

# Pressure Gradient Modeling for Near Horizontal Flow as a Function of Horizontal Flow

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**Abstract:** Two phase in horizontal and near horizontal pipe, down and upward flow, ( $\theta = 0^\circ$ ,  $-3^\circ$ , and  $+3^\circ$ ), has been studied experimentally. The used fluids in the system are water and air. A closed loop flow system which is composed of 2 in (51 mm) inside diameter and 5m length test pipe is designed with facilities for measuring pressure drop, flow rate and flow pattern visually observed throughout transparent pipe. The effects of gas and water flow rates have been experimentally observed. Generally, pressure drop increased when the gas and water flow rate is increased. Horizontal flow ( $\theta = 0^\circ$ ) has the smallest pressure drop with respect to other inclination angles ( $\theta = -3^\circ$ , and  $+3^\circ$ ). While in upward flow, the pressure drops were generally much higher. Flow pattern map changed depend on angle of flow, where the stratified is domain in horizontal and downward flow while slug flow is domain in upward flow. General formula have been proposed for pressure gradient of horizontal flow in general form, without need to measure the liquid holdup experimentally. Then, in order to take into account the effect of inclination angle, we have proposed new model for pressure gradient of upward and downward flow form as a function to pressure gradient of horizontal flow. The result of the presented correlation shows an acceptable agreement between the observed and predicted pressure gradient values.

**Key Word:** Two-Phase Flow, Pressure Gradient, Horizontal and Near Horizontal.

## 1- Introduction

Two phase flow systems are common in petroleum, chemical and nuclear industries. The prediction of pressure gradients and flow patterns occurring during the simultaneous flow of gas and liquid in pipes is necessary for design the petroleum and chemical industries. Petroleum engineers encounter two-phase flow most frequently in well tubing and in flow lines. Offshore producing has necessitated transporting both gas and liquid phases over long distances before separation. The flow may be vertical, inclined or horizontal and methods must be available for predicting pressure drop in pipe at any inclination angle. The complexity in the prediction and design of gas-liquid system lies in the simultaneous existence of the gas and liquid phases. The interface between the two phases can be distributed in many configurations; this phenomenon is called "flow pattern", which is considered a very important feature of two phase flow. Flow pattern and pressure drop are two important characteristics of two phase flow, it is necessary to know the flow pattern in order to estimate accurately pressure drop, and then to design correctly the size separation facilities and pipelines.

Extensive theoretical and experimental researches have been conducted on horizontal and inclined two-phase flow. Most published correlations for two-phase flow in pipes require the prediction of two-phase parameters; the liquid hold up, pressure drop and the two-phase friction factor. Some of these correlations require prediction of flow pattern. Flow pattern prediction for two-phase gas-liquid flow has been studied by several workers. Beggs and Brill<sup>1</sup> (1973) developed an empirical correlation for predicting pressure drop in inclined pipes based on experimental data, also they divided the flow pattern into three pattern; segregated, intermittent and distributed. The principal and the most widely used method is the mechanistic approaches of Taitel & Dukler<sup>2</sup> (1976). The authors developed a mechanistic model for predicting flow pattern transitions in horizontal and near horizontal gas-liquid flow. Barnea, Shoham, Taitel and Dukler<sup>3</sup> (1985) developed physical models for flow pattern transition for horizontal and vertical tube, and the modified for upward flow in pipes at any angle of inclination. Barnea<sup>4</sup> (1987) presented a model for predicting flow pattern transitions in gas-liquid flow in pipes. This model incorporates the effect of flow rate, fluid properties, pipe size and the inclination angle in a unified model. Transition mechanisms for each individual boundary are presented and a logical path for systematic determination of the flow pattern is suggested. The results of the model were compared with experimental data for the whole range of pipe inclination.

## 2- Experimental Work

The Experimental Work involved the measurement of gas and liquid flow rate; flow pattern and pressure drop in two phase flow in  $0^\circ$  horizontal,  $-3^\circ$  down and  $+3^\circ$  upward flow.

### Fluid Physical Properties

The physical properties of liquid and gas phases are determined from laboratory measurements at atmospheric pressure and temperature of  $30^\circ\text{C}$ . these properties are shown in Table(2):

**Table (2): Fluid Properties.**

	Water	Gas
$\rho(\text{kg/m}^3)$	1000	1.22
$\mu \text{ kg/m.sec}$	0.001	0.00002

### Experimental Facilities

The experiments in two phase flow loop as shown in fig (1). Two kinds of phases are used in this study, water and air. The individual phase of water is pumped from its tank ( $1\text{m}^3$ ) in to  $0.051\text{m}$  ID pipe. The water flow rate is measured by flow meter. The gas from compressor, its flow rates is measured by rotameter. The air-water flow into ( $0.51 \text{ mm}$ ) ID, ( $5 \text{ m}$ ) long Plexiglas pipeline, where the flow pattern are observed visually.

