pipeline specification and operation model is used to build the computational model and the available data is used to validate the computational findings. Obtained results are compare to presented previous studies and found to be in fairly agreement.

Chapter III

MATHEMATICAL AND COMPUTATIONAL WORKS

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MATHEMATICAL AND COMPUTATIONAL WORKS

3.1 MULTIPHASE FLOW MODELS

The fluid flow can normally be computed using the drift flux model or two fluid model. In the drift flux mode, the mixture of the two phases is considered for the solution. Therefore properties of the mixture need to be properly estimated which required carefully made assumption.

In the two fluid model, each of the two fluids is treated separately with consideration of the interface. The flow is governed by the continuity equation, momentum equation and the energy equation. The balance equations contains the interaction terms to incorporate the transfer of mass, momentum and energy from interface the phases which made it more complicated than drift flux model the single phase model.

Advantages of separated model over the drift flux model are:

- Suitable for weak coupling between phases.
- Rapidly changing inertia of each phase.
- Can predict more detailed changes and phase interactions.
- Can account for dynamic and non-equilibrium interaction between phases.
- Useful for analysis of transient phenomena, local wave propagation and related stability problems as well as flow regime transitions.
- Useful for three dimensional flow as developing the relative velocity correlation in a general three dimensional form extremely difficult.

Disadvantages of the separated model over the drift flux model can be summarized as:

- When total response of two phase mixture is more important the local behavior of the individual phase.
- With the strong coupling between phases.

3.2 MATHEMATICAL MODEL

The following assumption are considered:

1- Steady flow
2- Horizontal pipeline
3- Incompressible fluids (water and oil)
4- No heat transfer (adiabatic flow).
5- No slip condition at pipe walls.

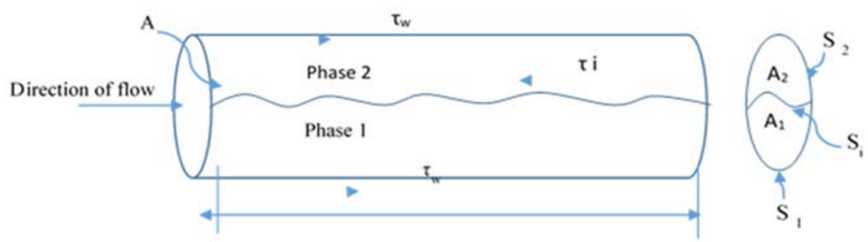

Figure (3.1): Flow control volume schematic

With reference to figure (3.1) and assumption made above, continuity equation application on the control volume yields that:

Phase 1:

$$\frac{\partial}{\partial t} + \left(\rho_1(1-\alpha)\right) + \nabla.\left(\rho_1(1-\alpha)u_1\right) = S_{12} + S_1 \text{ --------------(A)}$$

Phase 2:

$$\frac{\partial}{\partial t}(\rho_2 \propto) + \nabla.(\rho_2 \propto u_2) = -S_{12} + S_1 \text{ -------------------(B)}$$

Where S_1 represent external source of matter enters the system and $S_{12}$is source term represents rate of change per unit volume.

The above equations could be simplified as follows:

For steady state flow:

$$\nabla.(\rho_1(1{+}\propto)u_1) = S_{12} + S_1$$

And for phase 2:

$$\nabla.(\rho_2 \propto u_2) = -S_{12} + S_1$$

Further, if both phase are incompressible($\boldsymbol{\rho = constant}$):

Phase 1: $$\frac{\partial}{\partial t}(1{-}\propto) + \nabla.\big((1{-}\propto)u_1\big) = \frac{S_{12}+S_1}{\rho_1}$$

Similarly, phase 2: $$\frac{\partial \propto}{\partial t} + \nabla.(\propto u_2) = -\frac{S_{12}+S_1}{\rho_{12}}$$

Again if there is no phase change: $S_{12}\ and\ S_1 = 0$

Therefore we will have:

$$\frac{\partial}{\partial t}(1{-}\propto) + \nabla.\big((1{-}\propto)u_1\big) = 0$$

And $$\frac{\partial \propto}{\partial t} + \nabla.(\propto u_2) = 0$$

Which is the continuity equation for each phase.

Integration of equations A & B along the pipeline yields:

$$\frac{\partial}{\partial t}\,(\rho_1(1-\propto)A)+\frac{\partial}{\partial z}(\rho_1(1-\propto)Au_1)=\int(S_{12}+S_1)dA$$

And $$\frac{\partial}{\partial t}(\rho_2\propto A)+\frac{\partial}{\partial z}(\rho_2\propto Au_2)=\int(-S_{12}+S_2)dA$$

Adding the above two integrated equations gives:

$$\frac{\partial}{\partial t}\,(\rho_1(1-\propto)+\rho_2\propto)\,A+\frac{\partial}{\partial z}(\rho_1\,(1-\propto)Au_1+(\rho_2\propto Au_2))\ \text{--------(C)}$$

Now let G_{TP} = mass flux = $(\rho_1\,u_1(1-\propto)+\rho_2\,u_2\propto)$

And ρ_{TP} = mixture density = $(\rho_1(1-\propto)+\rho_2\propto)$ and substitute both values in equation ----(C) above we get:

$$\frac{\partial}{\partial t}\,(\rho_{TP}A)+\frac{\partial}{\partial z}(G_{TP}A)=0$$

Which is the continuity equation for the mixture.

Momentum balance equation:

Rate of change of momentum = rate of momentum outflow – rate of momentum inflow – rate of momentum accumulation = net forces acting on the control volume.

$$(W_1u_1+\frac{\partial}{\partial z}(W_1u_1)\,\delta z)-\,W_1u_1+\frac{\partial}{\partial t}(u_1\rho_1(1-\propto)A\delta z)$$

Where $W_1=\rho_1(1-\propto)A$, and thus net rate of momentum change for phase1 becomes:

$\delta z\left(\frac{\partial}{\partial z}\, u_1^2\rho_1(1-\propto)A\right)+\frac{\partial}{\partial t}(u_1\rho_1(1-\propto)A)$ ----(D)

Force acting on the control volume for phase 1:

$P(1-\propto)A - P(1-\propto)A + \frac{\partial}{\partial z}(P(1-\propto)A\delta z) - (P\delta z\frac{\partial}{\partial z}\big((1-\propto)A\big) - \tau_{w1}\delta z S_1 +$
$\tau_{wi}\delta z S_i$ ----(E)

Equating momentum rate of change and net forces acting on phase 1 resulted in:

$$-(1-\propto)\frac{\partial P}{\partial z}-\frac{\tau_{w1}S_1}{A}+\frac{\tau_i S_i}{A}=\frac{\partial}{\partial t}\big(u_1\rho_1(1-\propto)\big)+\frac{1}{A}\ \frac{\partial}{\partial z}(W_1u_1)$$

And for phase 2:

$$-\propto\frac{\partial P}{\partial z}-\frac{\tau_{w1}\rho_1}{A}-\frac{\tau_{w2}\rho_2}{A}=\frac{\partial}{\partial t}(\rho_2\, u_2\ \ \propto)+\frac{1}{A}\frac{\partial}{\partial z}(W_2u_2)$$

Under steady state condition, phase 1 becomes:

$-(1-\propto)\frac{\partial P}{\partial z}-\frac{\tau_{w1}S_1}{A}+\frac{\tau_i S_i}{A}=\frac{1}{A}\ \frac{\partial}{\partial z}(W_1u_1)$ ----(E)

And phase 2 becomes:

$-\propto\frac{\partial P}{\partial z}-\frac{\tau_{w1}\rho_1}{A}-\frac{\tau_{w2}\rho_2}{A}=\frac{1}{A}\frac{\partial}{\partial z}(W_2u_2)$ ----(F)

Dividing $\frac{equation\ E}{(1-\propto)}\, and\ F/\propto$ and subtracting gives:

$$\rho_1u_1\frac{du_1}{dz}-\ \rho_2u_2\frac{du_2}{dz}=\ -\frac{\frac{\tau_{w1}S_1}{A}}{(1-\propto)}+\frac{\frac{\tau_{w2}S_2}{A}}{\propto}=\ -\frac{F_{w1}}{(1-\propto)}+\frac{F_{w2}}{\propto}$$

This equation describe the difference at which the phases are getting the kinetic energy (relative motion).

