# OIL-WATER ANNULAR TWO-PHASE FLOW IN HORIZONTAL PIPE

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**ABSTRACT:**

The objective of this work is to gain insight into liquid-liquid annular flow, two-component Iraqi gasoil-water flow lengths in horizontal circular transparent pipe of 32mm inner diameter and 6m length, experiments done at atmospheric condition with oil and water as the working fluids. The flow patterns that appear are classified in flow pattern maps as functions of either mixture velocity and water cut or superficial velocities. The superficial water velocity ranged from 1.69 m/s to 3.38 m/s with superficial oil velocity around 0.39 m/s to 1.58 m/s. The effects of superficial water velocity, superficial oil velocity on annular flow lengths were taken into account. However, the essentials of the problem involve the determination of the pressure gradient. In this experimental work a video camera "high speed camera" system with image processing technique by MATLAB were used to extract the hold up for the fluid that being the annular flow. The theoretical study was executed using fluent program, a modified turbulent diffusion model is adopted. Simulation results show more physical predictions with respect to the particle deposition process and concentration profile. New data for hold up lengths were found which achieved good agreements with the previous works.

**Key words**: two-phase; two compound annular flow; flow regime; CFD.

# الجريان ثنائي الطور (زيت-ماء) خلال الانابيب الحلقية الافقية

**عصام محمد عبد** **زهراء عامر عبد**

**الخلاصة :**

الهدف من العمل الحالي هو تسليط الضوء على دراسة جريان ثنائي الطور لجريان حلقي لمائعين سائل-سائل في انبوب أفقي شفاف بقطر داخلي 32ملم وطول 6 م, لقد أجريت التجارب تحت الظروف البيئيه الطبيعيه في المختبر باستخدام كلا المائعين كطورين سائلين . نماذج الجريان تظهر مصنفه كخريطة توضيح أنواع الجريان وتكون كمعادله لسرعة الخليط .معدل سرعة الماء يتراوح من 1.69 م/ثانيه الى 3.38 م/ثانيه ومعدل سرعة النفط يتراوح من 0.39 م/ثانيه الى 1.58م/ثانيه. تم استخدام نظام تصويري باستخدام كاميرا عاليه السرعة وذات مواصفات تصويرية عاليه الدقه مع تقنية معالجة الصور بواسطة MATLAP والهدف هو الحصول على نظرة ثاقبة السائل-السائل تدفق ألحلقي. تم تنفيذ الدراسة النظرية باستخدام برنامج فلونت CFD، و اعتماد نموذج الانتشار المضطرب المحسن. نتائج المحاكاة تظهر التوقعات الفعلية أكثر فيما يخص عملية ترسب الجسيمات والتركيز. تم العثور على بيانات جديدة تتوافق مع ما أوجده الباحثون سابقا.

## NOMENCLATURE:

| | |
|---|---|
| $\Delta P$:- Pressure Gradient. (Pa/m$^2$) | A:- Cross section area. (m) |
| D:-Diameter. (m) | Do:-Oil Diameter. (m) |
| Dw:-Water Diameter. (m) | HL:-Holdup. (---) |
| L:- Length. (m) | Le:-Entrance Length. (m) |
| Qo:-Oil Flow Rate. (m$^3$/s) | Qw:-Water Flow Rate. (m$^3$/s) |
| Re:- Reynolds no. (---) | Us:-Superficial Velocity. (m) |
| L1:- lighter liquid. | L2:- heavier liquid |
| CFD:- Computational Fluid Dynamic. | QCV:- Quick-closing valve. |
| VOF:- Volume of Fluid. | RGB:- Red, Green, and Blue Image. |
| K:- Turbulence Kinetic Energy. | |
| $\sigma_k$, $\sigma_\varepsilon$ :- Constants in the $k-\varepsilon$ model. | |
| ε:- Dissipation Rate. | λ:- Input water cut. |
| ρ:- Density. (kg/m$^3$) | $\alpha$:- Input volume fraction. |
| $\mu$:- Viscosity. (kg/m.s) | I:- Turbulence Intensity. |

## INTRODUCTION :

Oil–water two-phase flow widely exists in petroleum industry such as crude oil production and transportation through oil pipelines. The occurrence of two phase and three phase flows in pipelines is very common in the petroleum industry.

Most of the work done in horizontal pipes has been for gas-liquid flow. Annular flow is a very interesting flow pattern that consists of a highly viscous oil core surrounded by a thin layer of water if the oil has a viscosity orders of magnitude larger than the water one, the resulting pressure drop is comparable to the one of water flowing alone at the mixture velocity.

**Simmons, et al. (2001)** used a different method to investigate the pressure gradient by phase distribution (impedance probe ,conductivity probe ) . Steel pipe of (3.8 cm) diameter . The viscosity ratio is (5.25) , and the density ratio 0.828 .The observation flow patterns were stratified with mixing , dispersion oil in water above the water layer , dispersion water in oil. **Rodriguez (2006)** studied oil–water two-phase flow experiments by using Gamma ray densitometry. It has been introduced for oil-water flow measurement recently, were conducted in a 15 m long, 8.28 cm diameter, inclinable steel pipe using mineral oil (density of 830 kg/m3 and viscosity of 7.5 mPa s) and brine (density of 1060 kg/m3 and viscosity of 0.8 mPa s). **(Hewitt)** studied liquid- liquid systems which are strongly influenced by the approaches used in gas – liquid flow work, so the objective was to evaluate the relevance of these approaches to this difference (flow regime , stratified flow and annular low)and the nature of the wetting of the solid surface of the channel. **(Andreiui, et al.)** reported experimental results of flow pattern and pressure drop for oil –water horizontal flow in small diameter tubes (3 mm and 6 mm) inner diameter. Oil to water ratio was from 560 to 1300 .The conclusion of the study was that the tube wall material influence the flow patterns at water, to oil flow rate ratios relatively low ( less than 0.2--0.3) also the flow pattern was core-annular flow. **Angeli, et al. (2000)** made the following general observations: Stratified flow exists in both types of fluid systems. Slug flow is common in gas-liquid systems but not in liquid-liquid systems. Complete dispersion of the gas in the liquid to form dispersed-bubble flow is common at low void fractions in gas-liquid flow. However, complete dispersion of the liquid-phase into the gas-phase does not generally occur in gas-liquid flows. **Chakrabarti, et al. (2005)** investigated of the pressure drop characteristics during the simultaneous flow of a kerosene and water mixture through a horizontal pipe of 2.5cm diameter. Measurements of pressure gradient were made for different combination of phase superficial velocities ranging from 0.03 to 0.25 m/s such that the regime encountered were smooth stratified, wavy stratified, and other patterns. A model was developed which consider the energy minimization and pressure equalization of both phases. **Roula and Dash (2012)** studied numerically the pressure drop of air-water flow through sudden contraction in small circular pipes at room temperature and near atmospheric pressure. Two-phase computational fluid dynamics (CFD) calculations, using Eulerian–Eulerian model with the air phase being compressible, are employed. The pressure drop is determined by extrapolating the computed pressure profiles upstream and downstream of the contraction. **Al-yaari and Abo-Sharkh (2011)** investigated numerically, using CFD FLUENT 6.2 for Oil-water stratified flow regime in horizontal pipe (0.0254) Volume of Fluid (VOF) multiphase flow approach utilizing with RNG k–ε turbulence model. The phase separation is investigated for the tested stratified flow points. **Rashmi, et al. (2009)** investigated numerically, using CFD package FLUENT 6.2 in conjunction with multiphase model, the three-dimensional dispersed flow of Oil-water in a horizontal pipe (ID=0.0024 m). They used k-ε model to describe the turbulence in continuous phase. They reported numerical results in terms of the phase distribution profiles and average in-situ hold-up.

