



## STRATIFIED WATER-OIL-GAS FLOW THROUGH HORIZONTAL PIPES

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### ABSTRACT

Stratified three-phase flow through horizontal pipe has been studied experimentally. The fluids used in the system are water, kerosene, and air. A closed loop flow system, which composed of 0.051 m inside diameter and 4 m length test pipe, is designed with facilities for measuring flow rate, pressure drop and thickness of each phase.

The effects of gas, liquid flow rates and water liquid ratio (WLR) have been experimentally observed. It was found that liquid (water, and oil) thickness decreased when the gas flow rate is increased with constant liquid flow rate, and increased when the liquid flow rate is increased at constant gas flow rate. Pressure drop increased when the gas and/or liquid flow rate is increased.

Three equations have been formulated, using the experimental data of the present work, to predict liquid, water thickness and system pressure drop in stratified three-phase flow in horizontal pipe. High correlation coefficients are obtained for these equations.

The experimental results are compared with the results obtained from three-phase model of Taital, Barnea, & Brill (1995). The comparison showed that the predicted data which obtained from three-phase flow model Taital et al. (1995) is in good agreement with experimental data.

### الجريان الطبقي للماء والنفط والغاز خلال الانابيب الافقية

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### الخلاصة

تمت دراسة الجريان الطبقي ثلاثي الأطوار خلال الأنابيب الأفقية مختبرياً. الموائع المستخدمة في المنظومة هي: الماء، النفط الأبيض و الهواء وباستخدام أنبوب فحص قطره 0.05 م وطوله 4 م ليتم حساب: معدل جريان الموائع، هبوط الضغط في المنظومة، و سمك كل طور.

تأثيرات معدل جريان الغاز و السائل هي المدروسة لمعرفة تأثيرها على سمك الأطوار السائلة حيث وجد أن سمك أي طور من الأطوار السائلة (ماء – نفط) يقل عند زيادة معدل جريان الغاز عند ثبوت جريان السائل , و يزداد السمك عندما يزداد معدل جريان السائل عند ثبوت معدل جريان الغاز . و وجد أن هبوط الضغط يزداد عندما يزداد معدل جريان الغاز و / أو يزداد معدل جريان السائل.

تم صياغة ثلاثة معادلات لتمثيل النتائج المختبرية : معادلة تقوم بحساب سمك السائل الكلي ومعادلة لحساب سمك الماء و معادلة لحساب هبوط الضغط للجريان الطبقي ثلاثي الأطوار في الأنابيب الأفقية و هذه المعادلات أظهرت تمثيلا جيدا للنتائج المختبرية .

و قد تم مقارنة النتائج المختبرية مع النتائج المستحصلة من موديل ميكانيكي و هو : تايتل , بارنيه و بريل 1995 و هذا المقارنة اظهرت بان القيم المستحصلة من الموديل الثلاثي الطور جيدة في تمثيل النتائج المختبرية .

## INTRODUCTION

Three-phase gas-oil-water flow commonly occurs in the petroleum industry. Perhaps the most relevant practice is the transportation of natural gas-oil-water mixtures through pipelines. Three-phase flow may also be encountered in pumping system, especially in surface gathering lines, and in well-bores and gas lift wells which produce water along with oil and gas. In off-shore and remote well sites, it is often intractable to separate oil and gas there. The transportation of oil and gas in multiphase pipelines is therefore becoming more common. The oil-water-gas mixtures produced are transported many kilometers to platform or central gathering stations where the fluids are separated.

Water production often increases significantly during the latter stage of a well and use of the conventional approximations of a two-phase oil-gas system neglecting the water, or combining the oil and water into a liquid phase, often becomes inaccurate.

There have been numerous investigations of two-phase flow regimes; in contrast, three-phase flow regimes have not been studied thoroughly. Because of the abundance of three-phase flow applications in the petroleum and chemical industries, a better understanding of this complex flow phenomenon is needed.

## PURPOSE OF STUDY

The main purpose of this study is to investigate the pressure drop of the system and the levels of the liquid layers (water and oil) and the gas layer experimentally. Flow pattern map have been constructed for 50% water liquid ratio (WLR). Three empirical correlations have been developed for predicting liquid, and water thicknesses and pressure drop in three-phase stratified flow in horizontal pipes. The experimental data have been compared with the theoretical data of three-phase model of Taital et al. (1995).

## FLUID PHYSICAL PROPERTIES

The physical properties of the liquid and gas phases are determined from laboratory measurements at atmospheric pressure and temperature of  $12^{\circ}C$  . These properties are shown in Table (1): -

**Table (1): physical properties of water, oil, and gas**

	Water	Oil (kerosene)	Gas (air)
Density $\rho \left( \frac{Kg}{m^3} \right)$	1000	775	1.22
Viscosity $\mu (Pa.s)$	0.001141	0.00127875	0.000018

### EXPERIMENTAL FACILITIES AND TEST PROCEDURE

The experiments were conducted in horizontal three-phase flow loop as shown in Fig (1). Three kinds of phases are used in this study (water, kerosene and air). The individual phase of oil and water are pumped from their individual tank ( $0.15m^3$ ) into 1 inch ID pipe. A two centrifugal pumps with maximum flow of ( $4m^3/hr.$ ) is used to pump the two immiscible liquid (oil and water) to the mixing tee (mixing tank) at the up stream of test section. The water and oil flow rate are measured by flow meter. The gas from compressor with maximum flow rate of ( $16m^3/hr.$ ) is also passed into the mixing tank. Its flow rate is measured by flow meter.

The gas-oil-water mixture from the mixing tank flow into a (0.051mm) internal diameter, and (4 m) long Plexiglas pipeline (transparent pipe), where the flow patterns are observed visually. The water and oil film thickness are measured by using a rule which was parallel with vertical diameter. The multiphase mixture is discharged into a ( $0.768m^3$ ) separator. The gas is discharged from the top to the atmosphere. The oil-water mixtures settle and separate into individual phases and return to their respective tank. The majority of the experiments were carried out in the system which operated at atmospheric pressure and temperature of ( $12^{\circ}C$ ). It should be noted that because of the waves at the gas-oil interface, the measurements obtained from these experiments did not provide a precise estimate of the film thickness. Only a range for the film thickness could be determined.