Adding equation E and F will result in the mixture momentum equation as follows:

$$-\frac{\partial P}{\partial z} = (\frac{\tau_{w1}S_1}{A} + \frac{\tau_{w2}S_2}{A}) + \frac{1}{A}\frac{\partial}{\partial z}(W_1 u_1 + (W_2 u_2)\ )$$

From the above analysis knowledge of the water hold up and interfacial shear analysis is mandatory to proceed with the analytical solution.

On the other hand, drift flux model may used as done by [Ben-Ran Fu, 2013] who proved that same approach can be adopted and can be further improved by making suitable averaging for the mixture properties such as density and viscosity to be used in the Hagen–Poiseuille equation for pressure gradient calculation along the pipeline.

3.3 COMPUTATIONAL WORKS

Alternatively computational fluid dynamics tools is proved to be very valuable in investigating the multiphase flow because of the flexibility and simplicity in manipulating the different parameters. Thus in this work commercial application of OLGA is used to make the required analysis. Computational flow model is constructed based on the actual pipeline geometry as indicated in table (3.1) below. Oil physical properties are also fed to the mode and indicated in table (3.2) while oil rheological properties is shown in table (3.3) and graphical illustrated in fig (3.2).

Table (3.1): Pipeline physical specifications

SN	Outer diameter [m]	0.1524
1	Internal diameter [m]	0.1366
2	Pipeline Length [m]	50 000
3	Roughness [mm]	0.125
4	Buried Depth(m)	1.2

Table (3.2): Oil physical properties

BS &Vol %)	Nil
Water Cut (Vol %)	83.2
Emulsion (Vol %)	Nil
API Gravity @ 60 °F (15.6 °C)	23.87
S. G. → Relative Density g/cm³ @ 60 °F (15.6 °C)	0.9107
Relative Density g/cm³ @ 60 °F (15.6 °C)	0.9099
Pour Point (°C)	< 6

Table (3.3) Oil rheological properties

Temperature ºC	**Viscosity mPa.s (cP) @ Shear rates 08s-1**
80	32.55
75	39.52
70	41.85
65	51.15
60	62.77
55	74.4
50	95.32
45	118.57
40	148.8
35	197.62
30	262.72
25	374.32
20	560.32

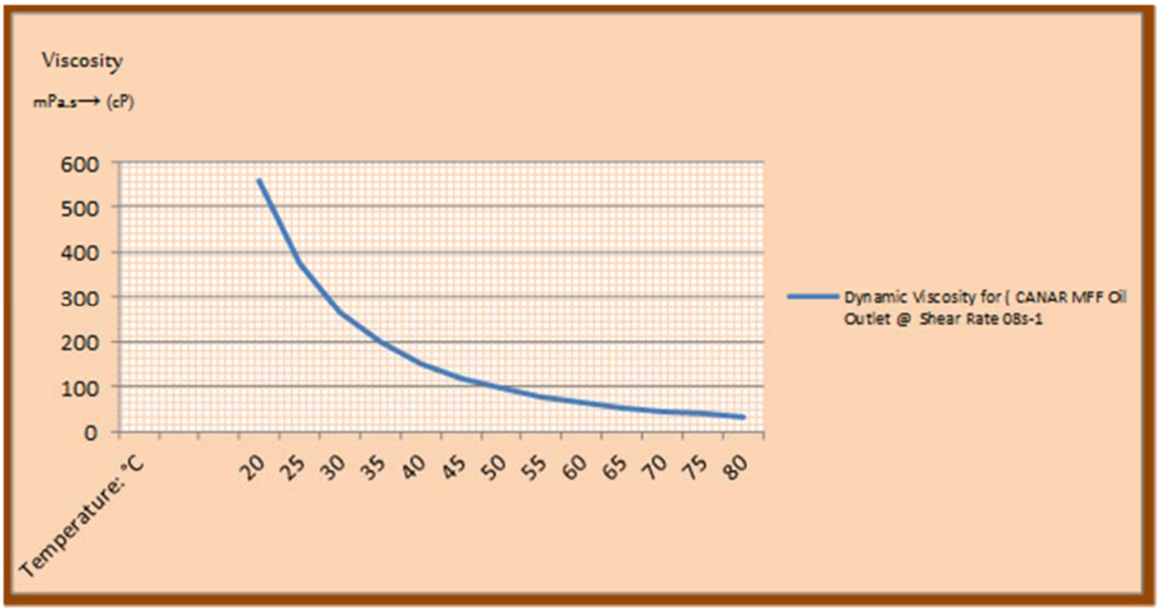

Fig (3.2): Graphical illustration of the oil rheological properties

3.4 MODEL VALIDATION

The model run made under the normal operating conditions and validated against the obtained history recoded data and found to give perdition at around 9% accuracy from the average recoded data

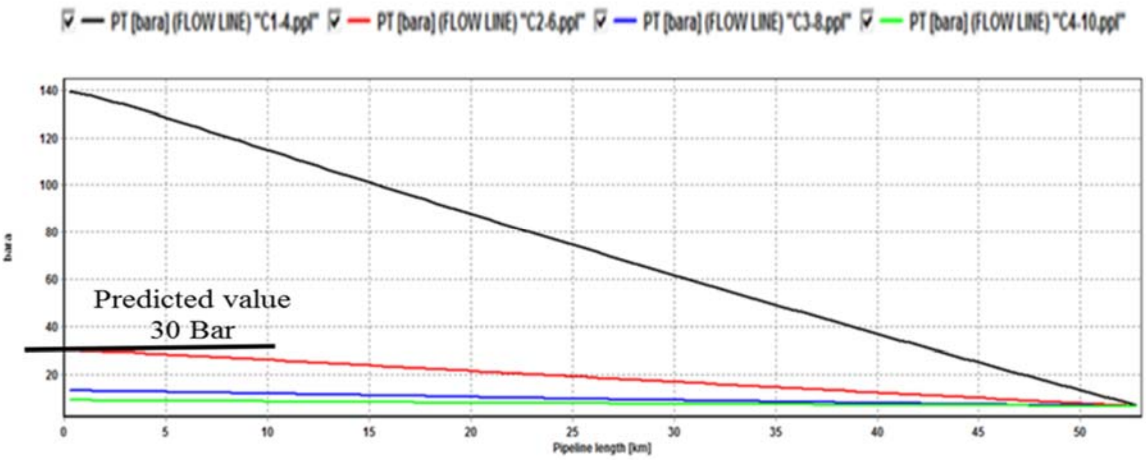

Fig (3.3): Predicted value of inlet pressure for model validation (against average recorded value of 27.5 Bar)

Chapter IV

RESULTS AND DISCUSSION

CHAPTER IV

RESULTS AND DISCUSSION

4.1 RESULTS AND DISCUSSION

Upon validation of the model, pressure drop in horizontal pipes is predicted at different values of water cuts, pipe diameters, inlet temperatures, etc. Three values for the flow rates are considered for each parameter and the results are plotted in the following charts. Accordingly, the results are discussed and consequently the conclusions are made.