### Summary of Test Procedure

The pressure drop and flow pattern are measured using the following standard test procedure:-

- 1- The gas flow rate is set by a gate valve which located at upstream of the flow meter.
- 2-The liquid flow rate is set by adjusting the gate valve and noting the rate indicator on the flow meter.
- 3- After the flow patterns are visually observed the following parameter are recorded:
  - The liquid and gas flow rate.
  - The pressure drop at the ends of test
- 4-The gas flow rate is changed and steps 1-3 are repeated.
- 5- The inclination angle of flow is changed and steps 1-4 are repeated.

## 3- Results and Discussion

In this study, the effect of liquid and gas flow rates, and inclination angle on flow pattern and pressure drop have been studies experimentally.

### The effects of inclination angle on flow pattern map.

Three flow pattern maps have been constructed for horizontal ( $\theta = 0^\circ$ ), down ( $\theta = -3^\circ$ ) and upward ( $\theta = +3^\circ$ ) flow, figures (2), (3) and (4) respectively. As shown in figure (2) in horizontal ( $0^\circ$ ) flow, firstly Stratified (smooth and wavy) flow occurs relatively at low gas and liquid flow rate,  $V_{sg}$  of ( $0-0.9 \text{ m/s}$ ) and  $V_{sl}$  ( $0-2.7 \text{ m/s}$ ), secondly Slug flow occurs at higher gas flow rate,  $V_{sg}$  ( $0.9-1.6 \text{ m/s}$ ), and the same range of liquid flow rate with respect to stratified flow, and Annular flow occurs relatively at high gas and liquid flow rate,  $V_{sg}$  ( $0-1.6 \text{ m/s}$ ), and  $V_s$  ( $2.7-3.5 \text{ m/s}$ ). As shown in figure (3) in upward ( $\theta = +3^\circ$ ) flow, the most flow pattern occur in the largest range of pattern map is the Slug flow with respect with other flow patterns,  $V_{sg}$  ( $0-1.6 \text{ m/s}$ ), and  $V_{sl}$  ( $0-2.5 \text{ m/s}$ ), due to the liquid tends to touch the top part of the pipe in upward flow. Wavy Stratified flow occurs with small range of low gas flow rate,  $V_{sg}$  ( $0-0.7 \text{ m/s}$ ), and relatively high liquid flow rate,  $V_{sl}$  ( $2.5-3$ ), and annular flow occurs relatively at high gas and liquid flow rate,  $V_{sg}$  ( $0.7-1.6 \text{ m/s}$ ) and  $V_{sl}$  ( $2.5-3 \text{ m/s}$ ) respectively. As shown in figure (4) in downward flow pipe ( $\theta = -3^\circ$ ), in compared with horizontal flow, the occurrence range of smooth and wavy stratified flow at all rang of gas flow rate,  $V_{sg}$  ( $0-1.6 \text{ m/s}$ ), and at higher liquid flow rate,  $V_{sl}$  ( $0-2.5 \text{ m/s}$ ), the area of slug flow occurs with all range of gas flow rate but relatively at high liquid flow rate  $V_{sl}$  ( $2-3 \text{ m/s}$ ), and annular flow occurs at small area of gas and liquid flow rate,  $V_{sg}$  ( $0.8-1.6 \text{ m/s}$ ) and  $V_{sl}$  ( $2.5-3$ ) respectively. Eventually the probability of

stratified flow in downward flow will increased with respect to slug flow, in another word, the liquid tends to flow with the bottom wall of the pipe in downward flow.