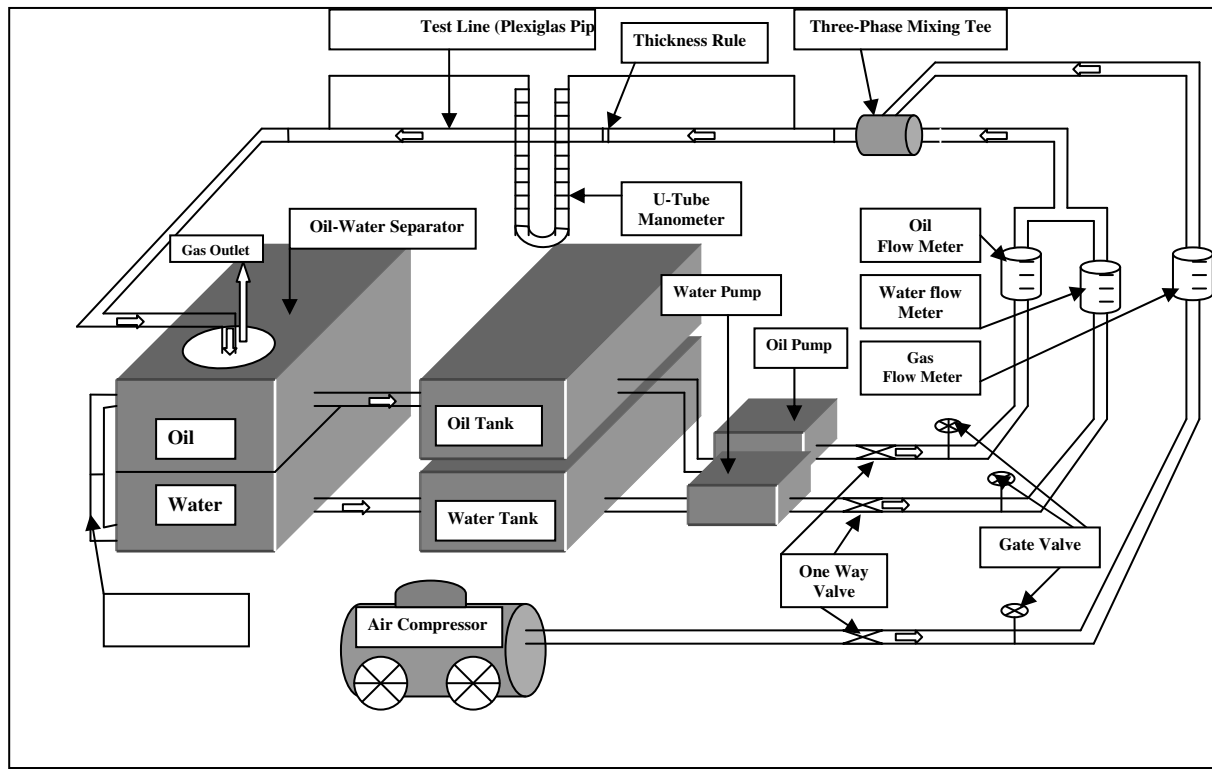


Fig.( 1) Three-Phase Flow Loop

## RESULTS

In this study, the effect of liquid (oil & water) and gas flow rates, and pressure drop have been studied experimentally. Flow pattern maps have been constructed for 50% WLR. Then experimental results are compared with Three-phase mechanistic model of Taital et al. (1995) for predicting liquid, water, and oil thickness and system pressure drop.

### The Effect of Gas Flow Rate on Dimensionless Thickness

Figure (2) show the effect of liquid and gas flow rates on dimensionless liquid thickness ( $h_L/D$ ). For constant liquid flow rate there is an inversely proportional relationship between dimensionless liquid thickness ( $h_L/D$ ) and gas flow rate ( $v_{sg}$ ). A proportional relationship is observed between ( $h_L/D$ ) and liquid flow rate ( $v_{sl}$ ) for constant gas flow rate.

The same results are obtained when plotting ( $h_w/D$ ) or ( $h_o/D$ ) instead of ( $h_L/D$ ) as shone in Figs. (3) and (4) respectively.