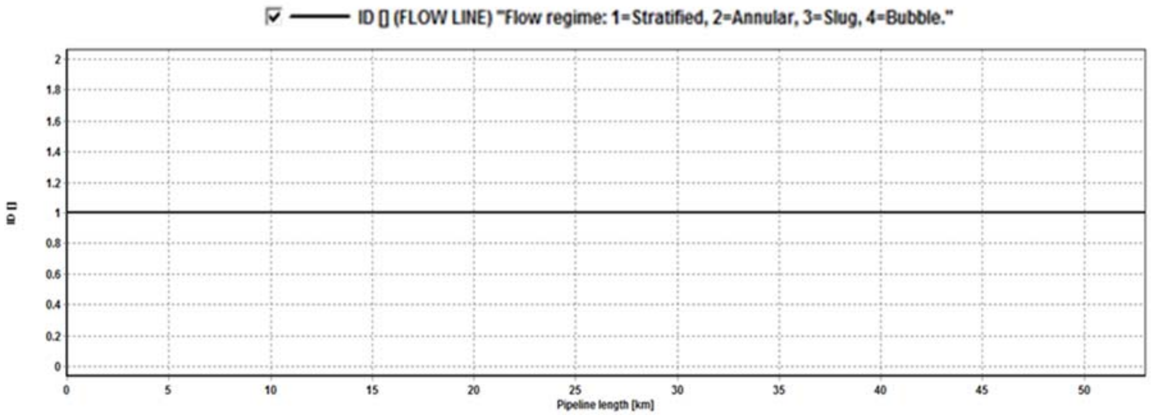

Fig (4.1): Flow regime along the pipeline at 1200 BLPD

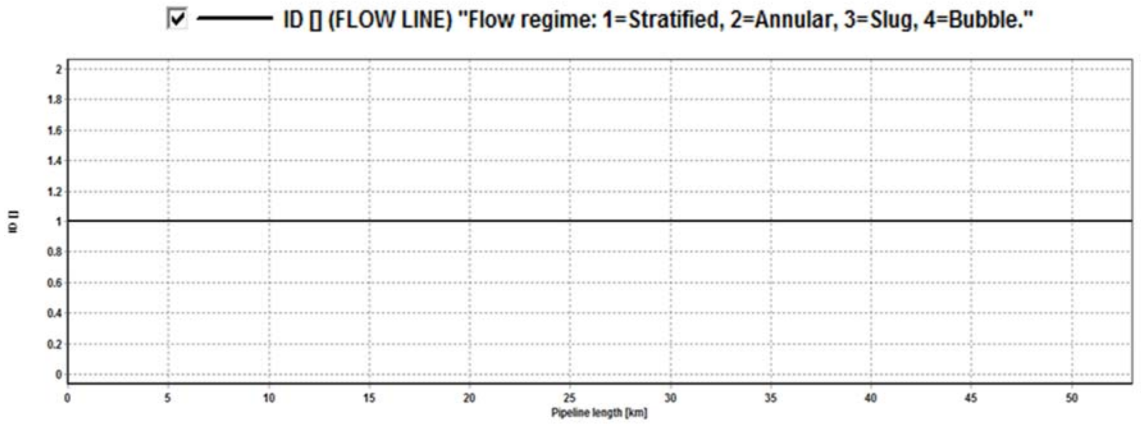

Fig (4.2): Flow regime along the pipeline at 4000 BLPD

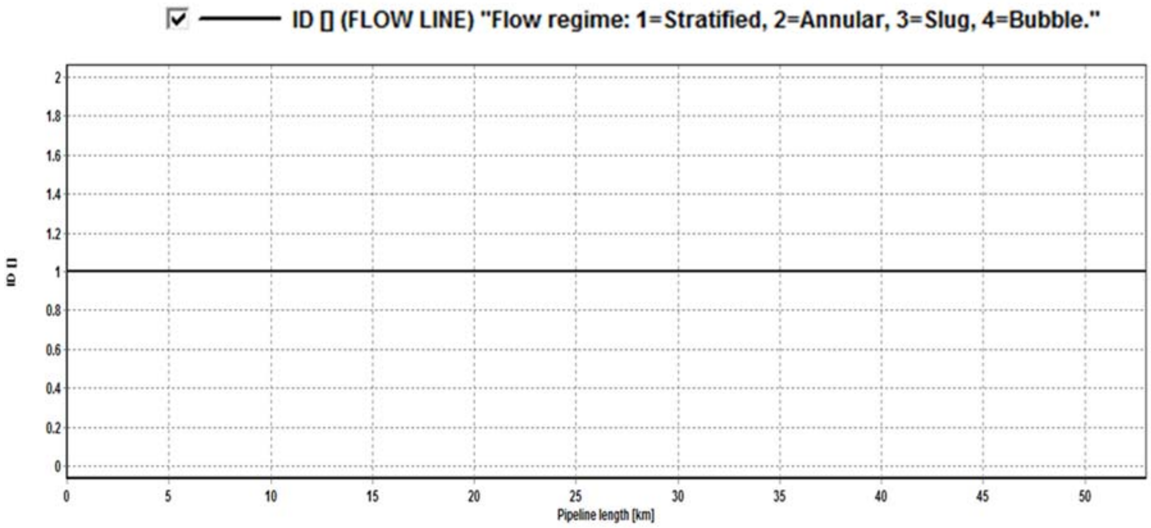

Fig (4.3): Flow regime along the pipeline at 6000 BLPD

Figures (4.1, 4.2 and 4.3) indicates the flow patterns prevails in 6 inch pipeline 1200, 4000 and 6000 BLPD flow rates which is found to be stratified flow for all the flow rates under investigation. This results agree well with that of [Kumara et al, 2009].

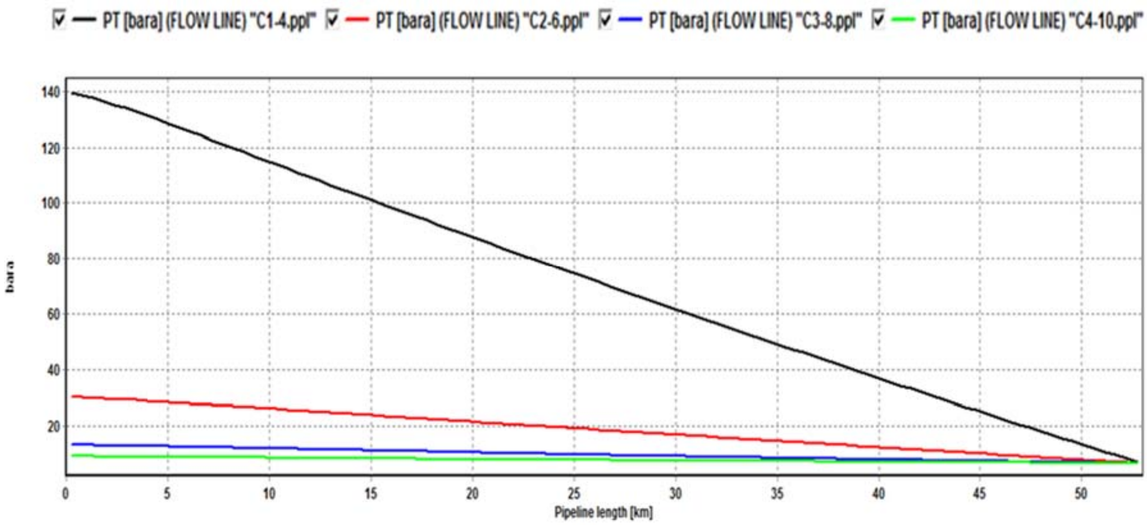

Fig (4.4): Influence of pipe diameter in the pressure drop at certain flow rate

Based on finding illustrated in Fig (4.4) it is clear that for the flow rates under study, 6 inches diameter is reasonable. Using of bigger pipes such as 8 or 10

inches will slightly improve the differential along the pipeline while using of smaller pipes (e.g. 4 inches) will sharply increase the inlet pressure requirement to achieve same landing pressure. Further, it can be noted that difference in local pressures between 4 and 6 inch pipes are greater in the beginning of the pipeline and this difference reduced as the flow propagate towards the end. This is attributed to the difference in the local flow velocity for the same flow rate resulting in larger friction losses in the beginning and the turbulent energy and energy dissipation rate are high enough to overcome the gravity effect .Worker in [*Ben-Ran Fu, 2013*], and [Melissa et al, 2000] concluded the similar finding.