#### **The effects of gas and water flow rate on pressure gradient.**

The relationship between pressure gradient and superficial gas velocity as a function to inclination angle change effect ( $0^\circ$ ,  $+3^\circ$ , and  $-3^\circ$ ) are shown in figure (5), (6) and (7) respectively. As shown in figure (5) the pressure gradient increase with increasing superficial velocity of gas and liquid due to the increasing in friction losses, as example, at constant  $V_{sl}$  of 0.7 m/s, when  $V_{sg}$  increased from 0.4- 1.5 m/s, the pressure gradient increase from 34- 137 Pa/m. Also we can see from figure (5) there are suddenly increasing in pressure drop after (1 m/s) of gas superficial velocity, at all values of  $V_{sl}$ , and that is due to the changing in flow pattern from stratified to slug flow, where, as example, with  $V_{sl}$  of 0.7, when gas superficial velocity increased from 0.4- 1, the pressure gradient increase from 34- 69 Pa/m, while when superficial gas velocity increase from 1 to 1.5 m/s, the pressure gradient increase from 69 to 137 Pa/m. and at constant  $V_{sg}$  of 0.4 m/s, when  $V_{sl}$  increased from 0.7 to 2.7 m/s the pressure gradient increase from 34 to 147 Pa/m. Figure (6) shows that the pressure gradient also increased with increasing of superficial velocity of gas and liquid, but, it is clear that, the pressure gradient in upward flow is greater than the pressure gradient in horizontal flow, because of two reasons, the first, there is an additional factor of pressure losses with friction losses, that is, hydrostatic or elevation losses. The second reason, due to the domain pattern in upward flow mostly is the slug flow. As example, with constant  $V_{sl}$  of 0.7 m/s, when superficial gas velocity increases from 0.4 to 1.4 m/s, the flow is slug flow in the all range of  $V_{sg}$ , the pressure gradient increases from 167 to 255 Pa/m. And with constant  $V_{sg}$  of 0.4 m/s, when  $V_{sl}$  increases from 0.7 to 2.7 the pressure gradient increases from 167 to 1294 Pa/m.

In downward flow of  $\theta = -3^\circ$ , figure (7) shows that there are no significant effect of superficial gas velocity on pressure drop at  $-3^\circ$ , due to, in downward flow, there are two inverse factors that causes the pressure losses, the first one is the friction losses, where in downward flow the velocity of fluid will increase so the friction losses will increase, the second factor, that is the hydrostatic losses, where, in downward flow there will be pressure gain due to this factor. Also, the results illustrate that, the pressure drop in downward flow is less than the upward flow, due to the domain pattern here is the stratified flow. As example, with constant  $V_{sl}$  of 0.7 m/s, with all range of  $V_{sg}$  from 0.4 to 1.4 m/s, the flow is smooth stratified flow, the pressure gradient increases from 186 to 196 Pa/m. And with constant  $V_{sg}$  of 0.4 m/s, when  $V_{sl}$  increases from 0.7 to 2.7 the pressure gradient increases from 186 to 1088 Pa/m.

#### **The effect of inclination angle on pressure gradient**

Figures (8, through 12) show the effect of inclination angle and direction of flow ( $\theta = 0^\circ$ ,  $-3^\circ$ , and  $+3^\circ$ ) on pressure gradient, the result show that, horizontal flow ( $\theta = 0^\circ$ ) has the smallest pressure drop with respect to other inclination angles ( $\theta = -3^\circ$ , and  $+3^\circ$ ), because of, the only factor that affect pressure drop in horizontal flow is the friction term, while with upward and downward flow, there are additional terms with friction losses that is, hydrostatic losses. Therefore, in upward flow, the pressure drops were generally much higher due to two reasons, the first is, in upward flow the hydrostatic term is positive ( $\sin(+)>0$ ) which can be added to the total pressure drop, the second reason is, the flow is predominately intermittent (slug) which is associated with higher pressure drops. While, the downward flow is associated with a pressure reversal phenomena since the hydrostatic pressure drop is negative ( $\sin(-)<0$ ) so the pressure drop was low.

Figure (8) shows that, at low  $V_{sl}$  of (0.7 m/s), clear confliction between friction losses and hydrostatic losses, where, at  $V_{sg}$  of lower than 0.9 m/s, the friction losses in downward flow is overcoming the hydrostatic losses in upward flow, as example at  $v_{sg}$  of 0.4 and 0.7 m/s the pressure gradient of downward flow are, 186 and 216 Pa/m respectively, but the pressure gradient of upward flow are, 167 and 176 Pa/m respectively. While at  $V_{sg}$  of greater than 0.9 m/s, the hydrostatic losses in upward flow is overcoming the friction losses in downward flow, as example at  $v_{sg}$  of 1 and 1.5 m/s the pressure gradient of downward flow are, 196 and 255 Pa/m respectively, but the pressure gradient of upward flow are, 225 and 255 Pa/m respectively.

Figures (9, through 12), at higher  $V_{sl}$  of (1, through 2.7) respectively, show that the hydrostatic losses are overcoming the friction losses, and this effect increase with increasing  $V_{sl}$  and  $V_{sg}$ .