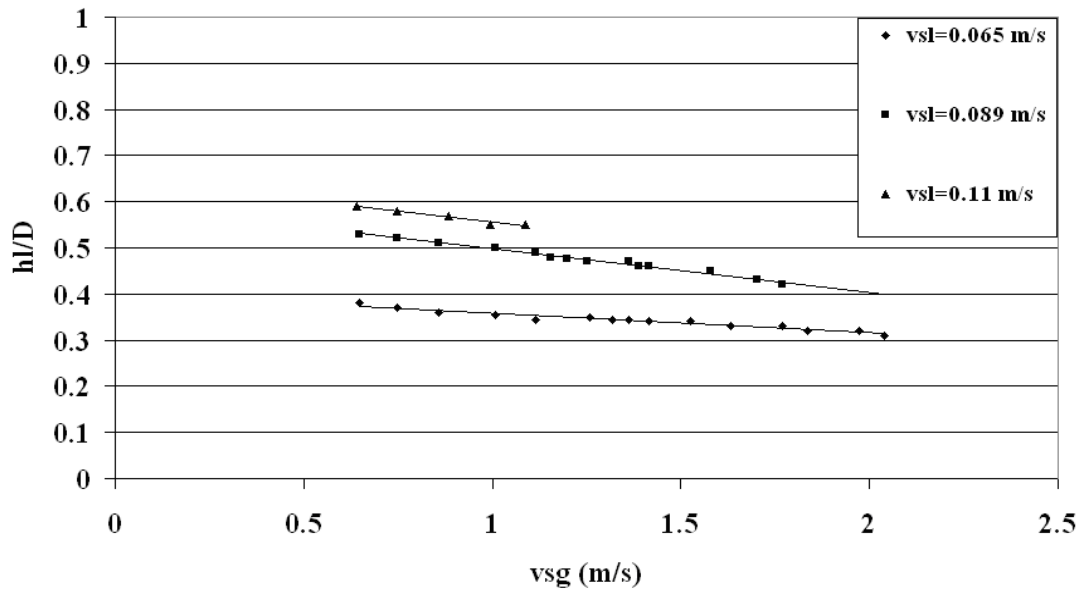


Fig.2 Relationship between vsg and hl/D for different vsl {WLR=50%}

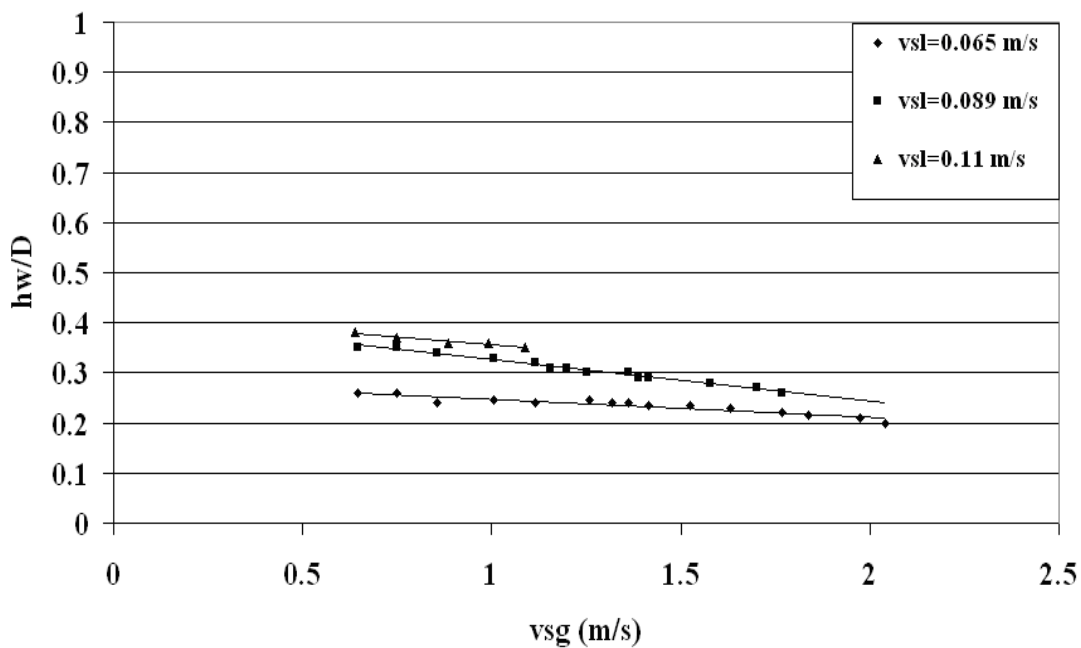


Fig.3 Relationship between vsg and hw/D for different vsl {WLR=50%}

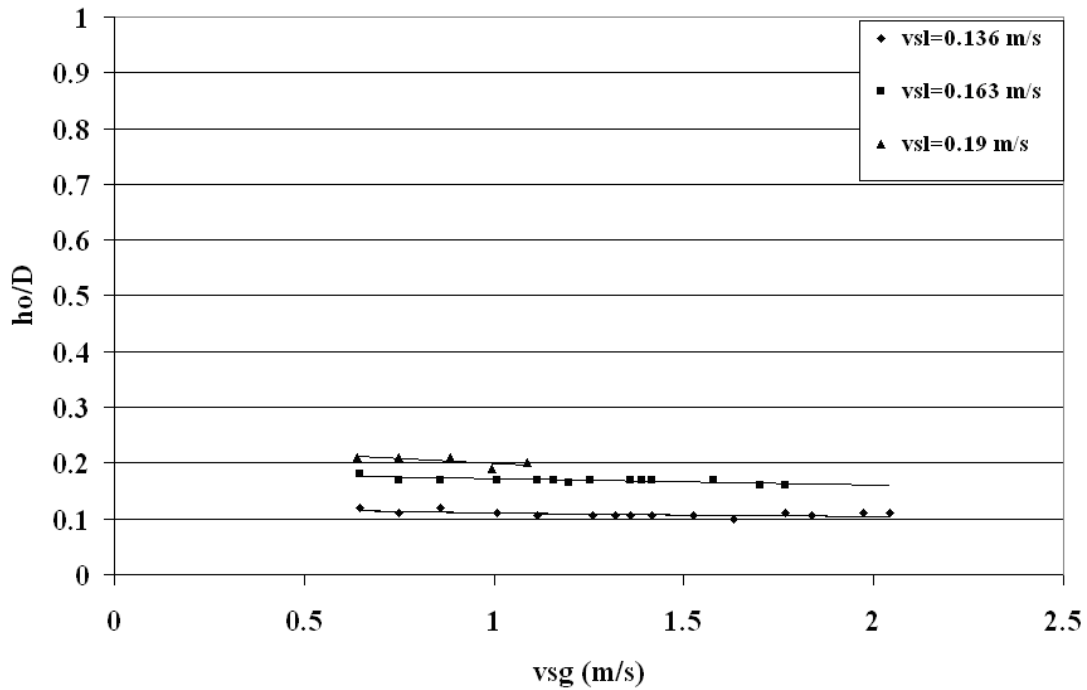


Fig.4 Relationship between vsg and ho/D for different vsl {WLR=50%}

The values of  $(h_L / D)$ ,  $(h_w / D)$ ,  $(h_o / D)$  are plotted on the same figure versus (vsg) for a constant (vsl). Several figures are obtained for different velocities (Fig.5 for vsl= 0.065, Fig.6 for vsl=0.089, Fig.7 for vsl=0.11. The water level is usually quit high and the liquid consists mostly of water. This is logical since the oil being closer to the fast moving gas, i.e., the oil is dragged by the gas at higher velocities compared with the water layer at bottom.