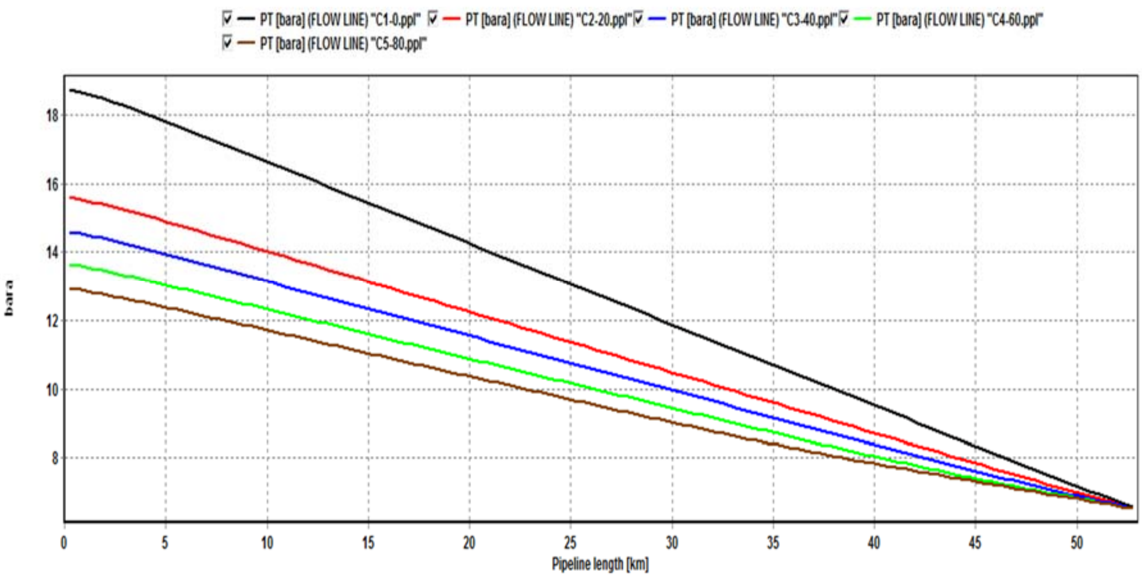

Fig (4.5): Pressure drop along the pipeline at different water cuts and flow rate of 1200 BLPD

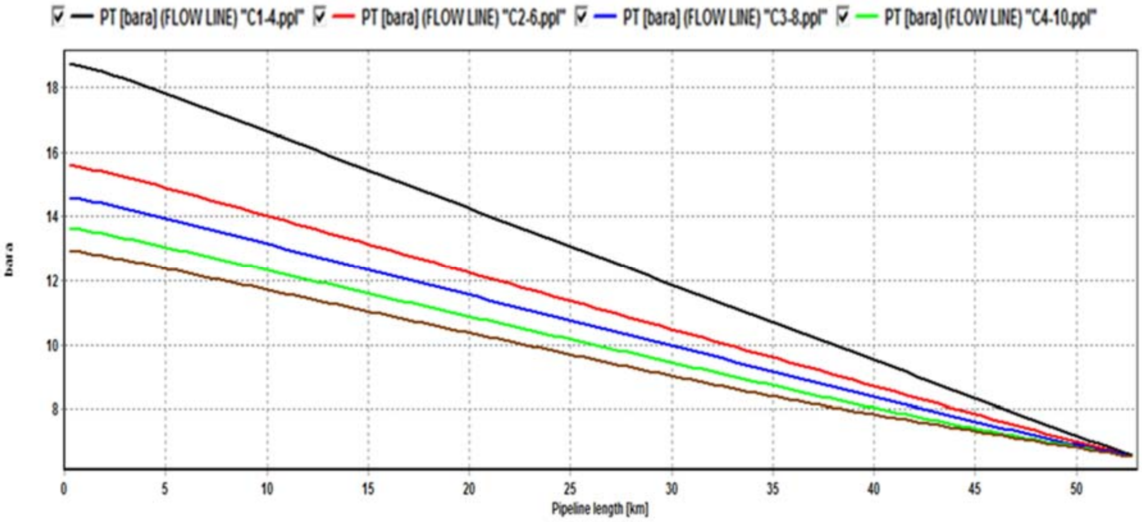

Fig (4.6): Pressure drop along the pipeline at different water cuts and flow rate of 4000 BLPD

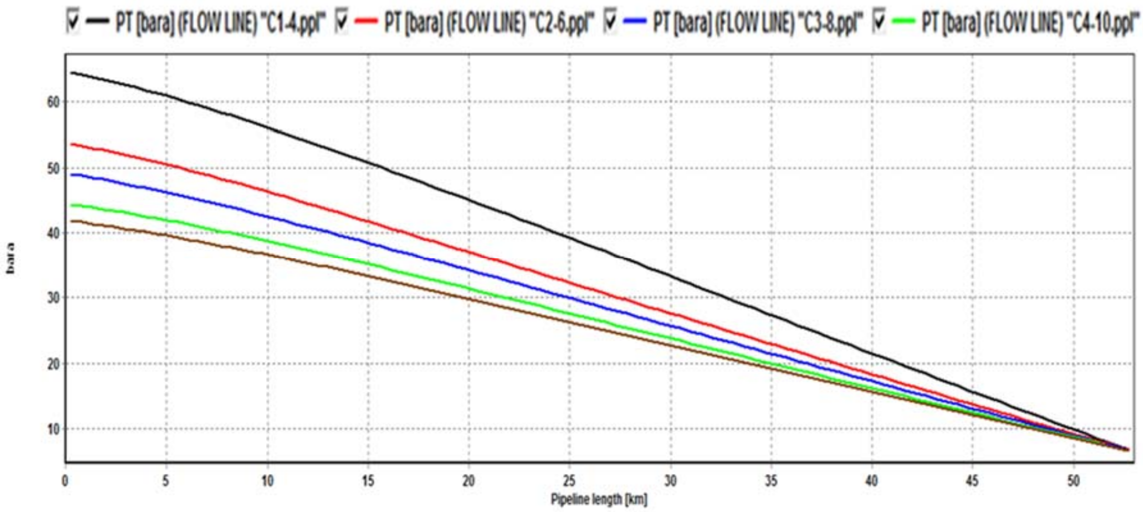

Fig (4.7): Pressure drop along the pipeline at different water cuts and flow rate of 6000 BLPD

Dilution of the crude oil by adding amount of water up to 20% is found to cause significant improvement in the pressure drop along the pipeline, and this improvement will further increase with the increase of the water percentages, however increase of water above 50% will cause less improvement in the pressure gradient. This is shown in fig (4.5, 4.6 and 4.7). However, decision on the percentage of water to be added must be subject to safety and economical feasibility assessment as pumping more water shall increase pumping cost and

the cost of water disposal at the destination as well as increasing the corrosion risk and hence endanger the integrity of the pipeline.

