Prediction of Frictional Pressure Drop for Tow-phase Flow in Horizontal Pipes

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Abstract:

In this paper, an experimental study on flow pattern pressure drop of two-phase oil-air flow is conducted by Cranfield university. The purpose of this study is to perform analysis on measured pressure drop under oil-air flow and compare it with some published correlations as well as to evaluate other pressure drop prediction models against experimental data. And displays that the suggested correlation has the best performance than the others. The effect of oil and air superficial velocities had been experimentally investigated .It was found that the pressure drop increases with increasing of oil and air flow rates.

The experimental results are compared with the results obtained from of (Beggs & Brill., 1973), (Lockhart & Martinelli., 1949) and (Dukler, et al., 1964). Statistical analysis showed that the Beggs & Brill correlation gave good agreement with experimental data.

Keywords*:* Pressure drop, Tow-phase , Gas and Liquid , Flow rate, Horizontal pipes.

الملخص:

في هذا البحث ، أجريت دراسة تجريبية حول انخفاض ضغط نمط التدفق لتدفق الهواء والزيت في طورين من جامعة كرانفيلد. الغرض من هذه الدراسة هو إجراء تحليل لانخفاض الضغط المقاس تحت تدفق الزيت والهواء ومقارنته ببعض العلاقات المنشورة وكذلك لتقييم نماذج أخرى للتنبؤ بانخفاض الضغط مقابل النتائج التجريبية. ويظهر أن العلاقة المقترحة أفضل أداء من غيرها من العلاقات الأخرى. وتم دراسة تأثير السرعات السطحية للزيت والهواء بشكل تجريبي ووجد أن انخفاض الضغط يزداد مع زيادة معدلات تدفق الزيت والهواء. وتمت مقارنة النتائج التجريبية مع النتائج التي تم الحصول

عليها من علاقات Beggs & Brill و Lockhart & Martinelli و Dukler وآخرون. أظهر التحليل الإحصائي أن علاقة Beggs & Brill أعطت توافق جيد مع النتائج التجريبية.

1- Introduction:

Two-phase has a continuing interest in engineering situations. It occurs extensively throughout industries such as tubular boilers, reboilers, oil and geothermal wells, gas and oil transport pipelines, refrigerators, heat exchangers and condensers. It is widely encountered in petroleum, chemical, civil and nuclear industries **(**Ghajer., 2004).

The ability to quantify void fraction and pressure drop are of considerable importance in systems involving two-phase flow. In addition, void fraction plays an important role in the modeling of two-phase pressure drop, flow pattern transition, and heat transfer and it is the key physical parameter for determining other two-phase parameters, namely two-phase density, and gas and liquid velocities (Zhao., 2005).

Many studies on two-phase, gas-liquid flow were published through horizontal, vertical, and inclined pipes. Some of these studies were concerned with finding an experimental data. Other, they found analytical relations or used these experimental data to drive empirical correlations, and the others compared many of the pressure drop and void fraction correlations to select the best one which able to find these parameter at a specific flow regime (Noora., 2013).

2- Theoretical background:

2.1- Superficial velocity

The superficial velocities of the liquid and gas phases (V_{sl} & V_{sg}) are defined as volumetric flow rate for the phase divided by the pipe cross sectional area (Chen., 2001), (Aldewani., 2003), (Shoham., 2006).

$$u_{s,l} = \frac{Q_l}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$u_{s,g} = \frac{Q_g}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The mixture superficial velocity is given by the sum of gas and liquid superficial velocities.

$$u_{s,m} = u_{s,g} + u_{s,l} = \frac{Q_g + Q_l}{A} \quad \ldots\ldots\ldots\ldots (3)$$

Furthermore, the mass flux G is defined as the summation of the superficial gas and liquid velocity multiplied with the density of each phase:

$$G = u_{s,g}.\rho_g + u_{s,l}.\rho_l \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Since in multiphase flow the fraction of the total mass flow is, in addition to the velocities, of great importance, one defines the vapor/mass quality x as the ratio of the gas mass flow rate $\dot{M}g$ to the total mass flow rate.