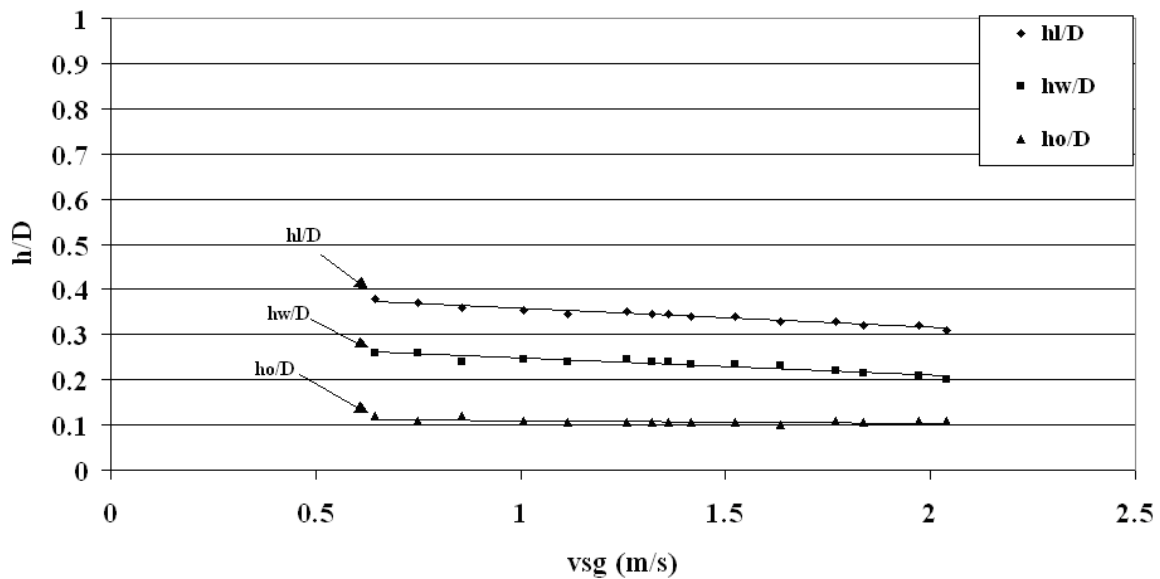


Fig.5 Relationship between vsg and h/D (vsl=0.065 m/s) {WLR=50%}

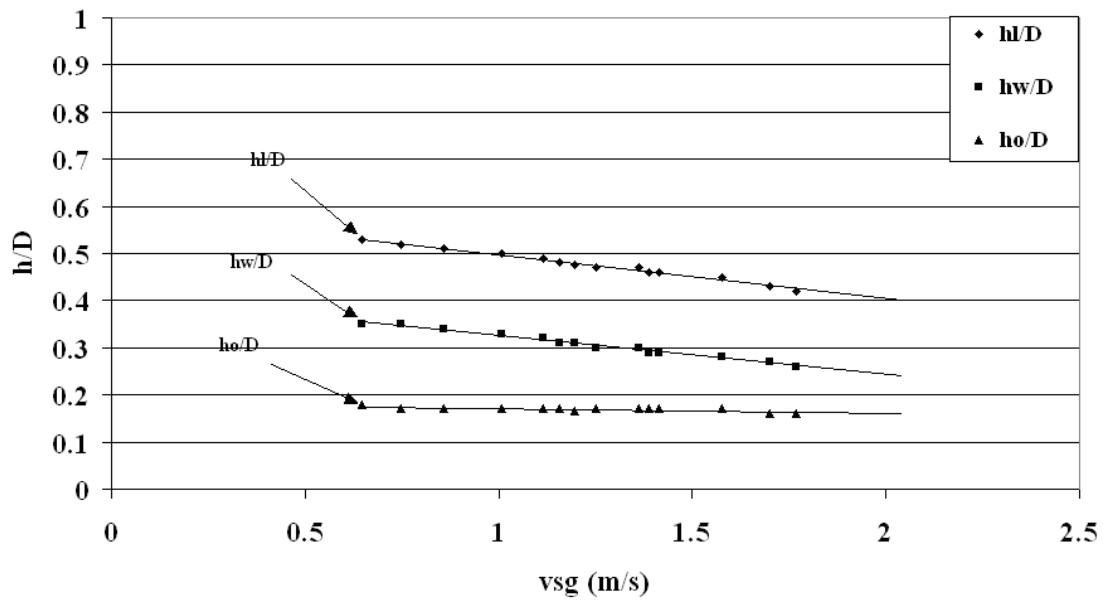


Fig. 6 Relationship between vsg and h/D (vsl=0.089 m/s) {WLR=50%}

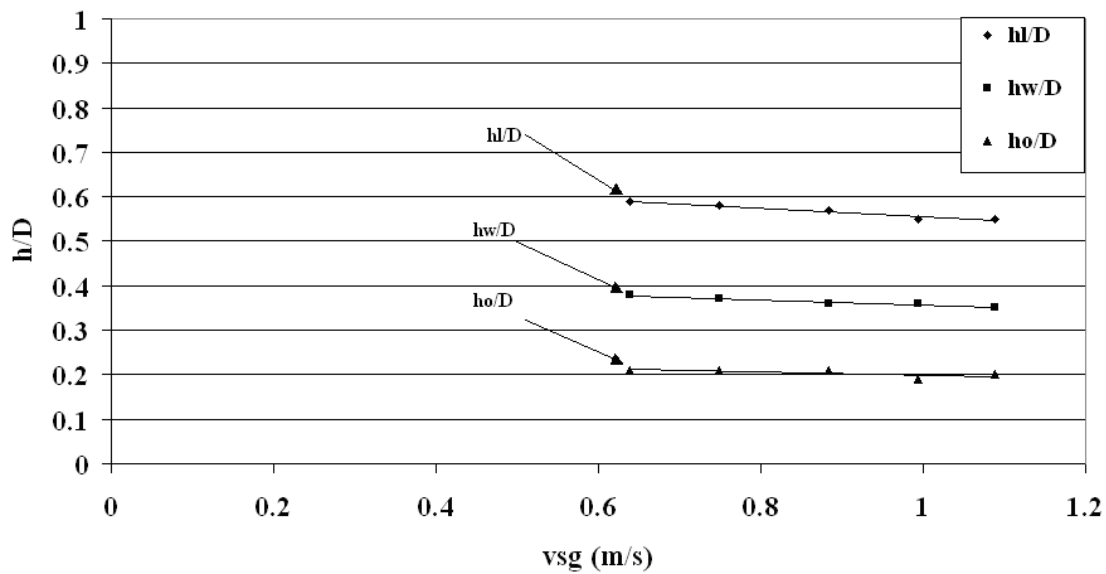


Fig.7 Relationship between vsg and h/D (vsl=0.11 m/s) {WLR=50%}

### The Effect of Gas Flow Rate on Pressure Drop

The effects of liquid and gas flow rate on pressure drop are presented in Fig.8. In general the pressure drop increased when the gas and/or liquid flow rate increased.

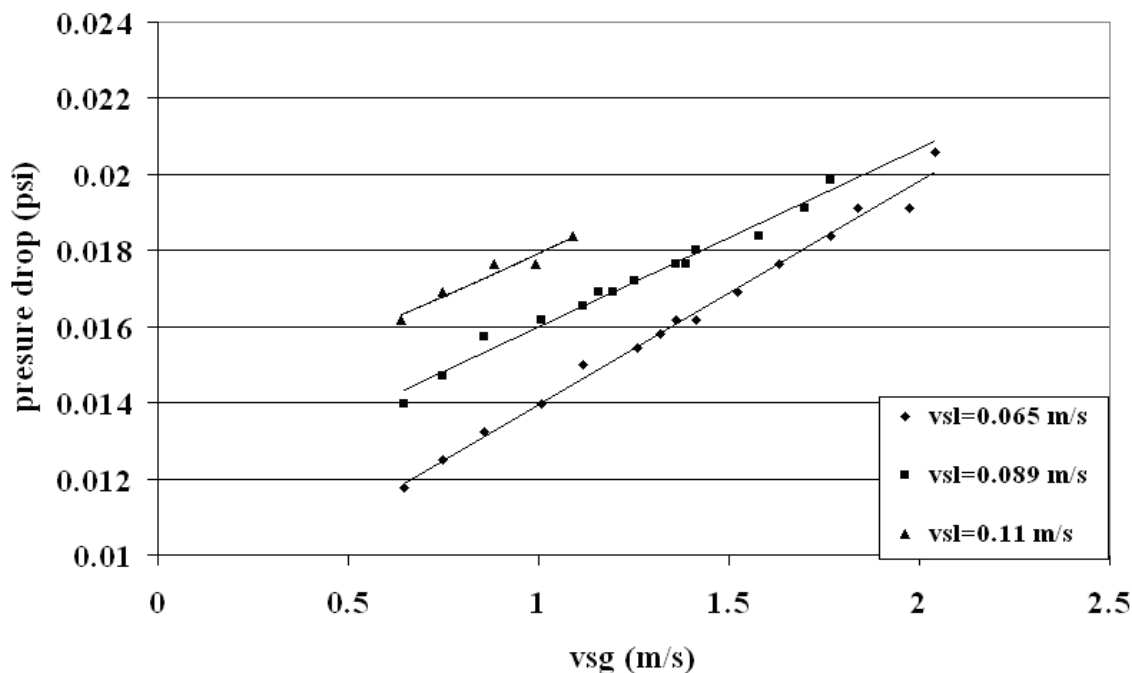


Fig. 8 Relationship between vsg and pressure drop for different vsl {WLR=50%}

### Flow Pattern Maps

Fig.9 depict the flow pattern map for the stratified three-phase flow through horizontal pipes