Pumping oil at higher flow rates in presence of water ate around 20% in this 6 inches, 53 km long pipeline resulted in increase in pressure requirement in the inlet. Inlet pressure of 18 bar at 1200 BLPD (fig (4.5)) has jumped to around 47 bar when the volumetric flow rate increased to 4000 BLPD (fig (4.6)). Further increase of flow rate to 6000 BLPD (fig (4.7)) have made the inlet pressure requirement to go up to 65 bar. There continue increasing the flow rate will continue increasing the inlet pressure but at lower rate.

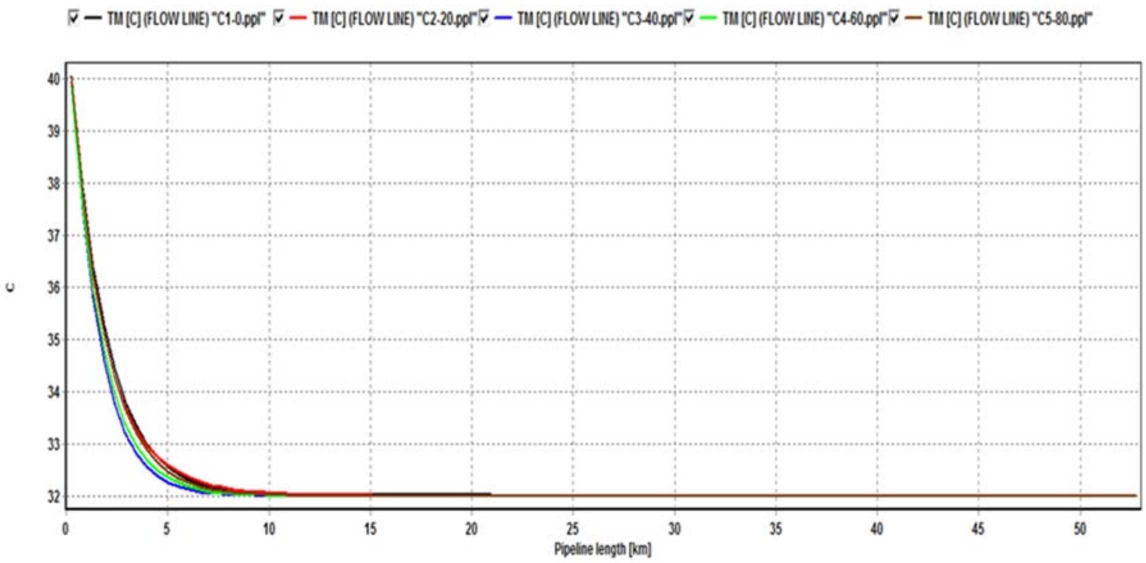

Fig (4.8): Temperature profile along the pipeline at different water cuts and flow rate 1200 BLPD

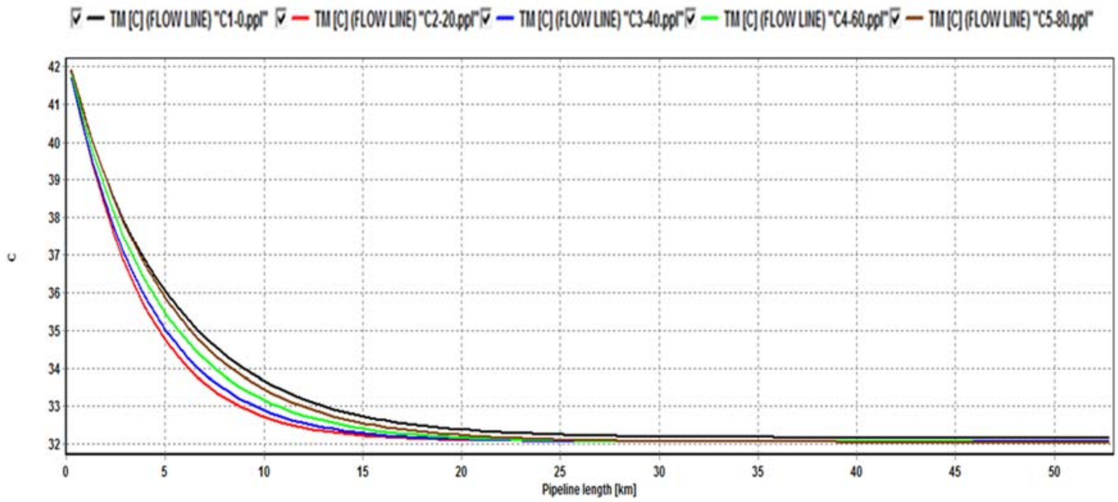

Fig (4.9): Temperature profile along the pipeline at different water cuts and flow rate 4000 BLPD

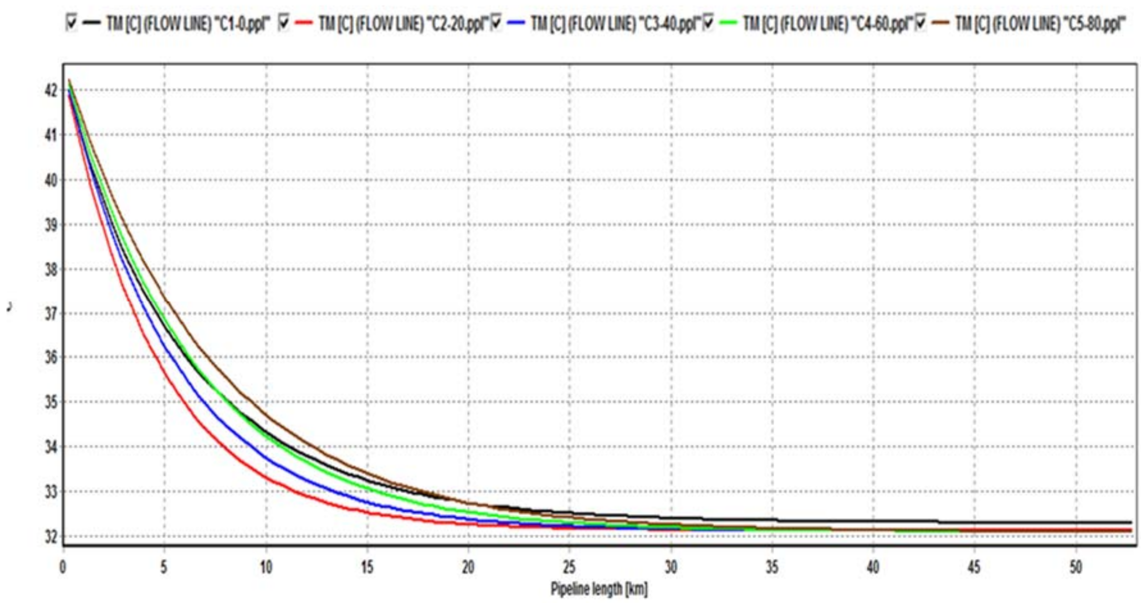

Fig (4.10): Temperature profile along the pipeline at different water cuts and flow rate 6000 BLPD

It is obvious that viscosity is main factor that affect the flow ability and hence the pressure loss along transporting pipelines. The viscosity of crude oil can be reduced by temperature increasing. However from fig (4.9) shows that water

content plays a role in improving the temperature profile along the pipeline which can be attributed to the high heat capacity of water compared to that of oil (nearly double), nevertheless, temperature effect is limited as the temperature difference between the ground and fluid will reach the balance with the ground temperature soon and continue flowing at the ground temperature.

Difference in heat capacity of the water and oil caused the temperature profile to improved as shown in (fig (4.9)) and (fig (4.10)) when the flow rate is increased from 4000 BLPD to 6000 BLPD. While the effect is remain limited to less than half the pipeline. Thus further increase in flow temperature is not expected to improve the pressure gradient.