**Lawrence and Panagiota (2014)** studied developed based on experimental observations of the interface configuration in stratified liquid–liquid flows. The experimental data were obtained in a horizontal 14 mm ID acrylic pipe, for test oil and water superficial velocities ranging from 0.02 m/s to 0.51 m/s and from 0.05 m/s to 0.62 m/s, respectively. Using conductance probes, average interface heights were obtained at the pipe center and close to the pipe wall, which revealed a concave interface shape in all cases studied. A correlation between the two heights was developed that was used in the two-fluid model. In addition, from the time series of the probe signal at the pipe center, the average wave amplitude was calculated to be 0.0005 m and was used as an equivalent roughness in the interfacial shear stress model.

The objective of this study is to present experimental and theoretical analysis for oil-water annular flow and heat in horizontal pipe, as follows: studying experimentally the hydrodynamic annular liquid-liquid gasoil-water flow for both liquid-liquid annular flows, proposing suitable model for the hydrodynamic of annular flow and heat transfer with the Computational Fluid Dynamics CFD technique by FLUEN.

**Experimental Apparatus and Procedure:**

A liquid-liquid flow facility has been built within the fluid laboratories of the Mechanical Engineering Department at University of Babylon. A schematic diagram of the experimental setup is shown in **Fig.1.**

A 27 experiments of two-phase two different fluids (Iraq gasoil-water) flow in horizontal pipe to investigation annular liquid-liquid flow without heat.

**Water Flow Loop:-**

The liquid is supplied by a centrifugal pump from tank fixed height of 0.3m. The following sections present a detailed description of all components used. A- **Water Tank** a cylindrical liquid tank of 760 litter capacity, with height of 1.2m, and 0.9m diameter, this tank is Thermally insulated by glass wool. B- **Centrifugal Pump** a centrifugal pumps are used for large discharge through smaller heads. It is of 2″×2″ size and 500 l/min as maximum discharge with 5m maximum head, voltage 380 volts, Frequency 50 $H_Z$, angular velocity 1460 rpm, current 15.3 Amp, power 1.2 KW, three phases, four poles been made in the company Toshiba. C- **Water Flow Meter** a scaled flow meter is used to control the water volume flow rate that enters the two phase mixing section. It has a volume flow rate range of (5-30) l/min.

**Oil flow loop:-**

The oil is supplied by a centrifugal pump from the tank at 10 cm height from the ground. The oil flow rate is measured before entering into the two phase mixer by a flow meter; a check valve of gate type is used to prevent the reverse flow of the oil. The following sections present a detailed description of all component used. A-**1 Oil tank** a cylindrical oil tank of 530 litter capacity, with height of 1.2 m, and 0.75 m diameter is used to storage the oil phase for recirculation flow in the test facility. C- **centrifugal pump** a centrifugal pump is chosen to deliver the oil phase loop(220V/9.91 A). Centrifugal pumps are used for large discharge through smaller heads. D- **Oil flow meter** a scaled flow meter is used to control the oil volume flow rate that enters the two phase mixing section. It has a volume flow rate range of (10-70) litter/min.

**Interface System:-**

It represents the interface connection between the pressure sensors which are set on the test pipe and the processor which is represented by a program on the personal computer. The interface system consists of two parts which are the data logger and the transformer which is put in a white plastic box.

**Thermometer:-**

It is used to record the temperature reading at different positions of the test pipe. Also it can transform (12) thermocouples reading to digital reading at the same time. The temperatures range recorded by this device is (0 to 200 $^{o}$C).

**Video system:-**

High speed filming using a digital video camcorder (AOS High Speed) was used as qualitative reference for the two other techniques in evaluating annular flow, it's capable of recording and storing data in camera memory .

**A Viscometer Cone Plate:-**

The rheological measurements are performed with a con and plate geometry with a cone diameter 25mm and a cone angle of 15 .All experiments are conducted at a constant gap of 0.5mm and an initial stabilization period of 2 minutes is given for achieving the temperature equilibration.

**Calibration Instruments:-**

The calibration is used to get more accuracy in the experimental work of the rig measuring devices. The instruments which include the weighting and stop watch devices, the U-tube manometer and the thermometer. Equation which is used to measure the calibration for each device uses a through knowledge of the percentage error , and the equation is:

$$pe\ \% = \frac{\text{standrad reading} - \text{instrument reading}}{\text{standard reading}} \qquad (1)$$

**Experiments Limitation:-**

A flow may be laminar at the beginning for the passage of water only and then the flow become to the turbulent at passage the oil fluid. Reynolds number for turbulent flow is given by **Holman, et al (1984).**

$$Re = (\rho_m \cdot U_m \cdot D)/\mu_m \qquad (2)$$

Where:

The entrance length (Le) required for fully developed velocity profile to form laminar and turbulent flow respectively are as:

For laminar flow $Le = 0.06D\ Re$ (3)

For turbulent flow $Le = 4.4\ D\ Re^{1/6}$ (4)

For the present work and according to the pipe diameter, higher velocity of the liquid-liquid phase, the entrance length is 0.8723 m as equation (4). Therefore, the design of the experimental set-up carried out for pipe according to the maximum entrance length.