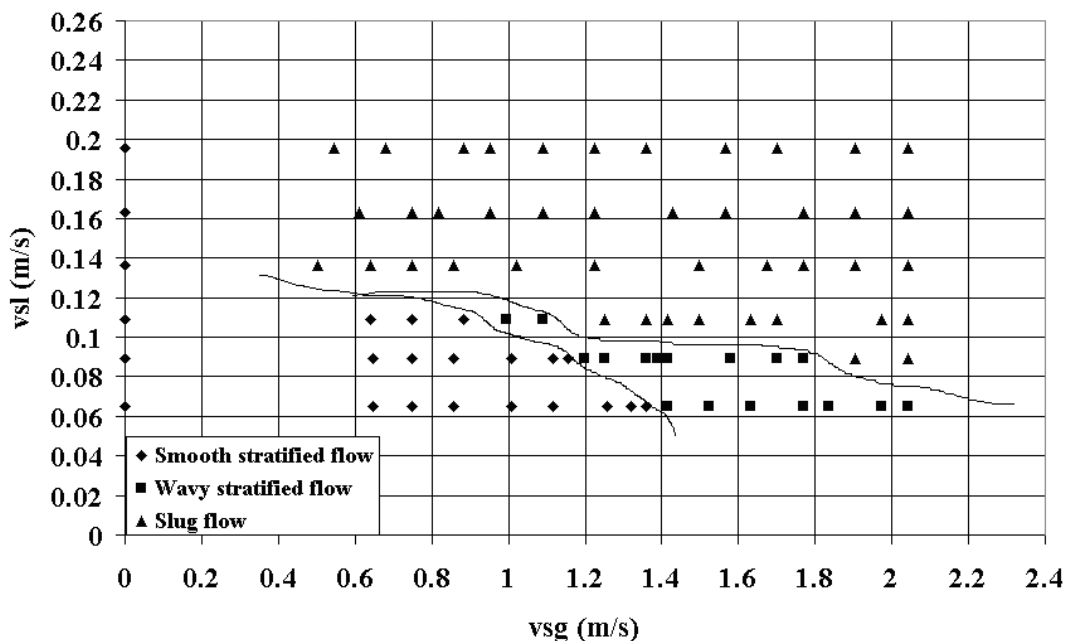


Fig.9 Relationship between vsg and vsl {WLR=50%}



### THE FORMELATED EQUATIONS

Three empirical correlations for estimating dimensionless liquid, and water thicknesses and system pressure drop in three-phase stratified flow in horizontal pipe are developed. The diameter of the pipe used is 0.051 m and the length is 4 m. Constant fluid physical properties (table.1) are used in these correlations. As shown below the dimensionless thickness and pressure drop are correlated as a function of liquid flow rate, gas flow rate, and water liquid ratio (WLR):-

The correlated dimensionless liquid film thickness equation is: -

$$\frac{h_L}{D} = a_1 + a_2 * (WLR * Q_L)^{a_3} + a_4 * ((1 - WLR) * Q_L)^{a_5} + a_6 * Q_G^{a_7} \quad (1)$$

Where,

$$\begin{aligned} a_1 &= -0.116227 & a_2 &= 0.451614 & a_3 &= 0.850409 & a_4 &= 0.48286 \\ a_5 &= 0.981403 & a_6 &= 0.364976 & a_7 &= -0.193155 \end{aligned}$$

$Q_L$  &  $Q_G$  :  $m^3 / hr$ .

WLR : fraction

The correlation coefficient for Eq. (5-1) is 0.96

The formulated dimensionless water film thickness equation is shown below: -

$$\frac{h_w}{D} = b_1 + b_2 * (WLR * Q_L)^{b_3} + b_4 * ((1 - WLR) * Q_L)^{b_5} + b_6 * Q_G^{b_7} \quad (2)$$

Where,

$$\begin{aligned} b_1 &= -0.117454 & b_2 &= 0.620129 & b_3 &= 0.590837 & b_4 &= 0.047055 \\ b_5 &= 0.805945 & b_6 &= 0.173923 & b_7 &= -0.375791 \end{aligned}$$

Here, the correlation coefficient equal to 0.99

The pressure drop equation is formulated as follows: -

$$\Delta P = c_1 * ((WLR * Q_L + (1 - WLR) * Q_L) * Q_G)^{c_2} \quad (3)$$

Where,

$$c_1 = 0.000863 \quad c_2 = 0.409815$$

The correlation coefficient for the above Eq. is 0.91

Figs.10, 11, and 12 show that there is a good agreement between experimental and predicted data obtained from Eqs.1, 2, and 3 for dimensionless liquid, and water thickness and pressure drop respectively.