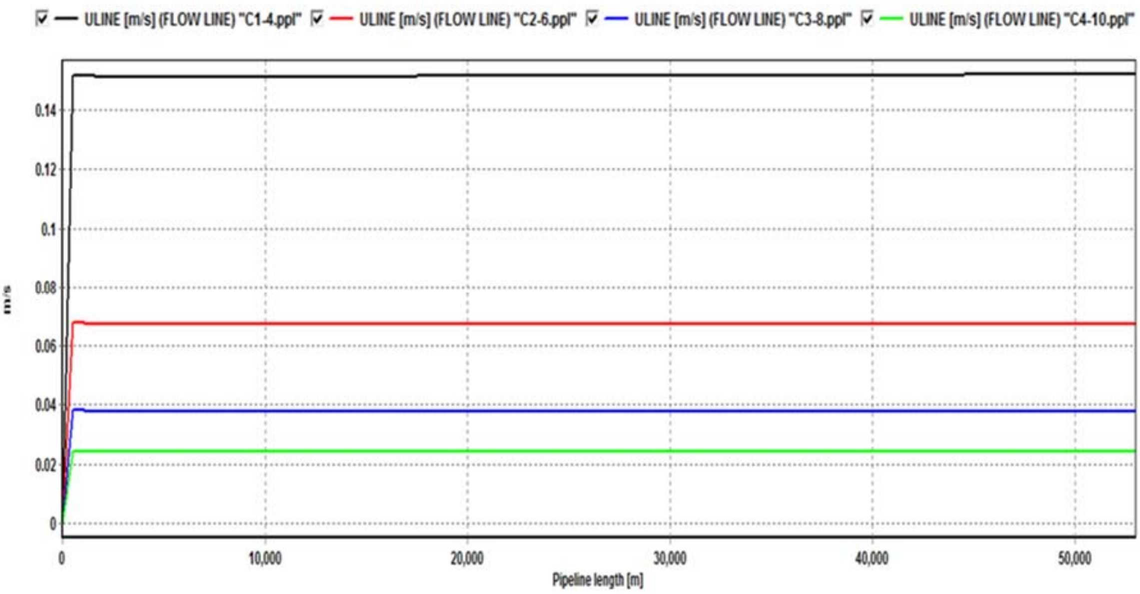

Fig (4.11): Velocity profile along the pipeline at different diameters and flow rate of 1200 BLPD

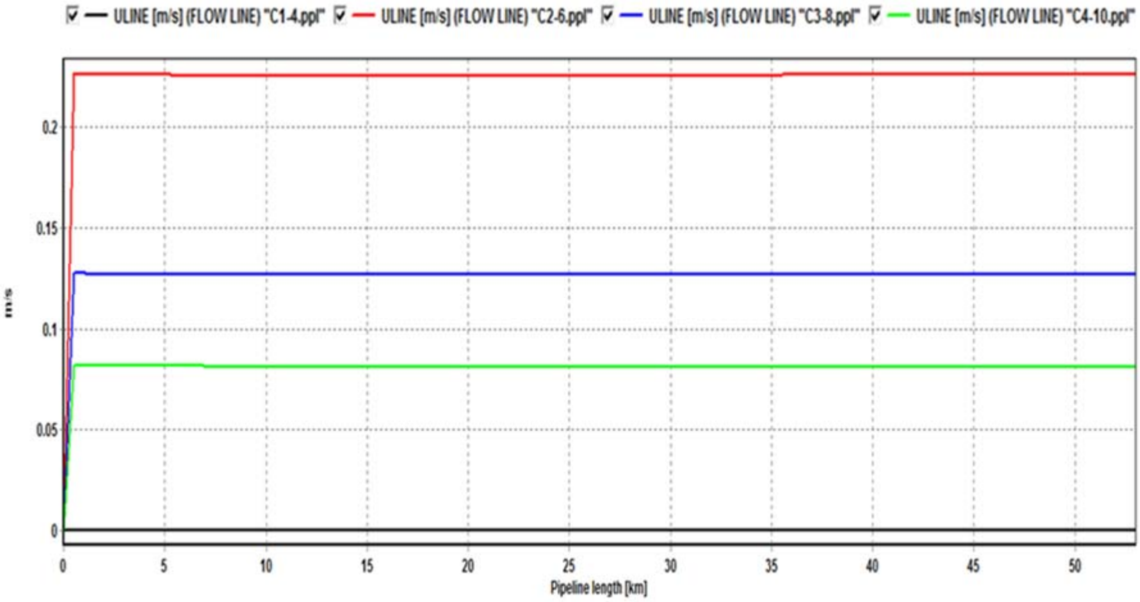

Fig (4.12): Velocity profile along the pipeline at different diameters and flow rate 4000 BLPD

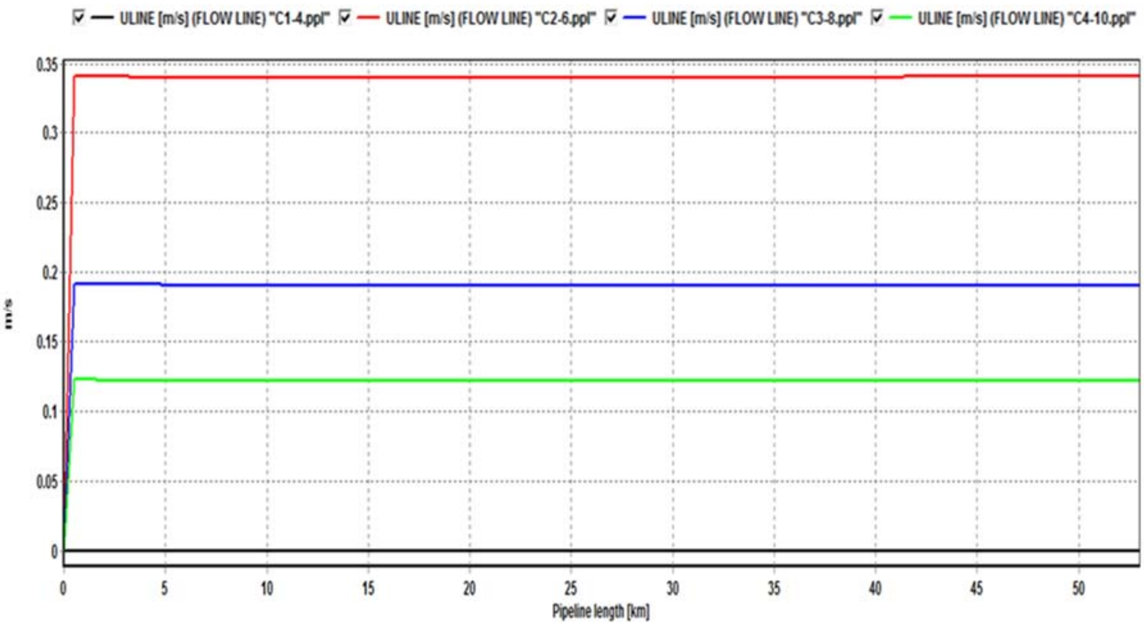

Fig (4.13): Velocity profile along the pipeline at different diameters and flow rate 6000 BLPD

Velocity profile during all the considered three flow rates are illustrated in the figures (14.11, 14.12 and 14.13) above and it proved that same like in the single phase flow and for certain volumetric flow rate the wider the pipeline the lower

the flow velocity and this is basically agree with the continuity principal and the published literature. The lower velocity will promote the possibility of having stratified flow [Kumara et al, 2009] and [Wei Wang et al , 2013] and thus less pressure drop is expected with lower velocities occurred in the wider diameter and this coincide with result obtained above for the effect of the pipe diameter on the pressure drop along the pipeline.