$$x = \frac{\dot{M}_g}{\dot{M}_g + \dot{M}_l} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Furthermore, the volumetric quality β is defined as the ratio of the volumetric flow rate of the gas phase to the total volumetric flow rate:

$$\beta = \frac{Q_g}{Q_g + Q_l} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Equivalent to the Reynolds number of a single-phase fluid, the superficial Reynolds number for a fluid of a two-phase combination is determined by the use of the superficial velocity:

$$Re_s = \frac{\rho.u_s.D}{\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

2.2- Flow patterns:

2.2.1- Two-phase flow pattern:

The term flow pattern is often used to describe multiphase flow. This refers to the fact that the gas and liquid phase distribute themselves within the flow into different regimes depending on operating conditions, physical fluid properties, flow rates and orientation and geometry of the pipe. Different flow patterns or flow regimes can occur when water and liquid flow simultaneously inside the pipeline.

More acceptable flow regimes were described by (Collier & Thome., 1994) is shown in figure 1.When gas and liquid are flowing concurrently inside a horizontal or near horizontal Pipeline, at low gas and liquid velocities, the gas and liquid will completely segregate from each other. The gas will flow on the top of the liquid. The gas-liquid interface is smooth. This flow regime is called stratified smooth flow.Starting from the stratified smooth flow when gas flow and/or liquid flow increases some waves will be generated at the gas liquid interface. The gas liquid interface becomes wavy. This flow is called stratified wavy flow. If gas flow is further increased, the waves at the gas liquid interface will grow. Some of the waves will be large enough to touch the upper inner pipe wall and block gas flow.

Waves that are large enough to fill the pipe and block gas flow are called liquid slugs. This flow is defined as slug flow.

In slug flow, the liquid in the pipe is not uniformly distributed along the pipe axis, with slugs being separated by gas zones. The gas zones contain a stratified liquid layer flowing at the bottom of the pipe. The liquid slugs may be aerated by small gas bubbles.

If the gas flow is increased even further, the gas will flow as a core in the center of the pipe and the liquid will flow as a ring around the pipe wall. The liquid ring may not be uniform along the entire circumference, but is thicker at the bottom of the pipe than at the top. Some small liquid droplets may be contained in the gas core. This flow is called annular flow. With very low gas flow and high liquid flow, the gas will flow as discrete bubbles within a continuous liquid phase. The gas bubbles are usually not uniform in size and most of the bubbles flow at the upper portion of the pipe due to the buoyancy effects. This flow is called dispersed bubble flow (Tang., 2011). Sketches of the various types are shown in figure 1.

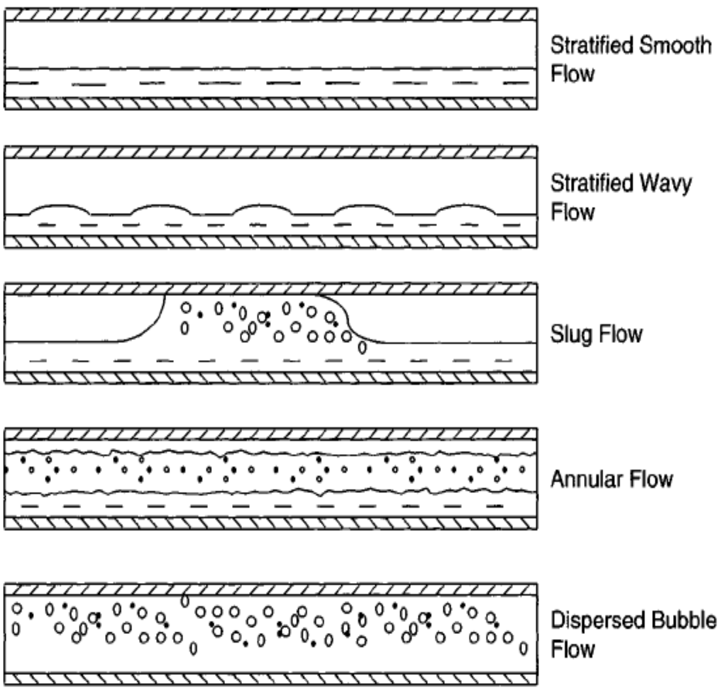


Figure (1): Sketched of flow pattern.