The most physically based explanation is that:

Superficial Velocities and flow rates , The flow rate and superficial velocity of the fluid flow was measured as follows. The liquid flow rate is red directly from the float flow meter in (l/min),while the superficial velocity determined from the following equation as:

$$Q = Us * A \qquad (5)$$

When the diameter of the entrance pipe for water is equal to (Dw= 11.2 mm) and the entrance pipe for oil equal to (Do=23.2 mm) so that the mixture velocity equals to the summation of the water and oil velocities. The liquid holdup depends on the flow pattern, Having estimated the range of stable annular flow attempts have next been made to predict the in-situ volume fraction occupied by either of the phases in the test pipe. The parameter of holdup of the heavier (water) phase (**Sunder, et al.**) can be expressed as :

$$H_L = \frac{V_{L2}}{V_{L1} + V_{L2}} \qquad (6)$$

where $V_{L1}$ and $V_{L2}$ are the respective volumes occupied by the lighter (oil) and the heavier (water) liquids. Also, the input volume fraction is expressed **Sunder,et al.(2005)** as :

$$\alpha = 1 - HL \qquad (7)$$

The inlet water cut( $\lambda$ )is defined by dividing the flow rate of water, $Q_w$, by the sum of flow rate of water and oil, $Q_w$+$Q_g$, such that:

$$\lambda = \frac{\square w}{Qw+Qo} \qquad (8)$$

The wall shear stress, the mean shear stress at the wall for Newtonian and non-Newtonian fluids and for all flow regimes is as:

$$\tau_w = \frac{D}{4}\,\frac{\Delta p}{\Delta x} \qquad (9)$$

**TWO-PHASE FLOW MODELING:**

The problem of the two-phase oil-liquid annular flow considers the transient tracking of a oil-liquid interface. This geometry details is accomplished by using Gambit 2.3.16. Gambit is Geometry And Mesh Building Intelligent Toolkit, A single, integrated preprocessor for CFD analysis.

**Mesh Generation**:-

The partial differential equations that governs fluid flow are not usually amenable to analytical solutions, except for very simple cases. Therefore, in order to analyze fluid flows, flow domains are split into smaller sub domains called elements or cells and the collection of all elements is known as mesh or grid. The governing equations are solved inside each of these portions of the domain. Grid generation is often considered as the most important and most time consuming part of CFD simulation as shown in **Fig. 2.**

**Governing Equations:-**

The governing differential equations of this work are continuity and momentum Equations in three dimensional.

**Conservation of Mass:-**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{V} = 0 \qquad (10)$$

**Conservation of Momentum:-**

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left[\mu\left(2\frac{\partial u}{\partial x}-\frac{2}{3}\nabla\cdot\vec{V}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]+B_x$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial y}\left[\mu\left(2\frac{\partial v}{\partial y}-\frac{2}{3}\nabla\cdot\vec{V}\right)\right]+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+B_y$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left[\mu\left(2\frac{\partial w}{\partial z}-\frac{2}{3}\nabla\cdot\vec{V}\right)\right]+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+B_z$$

(11)

**Boundary Condition**:

The boundary domain in the present problem is dependent on flow variables at the domain boundaries Specify fluxes of mass, momentum, energy, etc. into the domain. Defining boundary conditions involves: Identifying the location of the boundaries. Supplying information at the boundaries. Also, the turbulence kinetic energy **k** and its dissipation rate ε initial guess those are estimated with the following equations according to Launder and Spalding **Launder and Spalding (1974)**:

$$K= 3/2\ I^2\ Uin2 \quad (12)$$

$$\varepsilon=2K_{in}^{3/2}/d$$

(13)

The turbulence intensity for fully developed pipe flow is:

$$I=0.16Re^{-1/8} \quad (14)$$

**Image processing:**

The Image Processing Toolbox is a collection of MATLAB functions (called M-functions or M-files) that extend the capability of the MATLAB environment for the solution of digital image processing problems **Rafael Gonzalez, et al, (2009).**

**Extracting Image Data**:-

The recorded videos are made through the experimental work. This videos are transferred and stored in a personal computer hard drive. In the first step, storing the videos in the original acquired format, mpeg, and the further processing has been done to convert the videos into AVI codification for the output video format. All the videos files are loaded into MATLAP internal routines.

These videos files are loaded into MATLAB workspace as a sequence of frames. Each frame corresponds to a snapshot of the camera field of view a frame at each 0.033 sec, corresponding to a frame rate of 30frame/s. True color, or RGB. Here each pixel has a particular color; that color being described by the amount of red, green and blue in it. Such an image may be considered as consisting of a "stack" of three matrices; representing the red, green and blue values for each pixel. This means that for every pixel there correspond three values **Alasdair McAndrew (2004).**

**RESULT AND DISCUSION**:

The experimental and theoretical work results are illustrated in the present section, which include the results obtained for pressure reading, inlet water cut, shear stress and holdup for oil-water for different flow rates.

## Experimental Result:

### Flow Visualization:-

The first and simplest approach to study two-phase flow behavior in deviated pipes is to visualize the flow. Flow patterns play very important roles in two-phase flow to explaine the phenomena of two-phase flow. **Fig. 3** shows an instantaneous side view of oil-water flow into the pipe, obtained by high speed video camera (AOS imaging studio v3) . The mixture flow is from the left to the right with the distance in the flow direction shown equal to L = 60 mm. The oil superficial velocity is equal to 0.197 m/s and the water superficial velocity is (1.69 to 3.38) m/s. Using the video system, it is found that The annular pattern has been observed for an inlet oil superficial flow rate ($Q_{so}$) around from (5 to 15) l/min and superficial water flow rate ($Q_{sw}$) is equal to 10 l/min. As a result, they break down to form fine drop which are dispersed in the continuous oil medium.