Chapter V

CONCLUSION AND RECOMMENDATIONS

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION:

Oil water steady two phase flows in horizontal pipeline is investigated using OLGA computer application at flow rates of 1200, 4000 and 6000 BLPD and different pipe diameter and water concentration. The following could be concluded from the investigation under the study envelope:

Pressure gradient in single phase crude oil flow is much higher compared with the oil water mixture.

Presence of water (20% and above) reduces pressure gradient significantly, however further increase will not make bigger changes.

Heating will not improve the flow characterizes because its effect is very limited and temperature could not be sustained for longer distances.

For certain flow rate and mixture composition, the wider the diameter, the less pressure drop and the higher flow rates.

Optimal design of the pipeline or operating envelope could be achieved provided that detailed properties and economical constrains are well defined.

5.2 RECOMMENDATIONS:

Under all the three flow rated under this investigation, a stratified flow pattern is observed. However, under different conditions other flow patterns

would probably be achieved. Impact of different flow patterns in the pressure drop represent an interesting research field.

From the practice in the industry, it is observed that passing of the cleaning PIG in through the pipeline has frequently caused back pressure. Thus it would be attractive for the researched to study the impact of the PIG passing on the pressure profile.

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INVESTIGATION OF OIL WATER FLOW IN WIDE HORIZONTAL PIPES

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Abstract

Oil water flow in 6' pipeline is investigated at full scale using CFD application OLGA. The effect of flow rate, water cut, and temperature on the pressure gradient is investigated by manipulating different values at different flow rated. Results are presented and analyzed.

Keywords: *oil water, wide pipe, horizontal, pressure **gradient.***

1. Introduction

Simultaneous flow of two immiscible liquids is commonly encountered in different industries such as food and refrigeration industries as well as in nature. In petroleum industry, oil and water are usually produced together and required to be transported from the wells to the production facilities and the market. Understanding of the characteristics of the oil water flow in pipes is vital for smooth and cost effective operations of petroleum pipeline by optimizing the pumping power requirements
[1] and [2]

Unlike the liquid gas two phase flow, the oil water (liquid- liquid two phase flow) is actually affected by the variation in viscosities and the emulsion formed at the interface. Moreover, the oil rheological behavior may vary [2] which make it more complicated to study. Moreover, the flow patterns the flow take is also influencing the pressure gradient [1] [2] [3]

Different attempts were made to study the oil water flow in horizontal pipes from different aspects such as work of [2][3] and Mohammed [4] who conducted experimental and computational work to investigate the flow patterns and observed SW, SWD, SMW, SMO and three layers of flow and dispersed flow pattern.

Pressure drop along the oil water pipeline is of special interest for many researchers who tried to investigate how it is caused. Wei Wang et al [2], claimed that the impact of gravity viscosity and interfacial tension in the stabilization of oil water separated flow is significant. Moreover, the impact of shear stress in viscous oils is very clear and can be characterized by ignoring the velocity of the viscous phase (oil).the same has been studied in the flow through narrow pipes and pressure gradient is found to be quite higher compared to that of single phase flow W. Adrugi et al [6]

Other worker studied the effect of viscosity [3] [4] [5], however viscosity can be reduced by different means such as mixing with industrial solvents or increasing the temperature as [4]

Most these works have covered the flow in relatively narrow pipes and limited test sections length. Recent developments in CFD make it possible to widen the ranges of the analysis. Some workers have used different CFD tools for analysis of oil water floe in horizontal pipes from different aspects such as [4] [5].

Current work utilized the enhanced capacity of the CFD to investigate the oil water flow in horizontal pipes at full scale with focus on the pressure losses. Actual reading from an oil field in Sudan is used to build and validate the model. Then different parameters were manipulated and obtained results are discussed.

2. Mathematical model:

The fluid flow is governed by continuity equation, momentum equation and the energy equation. The balance equations contains the interaction terms to incorporate the transfer of mass, momentum and energy from interface the phases which made it more complicated than the single phase model.

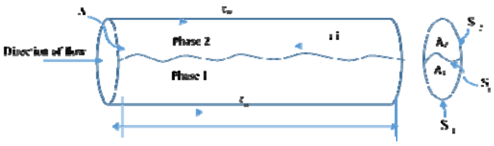

Fig (1): unit flow control volume

Continuity equation

With reference to fig (1) above, equation of mixture motion can derived as follows:

For phase 1:

$$\frac{\partial}{\partial t}(\rho_1(1-\propto)) + \nabla.(\rho_1(1-\propto)u_1) = S_{12} + S_1 \text{ --- (1)}$$

Phase 2:

$$\frac{\partial}{\partial t}(\rho_2 \propto) + \nabla.(\rho_2 \propto u_2) = -S_{12} + S_1 \text{ ---- (2)}$$

Where S_1 represent external source of matter enters the system and S_{12} is source term represents rate of change per unit volume.

For steady state flow of incompressible fluids with no phase changes these will reduces to

$$\frac{\partial}{\partial t}(1-\propto) + \nabla.((1-\propto)u_1) = 0 \text{ --- (3)}$$

And $\frac{\partial \propto}{\partial t} + \nabla.(\propto u_2) = 0$ --- (4)

Momentum balance equation:

Rate of change of momentum = rate of momentum outflow – rate of momentum inflow – rate of momentum accumulation = net forces acting on the control volume.

(W_1 u_1+∂/∂z (W_1 u_1) δz) W_1 u_1+ ∂/∂t(u_1 ρ_1 (1-∝)A δz) --- (5)

Where $W_1 = \rho_1(1-\propto)A$, and thus net rate of momentum change for phase 1 becomes:

$$\delta z\left(\frac{\partial}{\partial z} u_1^2\rho_1(1-\propto)A\right) + \frac{\partial}{\partial t}(u_1\rho_1(1-\propto)A) \text{ ---- (6)}$$

Force acting on the control volume for phase 1:

$$P(1-\propto)A - P(1-\propto)A + \frac{\partial}{\partial z}(P(1-\propto)A\delta z) - (P\delta z\frac{\partial}{\partial z}((1-\propto)A) - \tau_{W1}\delta z S_1 + \tau_{Wi}\delta z S_i \text{ ---- (7)}$$

Equating momentum rate of change and net forces acting on phase 1 resulted in:

$$-(1-\propto)\frac{\partial P}{\partial z} - \frac{\tau_{W1}S_1}{A} + \frac{\tau_i S_i}{A} = \frac{\partial}{\partial t}(u_1\rho_1(1-\propto)) + \frac{1}{A}\frac{\partial}{\partial z}(W_1 u_1) \text{ ---- (8)}$$

Similarly for phase 2

$$-\propto\frac{\partial P}{\partial z} - \frac{\tau_{W1}\rho_1}{A} - \frac{\tau_{W2}\rho_2}{A} = \frac{\partial}{\partial t}(\rho_2 u_2 \propto) + \frac{1}{A}\frac{\partial}{\partial z}(W_2 u_2) \text{ ---- (9)}$$

Adding the two equation under the steady state condition yields the mixture momentum equation as:

$$-\frac{\partial P}{\partial z} = \left(\frac{\tau_{W1}S_1}{A} + \frac{\tau_{W2}S_2}{A}\right) + \frac{1}{A}\frac{\partial}{\partial z}(W_1 u_1 + (W_2 u_2)) \text{ -- (10)}$$

3. Computational work and results

The commercial software OLGA is used to simulate the different operation cases and to predict the necessary parameters. Pipeline specifications as stated below are fed to the software and orientation is considered horizontal

Table (1): Pipeline specifications

SN	Outer diameter [m]	0.1524
1	Internal diameter [m]	0.1366
2	Pipeline Length [m]	50 000
3	Roughness [mm]	0.125
4	Buried Depth(m)	1.2

Further the crude oil specification fed to the software are as follows:

Table (2): Oil properties

S N	Property	Value
1	API Gravity @ 60 °F (15.6 °C)	23.87
2	S. G. → Relative Density g/cm³ @ 60 °F (15.6 °C)	0.9107
3	Relative Density g/cm³ @ 60 °F (15.6 °C)	0.9099
4	Water cut	Varying

Three different flow rates are considered for the simulation to represent the low flow rate at 1200 BLPD and medium rate at 4000 BLPD and high flow rate at 6000 BLPD.
Water cuts at 0, 20, 40, 60, and 80 % are used to reflect the impact of the dilution on the pressure gradient. Moreover the temperature profile is obtained along the pipeline at different concentration to reflect the viscosity impact as the viscosity if a function of the temperature.