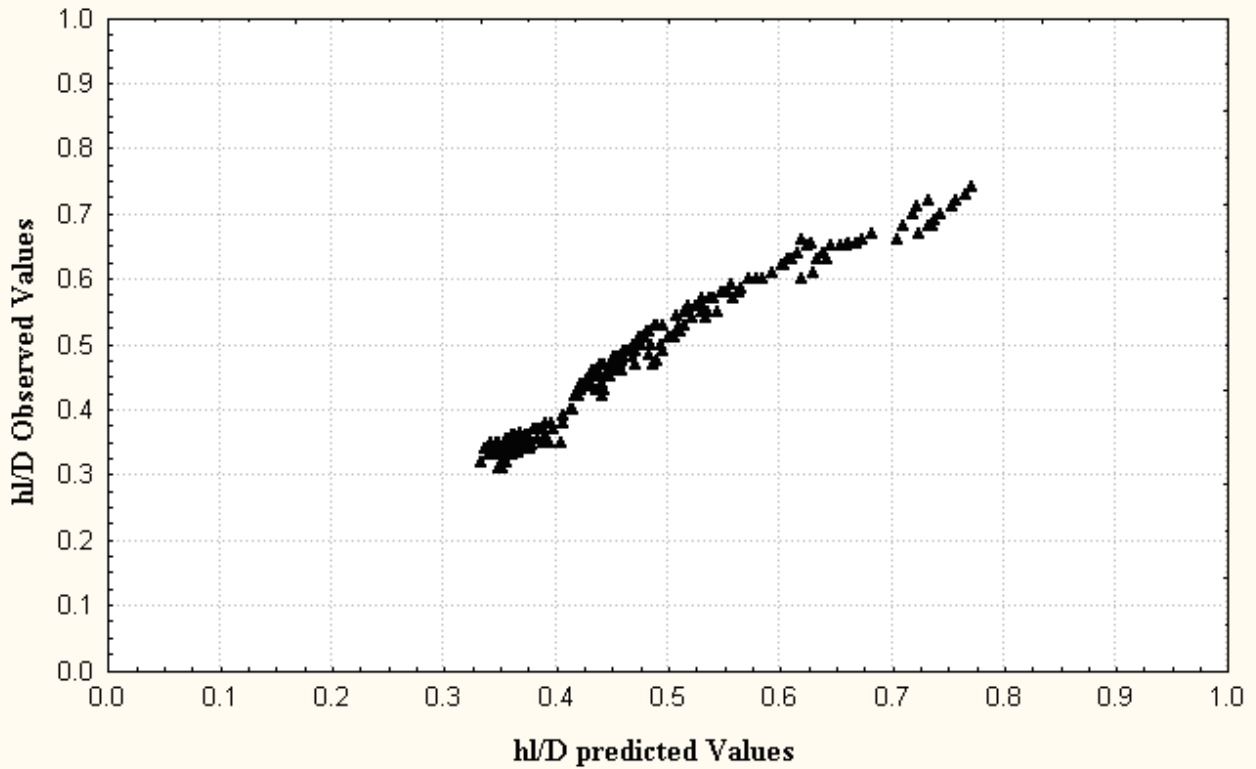


Fig.10 Relationship between  $h/D$  predicted vs.  $h/D$  observed Values

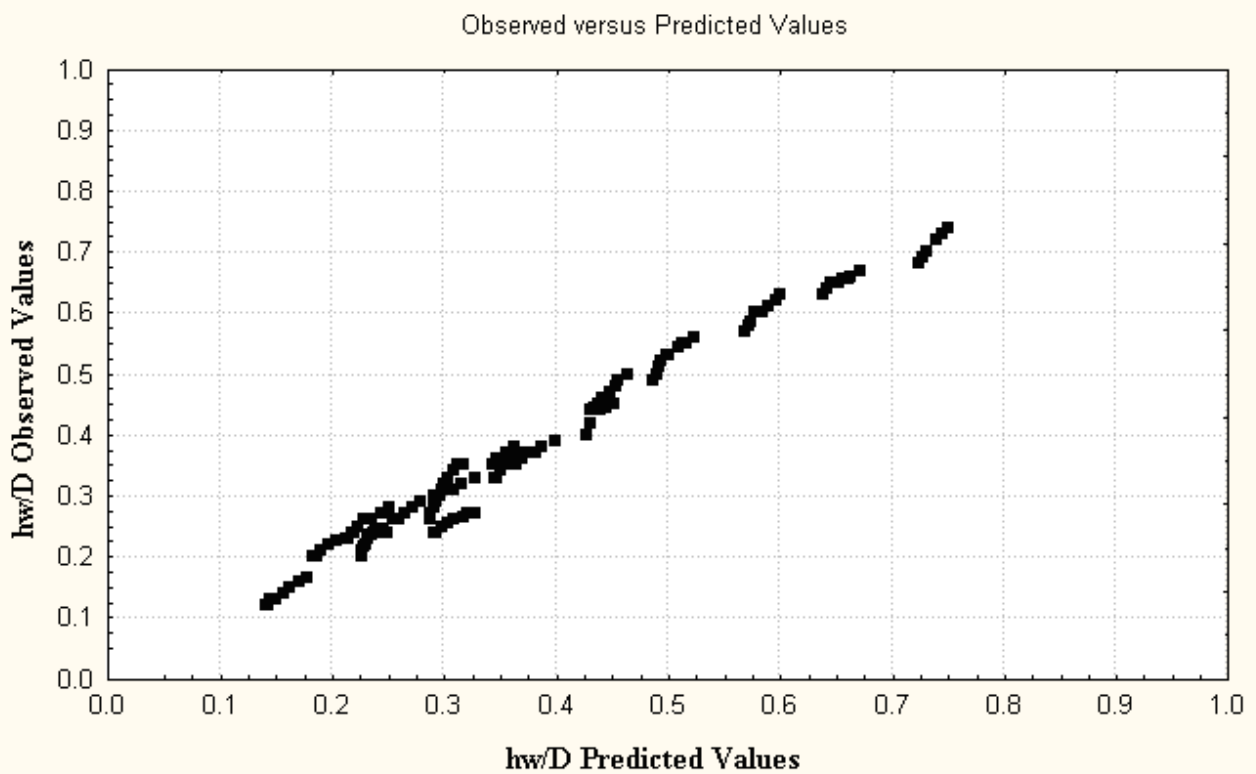


Fig.11 Relationship between  $hw/D$  predicted ve.  $hw/D$  observed Values

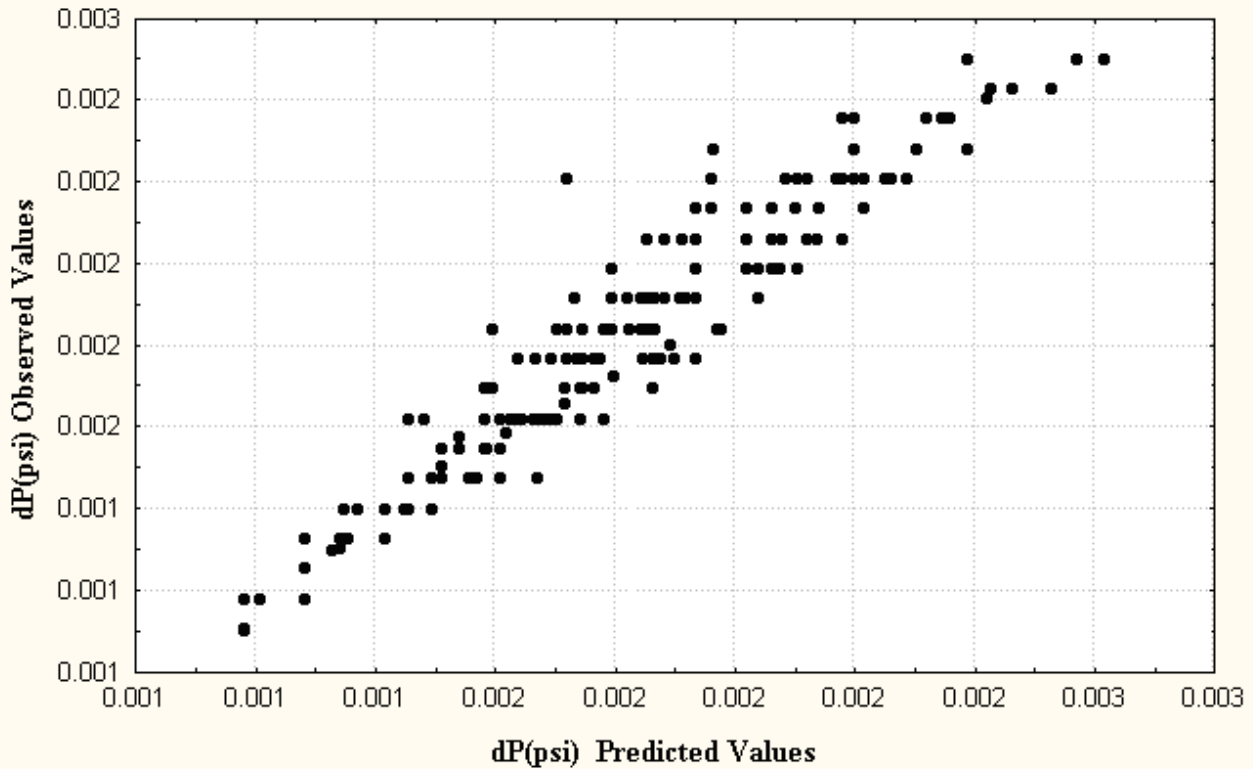


Fig.12 Relationship between dp predicted vs. dp observed values

### THREE-PHASE FLOW MECHANISTIC MODEL

Several three-phase flow models were found. All of the models are developed from the three-phase momentum equations with few changes from one to the other.