### pressure drop:-

Static pressure gradient is measured by interface pressure transducer. **Fig. 4** demonstrates the relation between pressure and distance along the pipe for different mixture superficial velocity. It is observed that the pressure increases by increasing the mixture superficial velocity. Also, the pressure tendency to drop along the pipe length increased. **Fig. 5** describes the effect of oil superficial velocity on the pressure gradient with a various water superficial velocity. It's increases at beginning with increased oil superficial velocity until reach maximum value, then tends to drop at maximum oil superficial velocity.

**Fig. 6** represents the effect on time evolution of pressure obtained by experimental for various water flow rate and constant oil flow rate, this experience gives more explain the effect of time on pressure gradient. It is noted that the pressure fluctuate as a function of time due to two-phase phenomena.

### Effect Inlet Water Cut:-

**Fig.7** shows the effect of inlet water cut on the pressure gradient for varies mixture superficial velocity . The pressure gradient increases till 60.9 kPa/m for oil velocity equal to 1.77 m/s at low value of inlet water cut. It is reported that, the pressure gradients decreases with decreasing oil superficial velocity till to (2.54) kPa/m at Uo equals to 0.39 m/s at high value of inlet water cut **.**

### Shear Stress ( $\tau_w$):-

**Fig. 8** presents wall shear stress increases with increasing the water superficial velocity, reading to (0.5) for Reynolds number equals to (45430) and water velocity equals to (1.69) m/s.

### Hold Up Extracted By Image Processing Technique HL:-

The value of liquid hold up ranges from 0 (total oil) to 1 (total water), The term void fraction or oil holdup is defined as the volume fraction occupied by the oil. Then calculated the water holdup and oil void fraction after the application of the theory of the " Quick Close" with a more taking pictures of the flow. It's decreases with increasing oil superficial velocity for the same water superficial velocity as shown in **Fig. 9**. Also, **Fig. 10** show the analysis of pictures that's taken from high speed camera by using theory of "Quick close" and after analysis by Matlap program for different values of oil and water flow.

## Simulation Results:

**Fig. 11** displays the annular flow that obtained after practice the condition and complete the iteration which lasted for more than 24 hours after the reduction of the system to reduce the iteration required and the time needed.

**Fig. 12** represents the pressure distribution along the pipe. It's start from (125.616) kpa at the inlet due to the high flow rate of mixture, then it decreases with distance until reach minimum value at the end of pipe.

## Comparison of Experimental and Theoretical Results:

### Pressure Gradient:-

**Fig. 13** presents comparisons between the model predictions and the measured data for pressure distribution along the pipe for mixture velocities of 4 m/s. It can be observed that the experimental simulated pressure drop results. Also, it can be observed that pressure continuously decreases to (118.1) kpa at the end of the pipe. But, the pressure values at different locations along the pipe are lower than the experiments pressure for the flow at two different amount of velocity mixture**.**The percentage theoretical pressure decreases over experimental pressure approach to 6%.

## Comparison of Experimental Data:

The conditions are not exactly the same however the most similar conditions were chosen to compare. It can be observed that the agreement is good. A set of experimental data for the spatial distribution of oil-water dispersed-pipe flow was presented**,** the original data presents a fair agreement.

### Pressure Drop:-

A comparison of the present pressure drop is accomplished with other previous works from the literature. It can be seen that present results are in good agreement with the correlation in behavior against both the change in gas and liquid superficial velocities. The **Fig. 14** presents the measured data for the water cut along the pipe, As can be seen, a fair agreement is observed in this comparison, too.

The comparison with the researcher **Ricardo, Oscar (2014)** as shown in **Fig.15** and the percentage deviation between the practical and the researcher work piece are 0.09% and the reason for this deviation is due to the difference in used conditions in practice as the researcher used the lowest rate of speed from (0.1,0.13,0.15) either practical employment was higher than this average.

## CONCLUSION :

1. The work reveals that the annular flow regime exists over a wider range of phase flow rates . As a result, regime maps and transition equations available for gas- liquid cases cannot be used as such to predict the patterns in liquid –liquid flows .
2. Pressure drop along the pipe was direct proportional for changes in oil-water superficial velocities, it's reach to maximum value (257) kpa at mixture velocity (3.66) m/s.
3. Void fraction has reverse behavior to that of hold up to wards changes in liquid superficial velocities and towards other flow characteristics.
4. CFD calculations using Fluent 6.3.26 were performed to predict the oil-water annular flow.
5. A model for the calculation of fully-developed, turbulent-turbulent oil-water annular flow in horizontal pipe is presented. The model is based on a numerical solution of the basic governing differential equations using a finite-volume method in a bipolar coordinate system, applying a simple mixing-length turbulence model. The moving wall assumption was implemented for the prediction of the interface behavior.
6. Volume of fluid (VOF) multiphase model with RNG-k-ε two equations turbulent model was selected among other different multiphase and turbulent models based on the convergence, prediction of the oil-water annular flow pattern and the smoothness of the interface.
7. Care should be taken while initializing the CFD solver to obtain convergence.

8. Mesh independent study has been achieved to decide on the optimum mesh size to be used in the simulation process.

9. In this study water dispersed in oil for volume fractions less than 0.6 which represents the inversion volume fraction at which the oil began to dispersed in water.
10. All simulations give good agreement with the expected flow regime annular.
11. The numerical model solves the resulting set of algebraic equations in an iterative way, simultaneously for both oil and water layers. The pressure gradient is calculated based on the condition that the velocity field in both layers must satisfy the total flow rate.

Fig.( 1) The experimental rig.