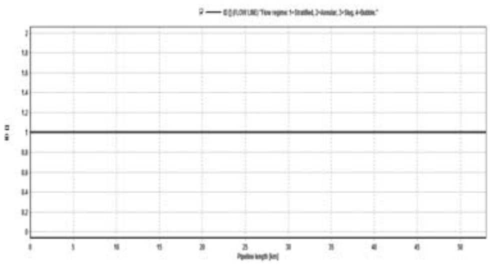

Fig (2): flow regime along the pipeline at 1200 BLPD

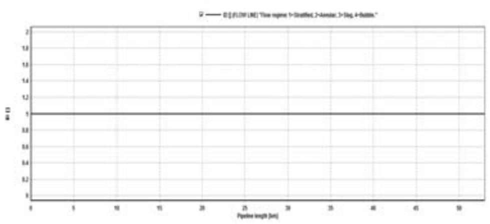

Fig (3): flow regime along the pipeline at 4000 BLPD

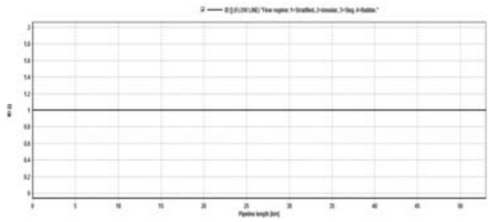

Fig (4): flow regime along the pipeline at 6000 BLPD

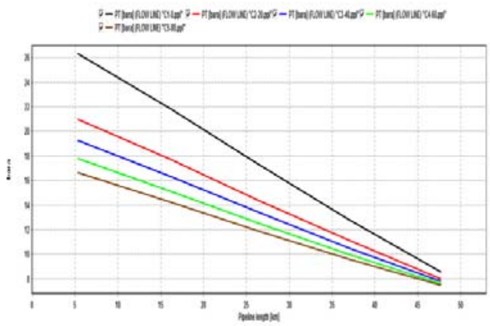

Fig (5): pressure drop along the pipeline at different water cuts and flow rate of 1200 BLPD

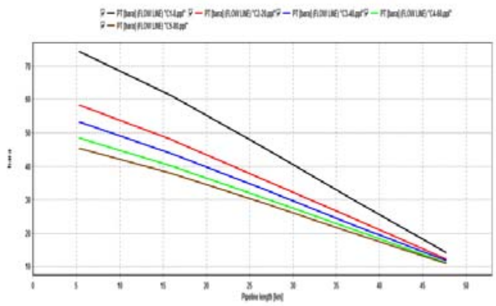

Fig (6): pressure drop along the pipeline at different water cuts and flow rate of 4000 BLPD

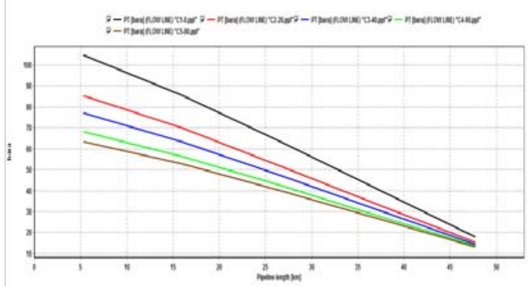

Fig (7): pressure drop along the pipeline at different water cuts and flow rate of 6000 BLPD

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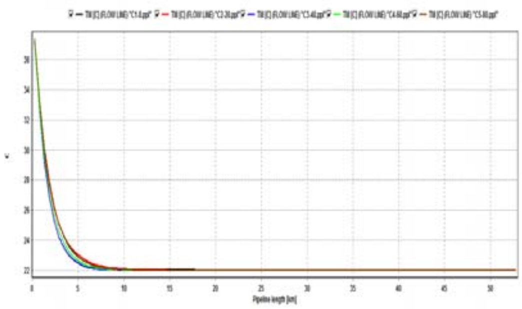

Fig (9): Temperature profile along the pipeline at different water cuts and flow rate 4000 BLPD

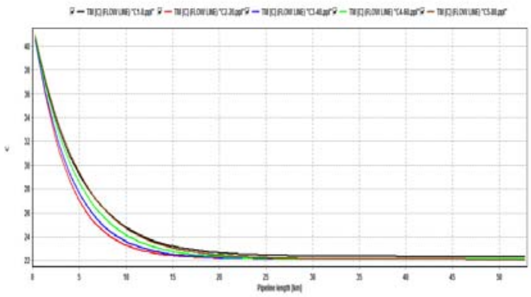

Fig (10): Temperature profile along the pipeline at different water cuts and flow rate 6000 BLPD

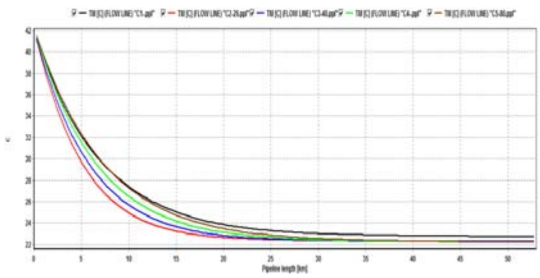

Fig (8): Temperature profile along the pipeline at different water cuts and flow rate 1200 BLPD

4. Discussion:

It is clear that the flow is separated all through the pipeline regardless the flow rate or the water cut as can be seen from figures 2, 3 and 4 This is basically because of the basic assumption of horizontal orientation of the pipeline and the difference in the densities as well as the absence of gas flow or accelerations. Thus oil and water tends to segregate and stratified flow pattern will prevail.

Pressure gradient is found to be extremely higher when oil is flowing solely when compared to oil water flow at any concentration as shown in fig (5). Nevertheless, increase of water cut in the mixture is mobility and hence reduce the pressure gradient. This observation is valid for all the three flow rates scenario examined in this work and illustrated in fig (6) and (7). Addition of water will dilute the mixture and reduces the viscosity. Thus the more water cut, the less mixture viscosity and hence the less pressure decline encountered.

It can also be noted that pressure gradient is increasing proportionally with the flow rate increase within investigated flow rates.

Mixture concentration (water cut) as concluded from Fig (6), (7) and (8) is found to have minor effect on temperature profile, however the profile will slightly improved with water cut increase. But it is better improved with reduced flow rates.

5. Conclusions:

The oil water flow in horizontal wide pipes can be significantly improved by increasing the water content in the mixture

6. Acknowledgment

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Nomenclatures

A: Cross sectional area of pipe

A_1, A2: Cross sectional area of pipe filled by phase 1 and 2 respectively.

SW: stratified wavy flow

SWD: stratified wavy drops

SMW: stratified mixed water layer

SMO : stratified mixed oil layer

BLPD: barrel liquid per day

W_1, W_2 rate of momentum change of phase 1 and 2 respectively.

Greek Symbols

μ: Viscosity, Pa.s

ρ: Fluid density kg/m3

τ_{xy}:: shear stress, Pa

α: liquid holdup

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