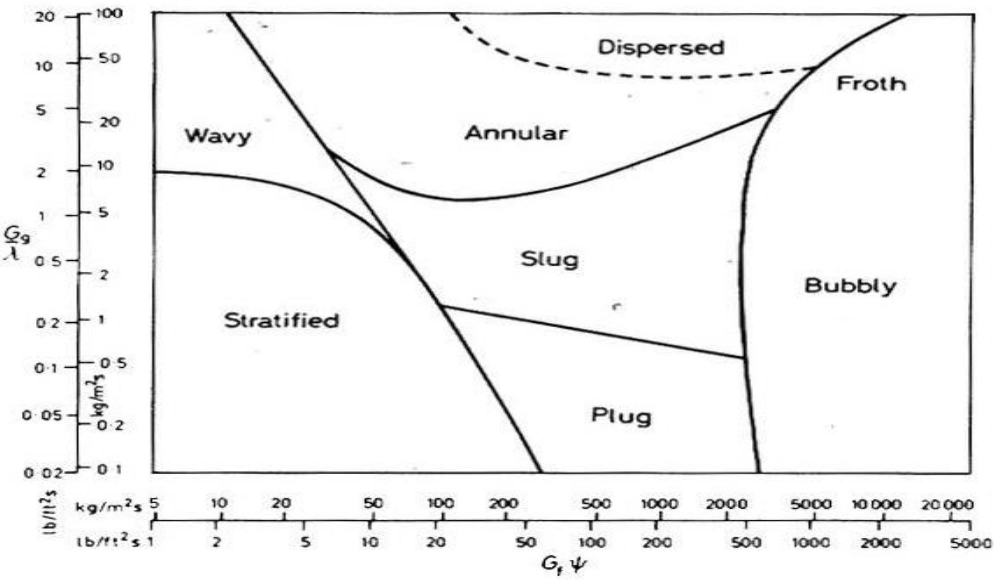


Figure (2): Flow pattern map for horizontal two-phase flow (Baker., 1954).

The existing flow regimes in horizontal pipes have been classified into four major type: stratified flow (stratified smooth and stratified wavy), intermittent flow (elongated bubble and slug flow), annular flow (annular mist and annular wavy flow) and dispersed bubble flow (Xiao, et al., 1990).

2.3- Pressure drop:

Accurate prediction of the pressure drop in multiphase flow system is essential for proper design of well completion , artificial lift system, surface flowing and gathering lines.

The prediction of pressure drop is complicated by interdependence of the controlling variables, i.e., flow regime, flow rate of different phases and fluid properties. Because of these complexities, empirical correlation to predict pressure loses are widely used.

The basic for any fluid flow calculation is an energy balance for the flowing fluid between two points. Assuming no external work is done on/or by the fluid, a general steady state mechanical energy balance equation in differential form can be written as (Wasp, et al., 1977).

$$\left(\frac{d_p}{d_L}\right)_{total} = \left(\frac{d_P}{d_L}\right)_{friction} + \left(\frac{d_P}{d_L}\right)_{elevation} + \left(\frac{d_P}{d_L}\right)_{acceleratin} \quad \text{.....} \ldots\ldots\ldots\ldots \text{(8)}$$

The total pressure lose is the sum of the pressure drops caused by potential energy change (elevation), kinetic energy change (acceleration) and frictional loses.