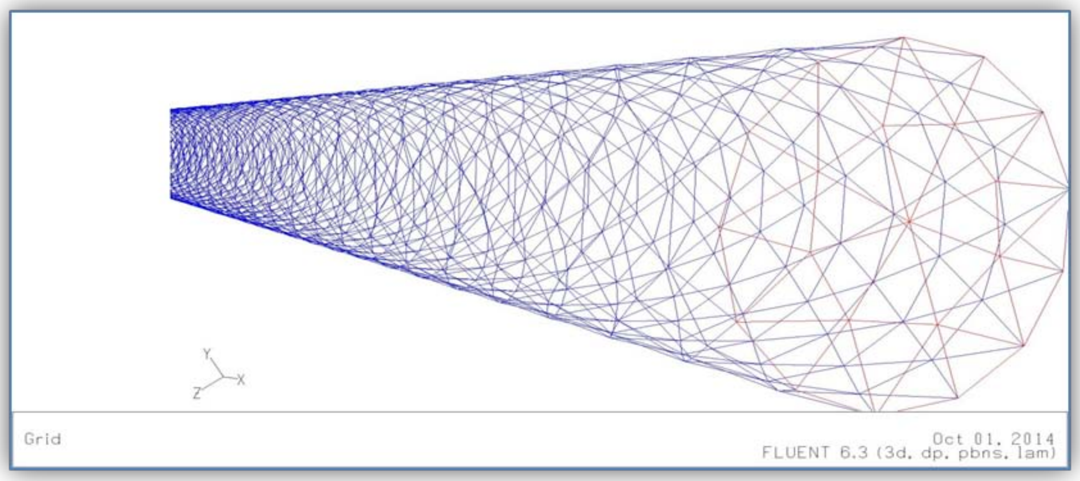
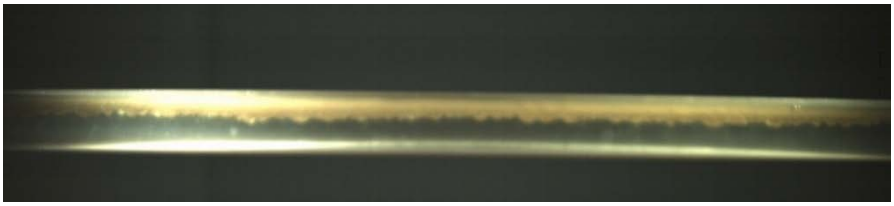
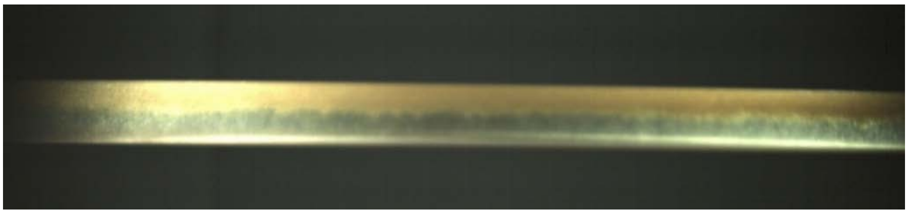


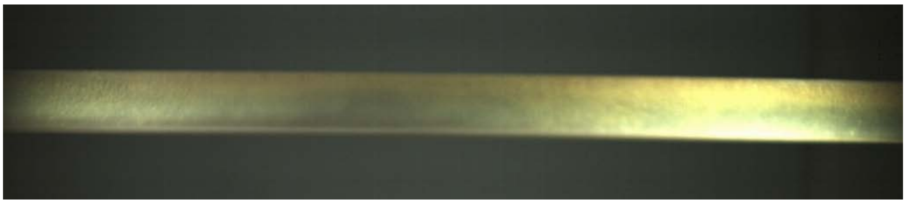

Fig. (2) The approach mesh used to create the pipe geometry.



a- Uo=0.197 m/s, Uw=1.69 m/s



b- Uo=0.197 m/s, Uw=2.54 m/s



c- Uo=0.197 m/s, Uw=3.38 m/s

Fig. (3) Flow visualization at Qo=5 l/m and Ow=10.15.20 l/m.

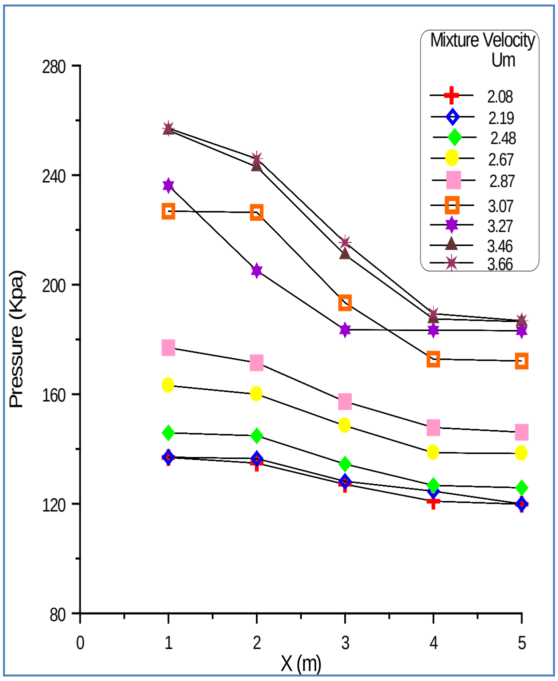



Fig. (4) Variation along test section for different mixture superficial velocity .

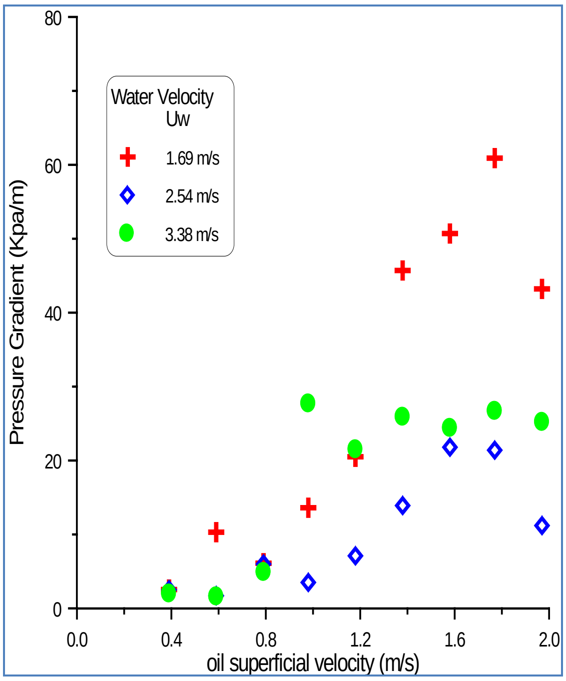



Fig.(5) Effect of oil superficial velocity on the pressure drop.