Taital et al. (1995) developed a three-phase model for horizontal and near-horizontal three-phase flow. The model starts with the momentum balance equations for each phase.

$$-A_w \left( \frac{dp}{dx} \right) - \tau_w S_w + \tau_i S_i - \rho_w A_w g \sin \beta = 0 \tag{4}$$

$$-A_o \left( \frac{dp}{dx} \right) - \tau_o S_o - \tau_i S_i + \tau_j S_j - \rho_o A_o g \sin \beta = 0 \tag{5}$$

$$-A_g \left( \frac{dp}{dx} \right) - \tau_g S_g - \tau_j S_j - \rho_g A_g g \sin \beta = 0 \tag{6}$$

Summing Eqs.4 and 5 yields:

$$-\left( \frac{dp}{dx} \right) - \frac{\tau_L S_L}{A_L} + \frac{\tau_i S_i}{A_L} - \rho_L g \sin \beta = 0 \tag{7}$$

Where;

$$\tau_L S_L = \tau_w S_w + \tau_o S_o \quad (8)$$

$$\rho_L = \frac{\rho_w A_w + \rho_o A_o}{A_L} \quad (9)$$

And;

$$A_L = A_w + A_o \quad (10)$$

Note that Eq.7 is the combined momentum equation for the liquid phase, which composed, of water and oil layers. Therefore, Eqs.8 and 9, have the same form as two-layer momentum equations for liquid and gas as derived by classical Taital and Dukler model (1976).

The pressure drop can be eliminated by adding Eqs.6 to 7 to yield:

$$-\frac{\tau_L S_L}{A_L} + \frac{\tau_G S_G}{A_G} + \tau_j S_j \left( \frac{1}{A_L} + \frac{1}{A_G} \right) - (\rho_o - \rho_G) g \sin \beta = 0 \quad (11)$$

In the same way the pressure drop is eliminated from Eqs.4 and 5 to yield:

$$-\frac{\tau_w S_w}{A_w} + \frac{\tau_o S_o}{A_o} - \frac{\tau_j S_j}{A_o} + \tau_i S_i \left( \frac{1}{A_w} + \frac{1}{A_o} \right) - (\rho_w - \rho_o) g \sin \beta = 0 \quad (12)$$

Eqs.11 and 12 must be solved simultaneously to yield the liquid level ( $h_L$ ), and the water level, ( $h_w$ ).

In this study, Taitel et al (1995) model is used for comparison with the experimental data of this study.

### **Comparison with Mechanistic Model**

The results of the Three-phase mechanistic model of Taital et al. (1995) are plotted against the experimental data (  $\frac{h_L}{D}, \frac{h_w}{D}, \frac{h_o}{D}, \& \Delta P$  ) as shown in Figs.13 through 16.

It is clear that the good agreement is obtained between the experimental results of the presented study and that of Taital et al. (1995) model.

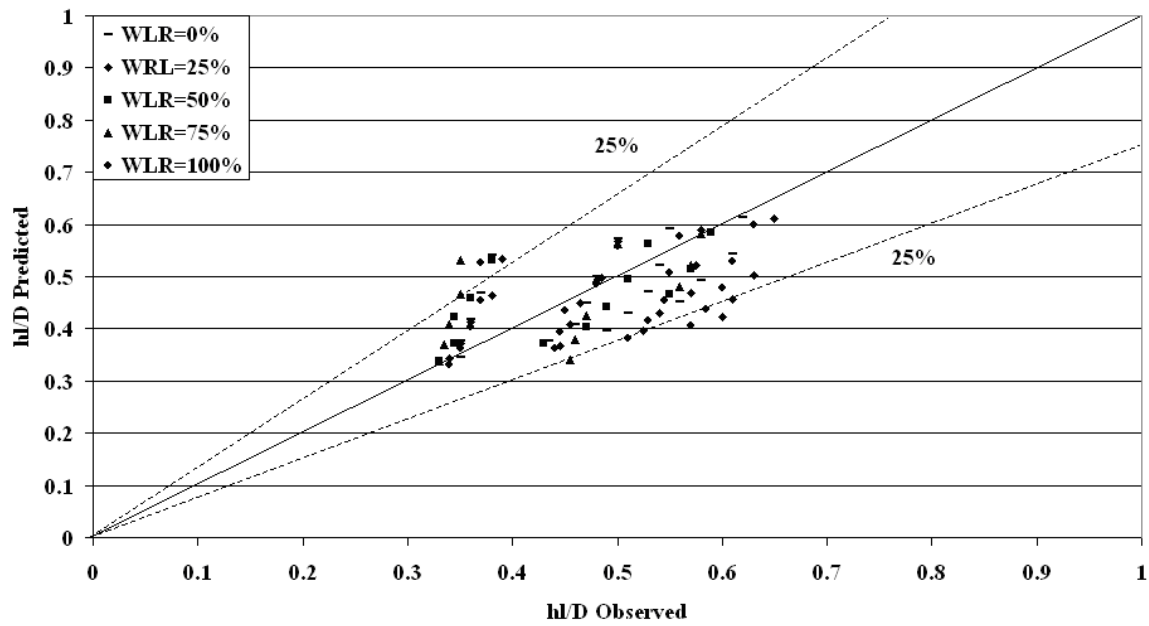


Fig. 13 Relationship between  $hl/D$  Observed vs.  $hl/D$  Predicted {by Taital et al. model (1995)}

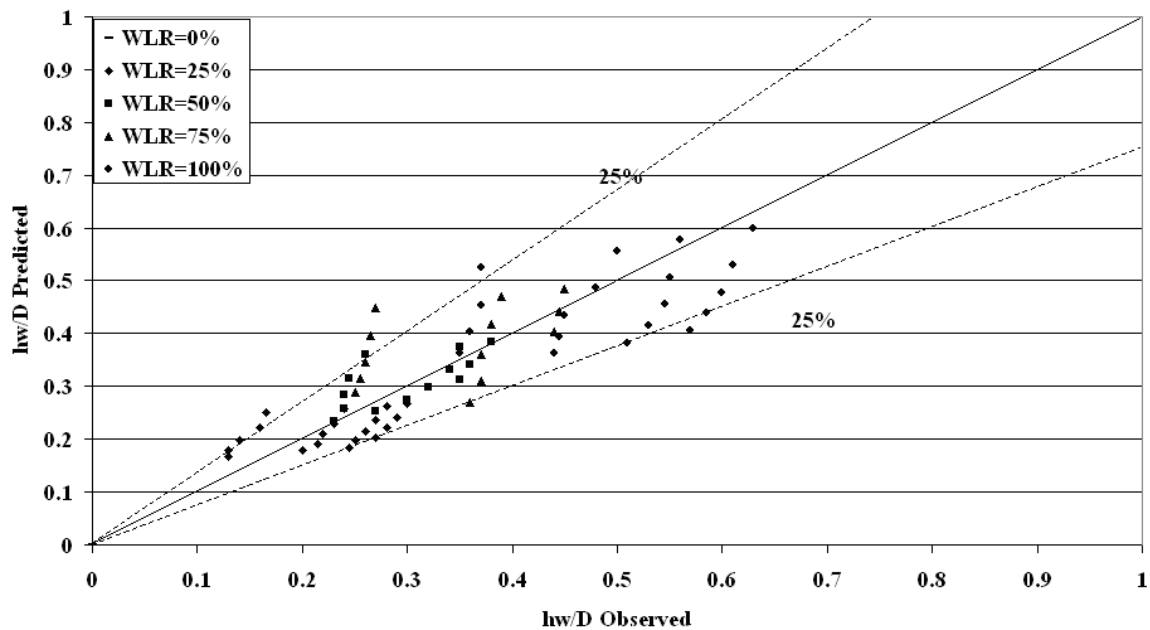


Fig.14 Relationship between  $hw/D$  Observed vs.  $hw/D$  Predicted {by Taital et al. model (1995)}