Definition of each term in the total pressure drop equation of two-phase flow is given by (Goyon, et al., 1988).

$$\left(\frac{d_P}{d_L}\right)_{fric.} = \frac{f_{tp}\rho_{tp}V_{tp}^{2}}{2g_c d} \quad \text{.........................} (9)$$

$$\left(\frac{d_P}{d_L}\right)_{ele.} = \frac{g}{g_c}\rho_{tp}\sin\theta \quad \text{.........................} (10)$$

$$\left(\frac{d_P}{d_L}\right)_{acc.} = \frac{\rho_{tp}V_{tp}dv_{tp}}{g_c d_L} \quad \text{.........................} (11)$$

3- Effect of liquid and gas flow rates on pressure gradient (∆p):

3.1- Two-Phase Flow Pressure Drop Correlations:

Literature on two-phase flow pressure drop correlations can be classified in different ways. The correlations can be classified based on several criterions such as inclination angle, flow pattern or method of development. Even though there are several types of criterions to classify the correlations, only selected criterions are considered here to classify the correlations in order to facilitate a systematic approach in the study.

Classifying the correlations based on their applicability for certain angle of inclination will yield correlations grouped based on horizontal flow, inclined flow, vertical flow or correlations that can be used for any type of inclination.

In this study only correlations which are proposed for horizontal flow and correlations that can be used for any inclination are collected from the open literature to investigate their performance in horizontal two-phase flows.

3.1.1- Homogeneous Flow Models:

Homogeneous flow model is the simplest approximation of a two-phase mixture flow where the two-phases are assumed to have the same flow velocity. Based on this assumption, a friction factor term similar to a single phase flow may be applied to solve for the frictional pressure drop. A term called two-phase friction factor, is used in the two-phase pressure drop correlations and a pressure drop calculation technique and formulation structure that is similar to the single phase friction factor implemented shown in the equation (12).

$$\left[\frac{\Delta P}{\Delta L}\right]_{tp} = \frac{2 f_{tp} G_{tp}^{2}}{D \rho_{tp}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

The homogenous density (ρ_{tp}) in the equation above is usually calculated as follows**:**

$$\frac{1}{\rho_{tp}} = \left(\frac{\chi}{\rho_g} + \frac{1-\chi}{\rho_\ell}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

In equation (12) f_{tp} has to be known in order to calculate the frictional two-phase flow pressure drop.

Dukler et al. (1964) proposed two methods to calculate the two phase pressure frictional drop based on similarity analysis. Equations to calculate Reynolds number and friction factor were suggested by using analogy between single phase and two phase flows. The authors proposed two types of correlations for two cases. In the first case, the slip velocity was assumed to be zero and hence equations for a homogeneous flow are given as below. This correlation will be referred as (Wasp, et al., 1977) in this study.

$$\left[\frac{\Delta P}{\Delta L}\right]_{tp} = \frac{2 f U_{tp}^{2} D \rho_{ns}}{\mu_{ns}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$\mu_{ns} = \mu_\ell \lambda + \mu_g \left(1-\lambda\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$\rho_{ns} = \rho_\ell \lambda + \rho_g \left(1-\lambda\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Where:

$$\lambda = \left[\frac{Q_\ell}{Q_\ell + Q_g}\right] = \frac{1}{1 + \left(\frac{\chi}{1-\chi}\right)} \quad \ldots\ldots\ldots\ldots (17)$$

$$\mathrm{Re}_{ns} = \frac{U_{tp}\rho_{ns}D}{\lambda_{ns}} \quad \text{……………… (18)}$$

$$f = 0.0014 + \frac{0.125}{\mathrm{Re}_{ns}^{0.32}} \quad \text{………… (19)}$$

Beggs and Brill (1973) The Beggs and Brill method works for horizontal or vertical flow and everything in between. It also takes into account the different horizontal flow regimes**.** And they developed a correlation based on experimental measurement which were made in 25.4mm (1 inch) pipes in different inclinations.

They stated that the no-slip two-phase friction factor can be obtained from (Moody., 1944) for smooth pipe as shown below in equation (16) as a function of the no-slip Reynolds number.