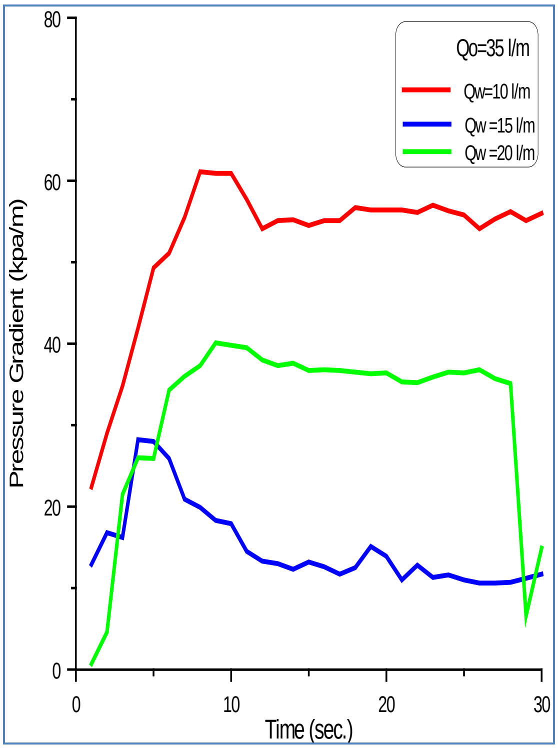



Fig. (6) Effect of time evolution on pressure gradient.

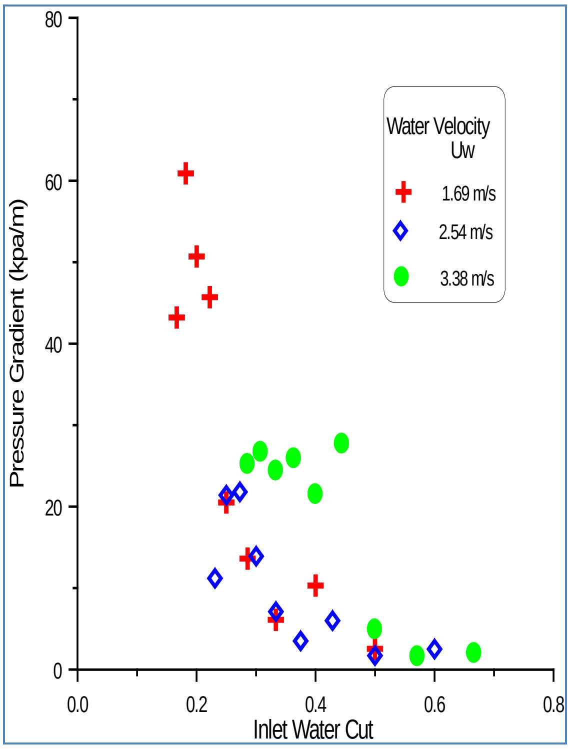



Fig. (7) Effect of inlet water cut (λ) on the pressure gradient for different water superficial velocity.

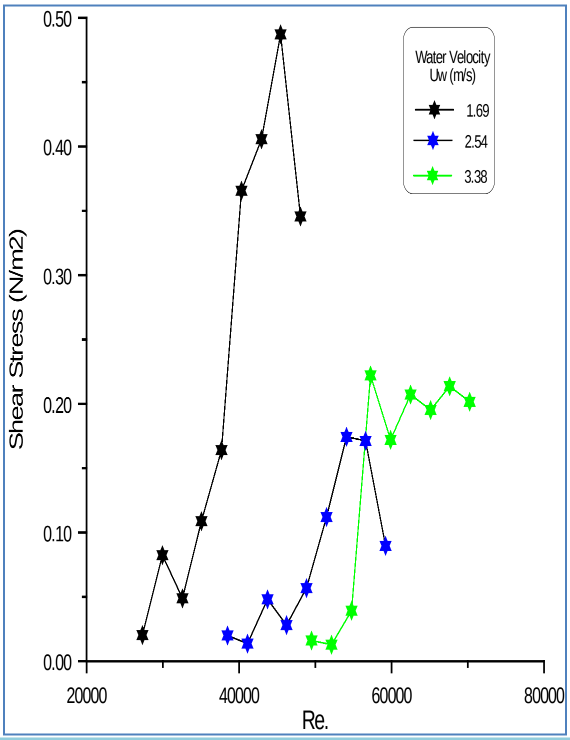



Fig. (8) Effect of Reynolds number on shear stress at wall for different water superficial velocity .

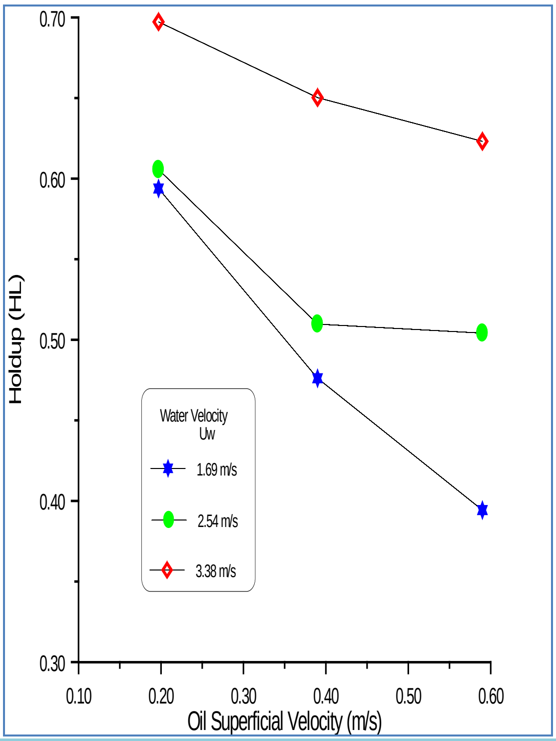



Fig. (9) Relation between Liquid holdup (HL) and Oil Superficial Velocity.