#### **4- Proposed model**

It has been proposed by Duckler and Hubbard<sup>5</sup>(1975) that the total pressure drop in two-phase flow is assumed to be given by equation (1) which requires knowledge of the liquid holdup experimentally:

$$\left(\frac{\Delta p}{\Delta l}\right) = \frac{(4f_m \rho_m v_{ns}^2)}{(2g_c D H L^{0.75})} \quad (1)$$

Where:

$$\rho_m = \rho_l H_l + \rho_g H_g \quad (2)$$

$$v_{ns} = v_{sl} + v_{sg} \quad (3)$$

$$f_m = 0.1011 R_e^{-0.25} \quad (4)$$

Where:

$$R_e = \frac{\rho_m v_{ns} D}{\mu_m} \quad (5)$$

$$\mu_m = \mu_l H_l + \mu_g H_g \quad (6)$$

$$H_g = (1 - H_l) \quad (7)$$

We have proposed the pressure gradient of horizontal flow in general form, without need to measure the liquid holdup experimentally, by the following expressions:

$$\left(\frac{\Delta p}{\Delta l}\right) = \frac{4f_m \rho_{ns} v_{ns}^2}{2g_c D \lambda_l^{0.75}} \quad (8)$$

In which:

$$R_e = \frac{\rho_{ns} v_{ns} D}{\mu_{ns}} \quad (9)$$

$$\rho_{ns} = \rho_l \lambda_l + \rho_g \lambda_g \quad (10)$$

$$\mu_{ns} = \mu_l \lambda_l + \mu_g \lambda_g \quad (11)$$

$$\lambda_l = \frac{v_{sl}}{v_{sl} + v_{sg}} \quad (12)$$

Then, in order to take into account the effect of inclination angle, we have proposed the pressure gradient of upward and downward flow form as a function to pressure gradient of horizontal flow by the following expressions:

$$AE\% = a Vsg^{-b} \quad (13)$$

Where

$$AE\% = \text{Abs} \left( \frac{(\Delta P_{\theta=0^\circ} - \Delta P_{\theta=\pm 3^\circ})}{\Delta P_{\theta=0^\circ}} \right) * 100 \quad (14)$$

For upward flow ( $\theta = +3^\circ$ ):

$$a = -119 Vsl^2 + 457 Vsl + 61 \quad (15)$$

$$b = 0.1754 Vsl + 1.213 \quad (16)$$

For Downward flow ( $\theta = -3^\circ$ ):

$$a = -20 Vsl^2 + 52 Vsl + 263 \quad (17)$$

$$b = 0.1987 Vsl + 1.6312 \quad (18)$$

As shown in figures 13, 14, and 15, the new models show good agreement with new sets of experimental data obtained under completely different operating conditions.



## 5- Conclusions

The flow pattern which observed in present experimental study are stratified, slug and annular in the used range of gas and liquid superficial velocities, (0.4 – 1.5 m/s) and (0.7 – 2.7 m/s) respectively. The flow pattern map changes with respect to inclination angle and direction of flow, where, in horizontal flow the smooth and wavy stratified flow occur at low liquid and gas flow rate, slug flow occur at low liquid and high gas flow rate, while annular flow rate happened at high liquid and gas flow rate relatively, but in downward flow the stratified flow will be the most occur, while slug flow will take the most range of gas and liquid flow rate in upward flow. In general, the pressure gradient is increases when the water and gas flow rate are increased. The result show that, horizontal flow ( $\theta = 0^\circ$ ) has the smallest pressure drop with respect to other inclination angles ( $\theta = -3^\circ$ , and  $+3^\circ$ ), because of, the only factor that affect pressure drop in horizontal flow is the friction term. In upward flow, the pressure drops were generally much higher due to two reasons, the first is, in upward flow the hydrostatic term is positive ( $\sin(+)>0$ ) which can be added to the total pressure drop, the second reason is, the flow is predominately intermittent (slug) which is associated with higher pressure drops. While, the downward flow is associated with a pressure reversal phenomena since the hydrostatic pressure drop is negative ( $\sin(-) < 0$ ) so the pressure drop was low. New correlations have been proposed to calculate the pressure gradient as a function to inclination angle. The results of the presented correlation shows an acceptable agreement between the observed and predicted pressure gradient values.

## Nomenclature

D=Insider pipe diameter, m  
 $\Delta p$ =Pressure drop, Pa  
 $\Delta p/L$ =Pressure gradient, Pa/m  
HL=Liquid Holdup  
Hg=Void fraction  
 $\lambda l$ = No slip holdup  
Vsl=Liquid superficial velocity, m/s  
Vsg= Gas superficial velocity, m/s  
Re =Reynold's number  
f=Friction factor  
L=Length, m  
 $\mu$ = Fluid viscosity, kg/m.  
 $\rho$ =Fluid density, kg/m  
AE%= Angle Effect

## Subscripts

g = Gas phase  
l =Liquid phase  
m =Mixture, or measured  
c = calculated  
ns = no slip  
s = Superficial

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