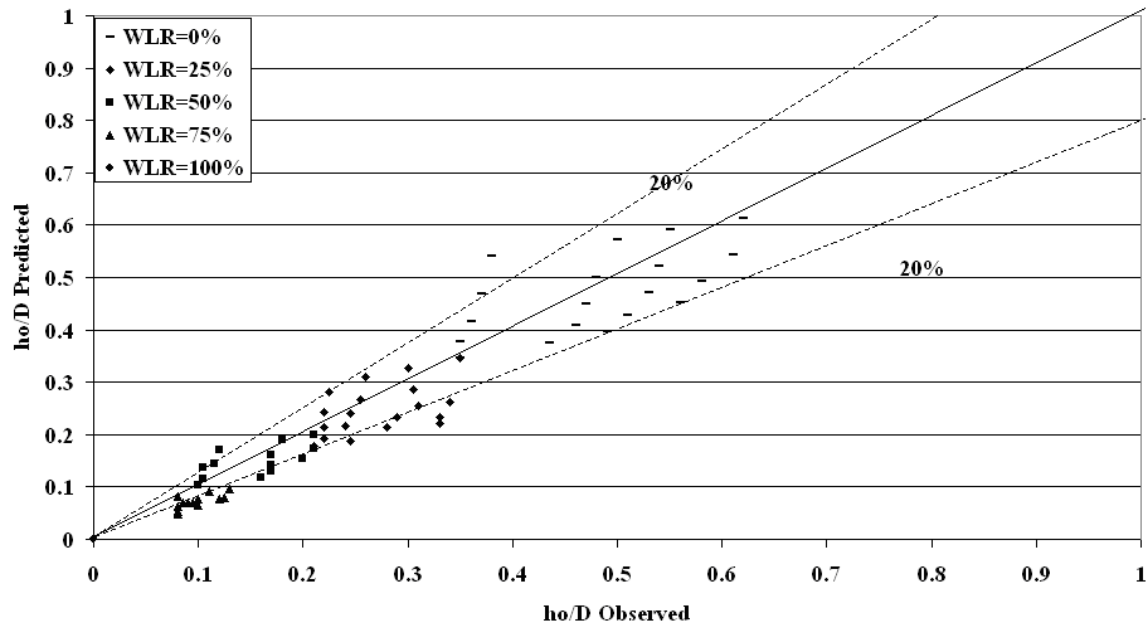


Fig.15 Relationship between  $h_o/D$  Observed vs.  $h_o/D$  Predicted {by Taital et al. model (1995) }

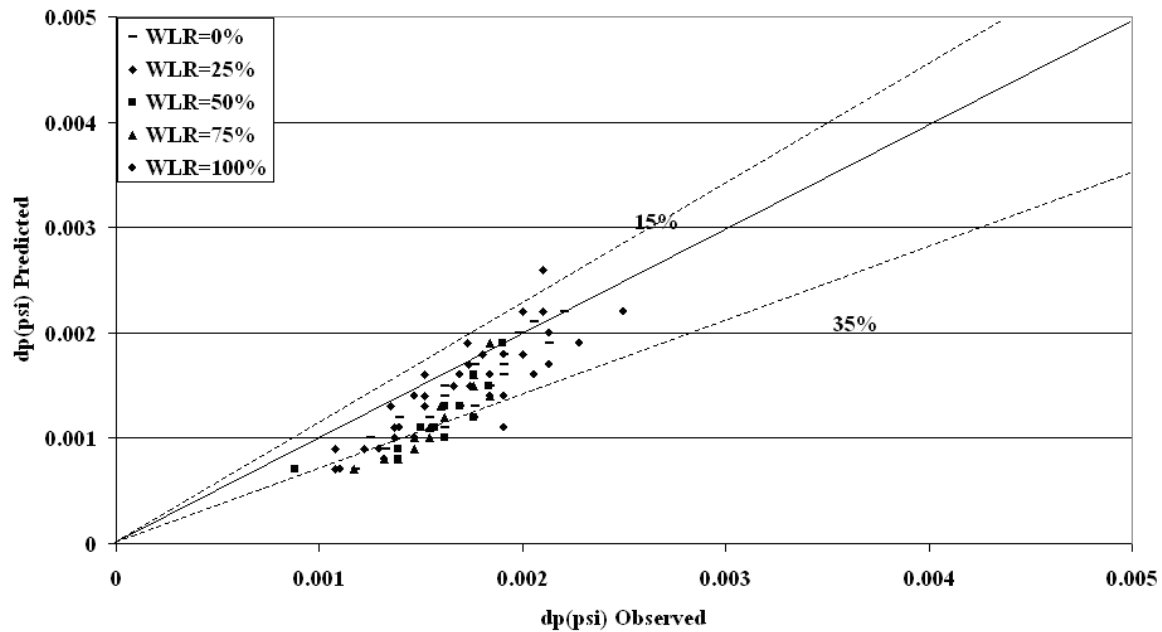


Fig.16 Relationship between  $dp$  Observed vs.  $dp$  Predicted {by Taital et al. model (1995) }

## Conclusions

1. Three equations have been developed by correlating the experimental data. These equations can be used to predict liquid, and water thicknesses and system pressure drop for the conditions specified in the present work.
2. Three-phase flow model Taital et al. (1995) gave good prediction for liquid, water thicknesses, and pressure drop.
3. In three-phase flow (water, oil, and gas) the water level is usually quit high and the liquid consists mostly of water for equal rate of water and oil (WLR=50%).

**SYMMOLS AND ABBREVIATIONS**

<b>Symbol</b>	<b>Definition</b>	<b>Unit</b>
$A$	Pipe area	$m^2$
$h$	Film thickness	$m$
$P$	Pressure	$Pa$
$Q$	Flow rate	$m^3 / s$
$S$	Perimeter	$m$
$V_s$	Superficial velocity	$m / s$
$\beta$	Inclination of pipe	deg.
$\rho$	Density	$kg / m^3$
$\tau$	Shear stress	$Pa$

<b>Subscript</b>	<b>Definition</b>
W	Water
O	Oil
G	Gas
L	Liquid
i	interface between oil and water
j	interface between gas and oil
K	Water, Oil, or Gas

<b>Abbreviation</b>	<b>Definition</b>
WLR	water liquid ratio
Exp.	Experimental
Pre.	Predicted
SS	smooth stratified flow
SW	wavy stratified flow

**References**

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