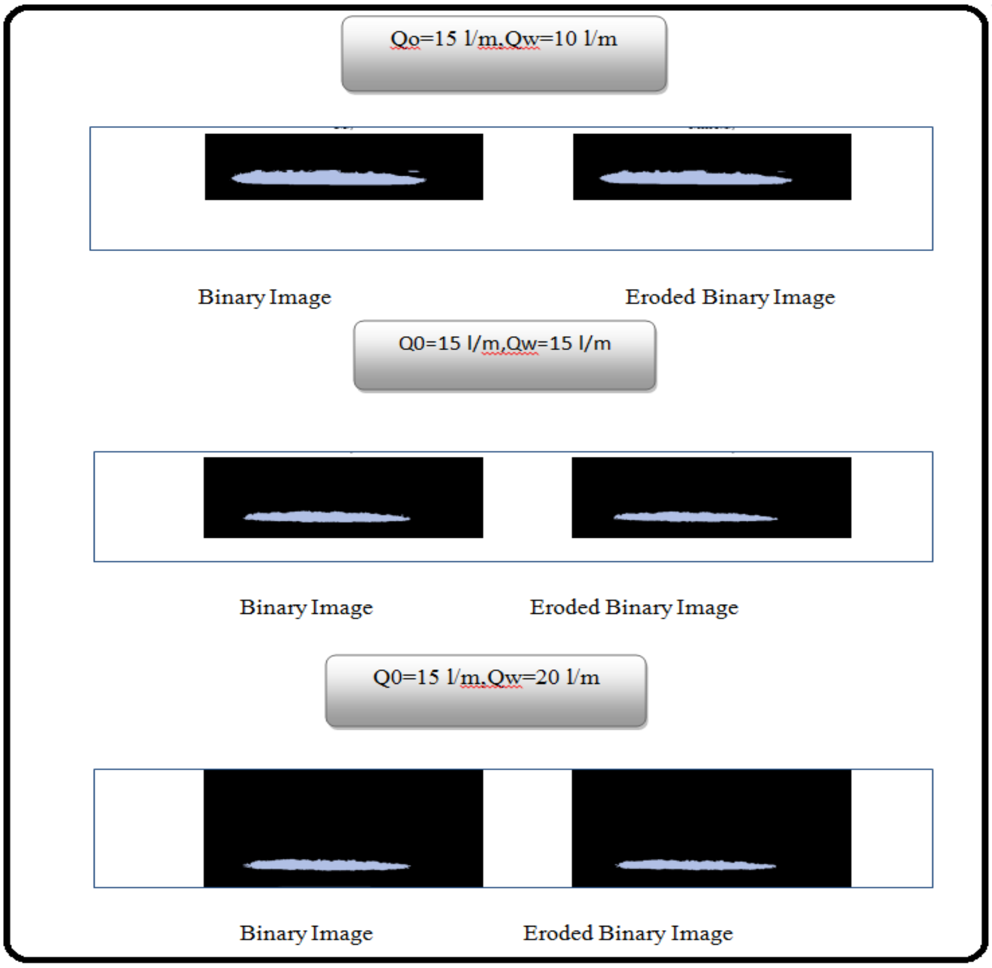



Fig.(10) The Analysis of Images Flow at Qo=5 l/m, Qw=10,15 and 20 l/m.

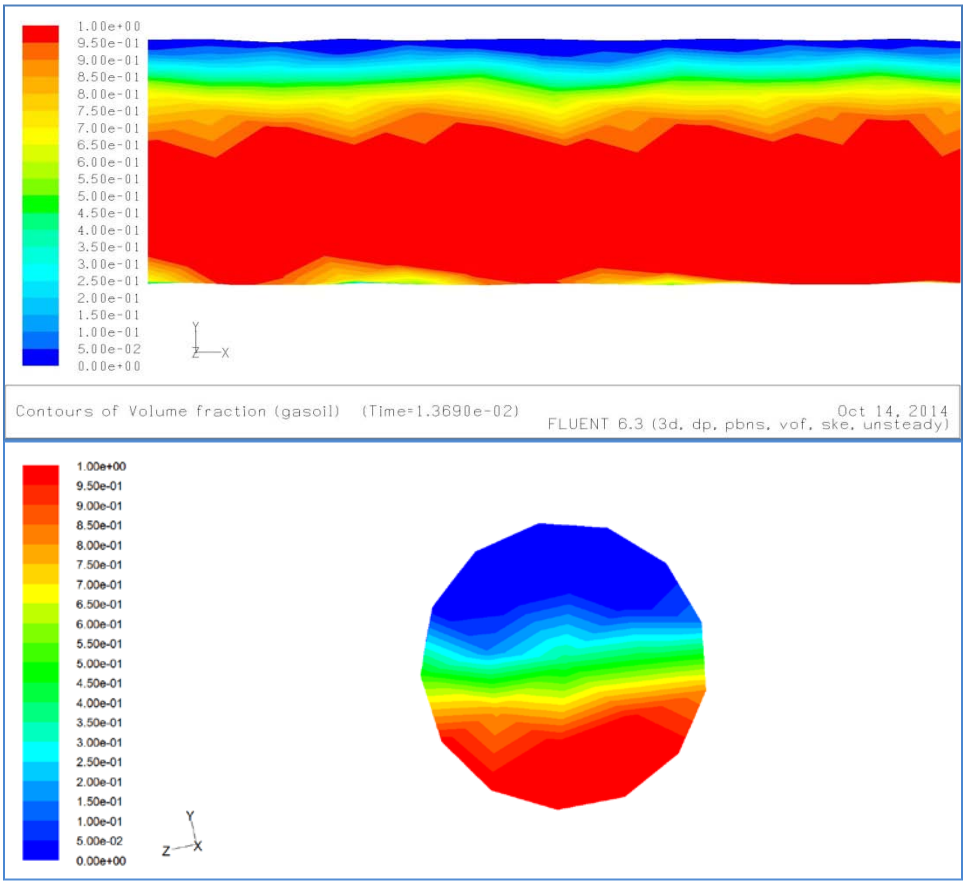



Fig. (11) a- Flow distribution VF 0.6, Um 4 m/s, b- cross section of the flow.