The followingparameters are used in the calculations.

$$\lambda_l = \frac{u_l}{u_m} \quad \text{…………………. (20)}$$

$$L_1 = 316\lambda_l^{0.302} \quad \text{……………...(21)}$$

$$L_2 = 0.0009252\lambda_l^{-2.4684} \quad \text{…..(22)}$$

$$L_3 = 0.10\lambda_l^{-1.4516} \quad \text{…………...(23)}$$

$$L_4 = 0.5\lambda_l^{-6.738} \quad \text{……..………(24)}$$

Determining flow regimes

Segregated if

$\lambda_l < 0.01$ and $F_r < L_1$ or $\lambda_l \geq 0.01$ and $F_r < L_2$

Transition if

$\lambda_l \geq 0.01$ and $L_2 \leq F_r \leq L_3$

Intermittent if

$0.01 < \lambda_l \leq 0.4$ and $L_3 \leq F_r \leq L_1$ or $\lambda_l \geq 0.4$ and $L_3 < F_r \leq L_4$

Distributed if

$\lambda_l < 0.4$ and $F_r \geq L_1$ or $\lambda_l \geq 0.4$ and $F_r > L_4$

The frictional pressure gradient is calculated using:

$$\left(\frac{dp}{dl}\right)_F = \frac{2 f_{tp} \rho_m u_m^2}{g_c D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(25)$$

$$\rho_m = \rho_l \lambda_l + \rho_g \lambda_g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(26)$$

f_{tp} the two phase friction factor is

$$f_{tp} = f_n e^s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(27)$$

Here, $f_{ns}$is the no-slip friction factor and (S) is a liquid holdup parameter:

$$f_{ns} = \left[4\log\left(\frac{\mathrm{Re}_{ns}}{4.5223\log\left(\mathrm{Re}_{ns}\right) - 3.8215}\right)\right]^{-2} \quad \ldots\ldots\ldots\ldots.. (28)$$

The "no slip" Reynolds number, Re_{Ns} is given by:

$$Re_{Ns} = \frac{(\rho_l u_l + \rho_g u_g) D}{\mu_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

$$\mu_m = \mu_l \lambda_l + \mu_g \lambda_g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

The value of S is governed by the following conditions:

$$S = \ln(2.2y - 1.2) 1 < y < 1.2 \quad .... (31)$$

$$S = \frac{\ln(y)}{(-0.0523 + 3.182\ln(y) - 0.8725[\ln(y)]^2 + 0.01853[\ln(y)]^4)} y \leq 1 \; or y \geq 1.2 \quad ....(32)$$

Where y is calculated by:

$$y = \frac{\varepsilon_L}{\varepsilon_{L\beta}^{\;2}} \quad ....(33)$$

4- Pressure Drop Analysis for Oil-Air Flow:

Pressure gradient was measured during the oil-air tests in 1 inch rig under different flow conditions.