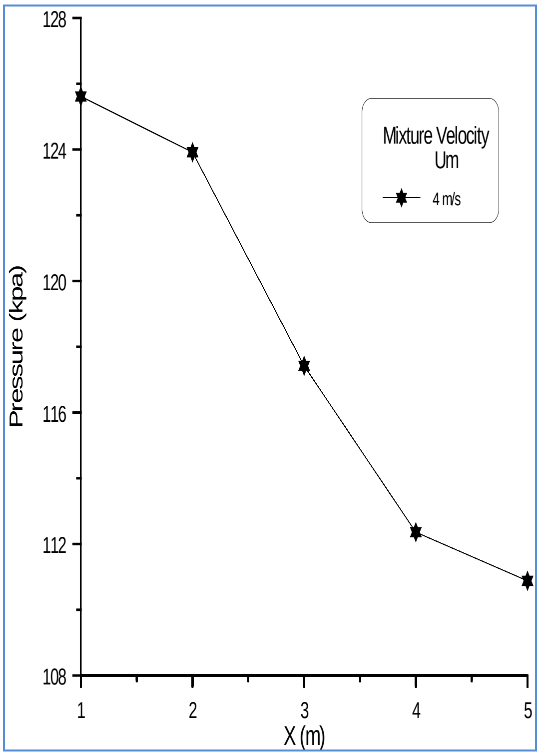



Fig. (12) Theoretical pressure drop at for oil-water flow at Um 4 m/s, vf 0.6 case.

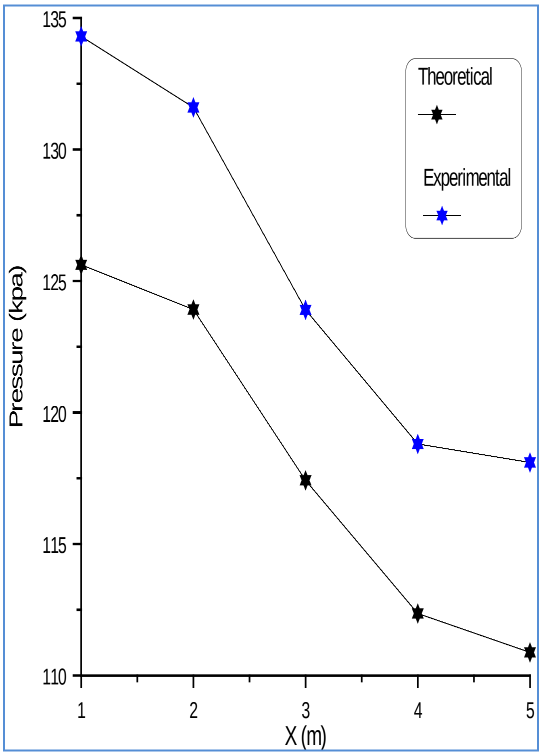



Fig. (13) Experimental and theoretical pressure comparison for oil-water flow at Um 4 m/s, vf 0.6.

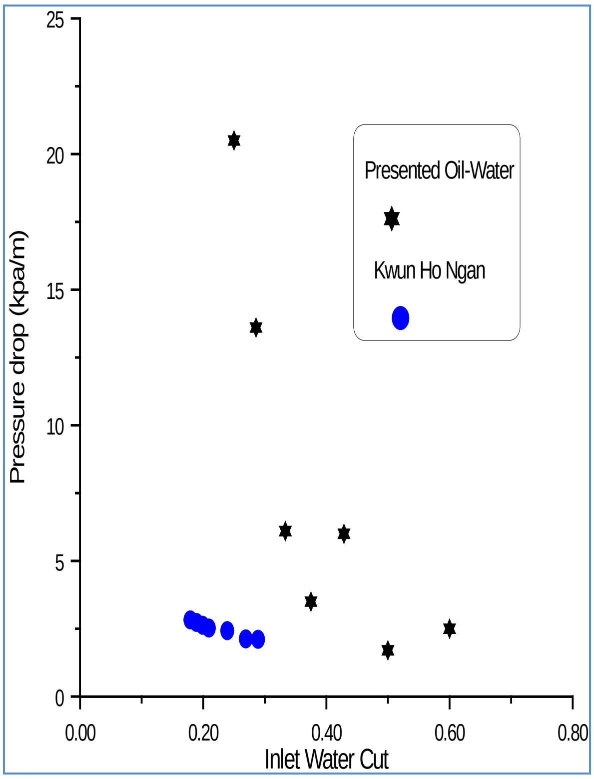



Fig. (14) Comparison pressure drop with Kwun Ho Ngan (2010) versus Inlet water cut λ.

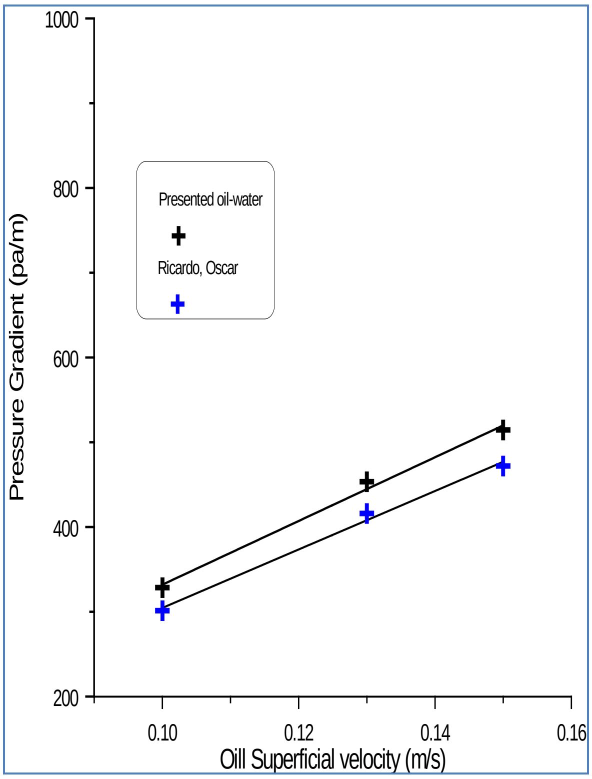



Fig. (15) Comparison pressure drop with Ricardo, Oscar (2014) oil superficial velocity.

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