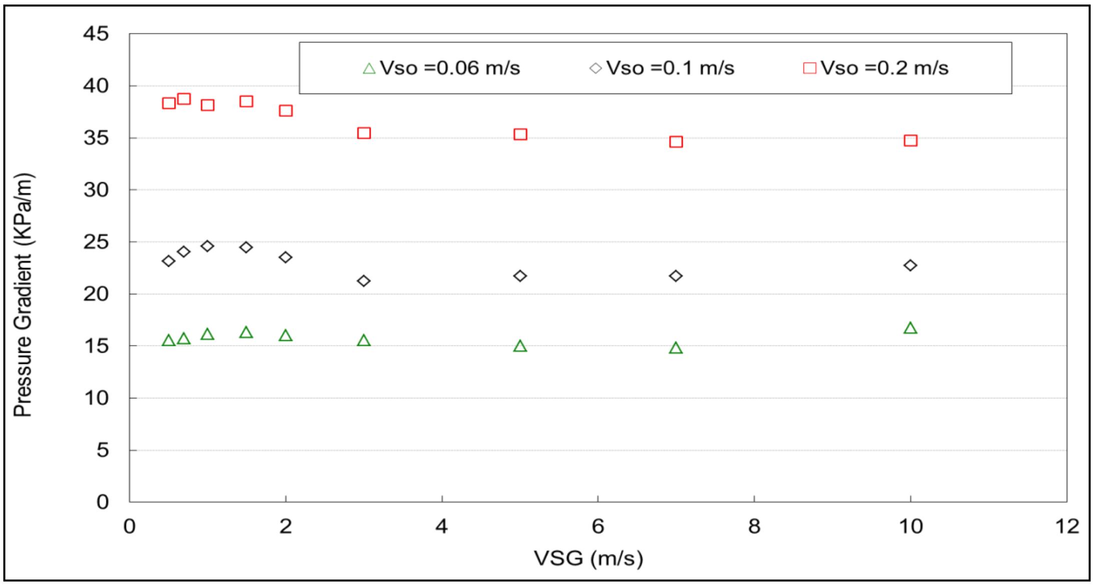


Figure (3): Effect of gas superficial velocity on the pressure drop.

Figure 3 shows the effect of a specific liquid superficial velocity on the pressure drop at different gas superficial velocities. It can be seen that the pressure gradient increases by increasing gas superficial velocity (V_{sg}) up to around 1.5 m/s, and then decreased by further increasing of the V_{sg} up to 3 m/s. When V_{sg} is between 3 m/s and 10 m/s, the pressure gradients increases again for V_{so}= 0.1 m/s, while experiences little changes for V_{so} = 0.2 m/s.

Figure 4 illustrates that the pressure gradients for oil-air flows at all the testing points are higher than those for single phase oil flow at the same V_{so}.

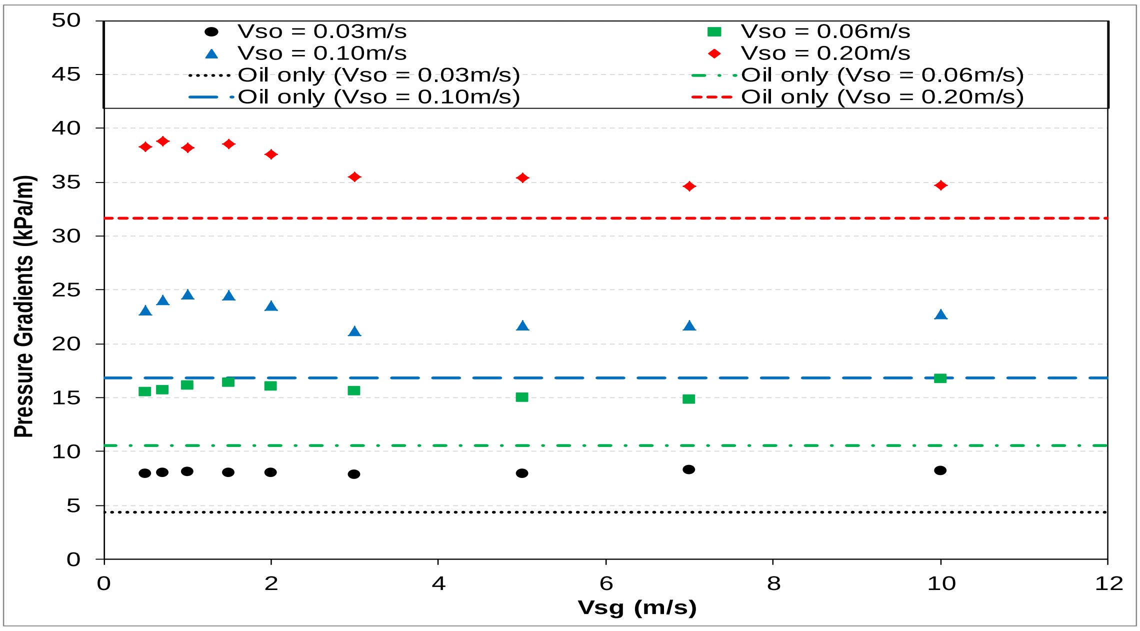
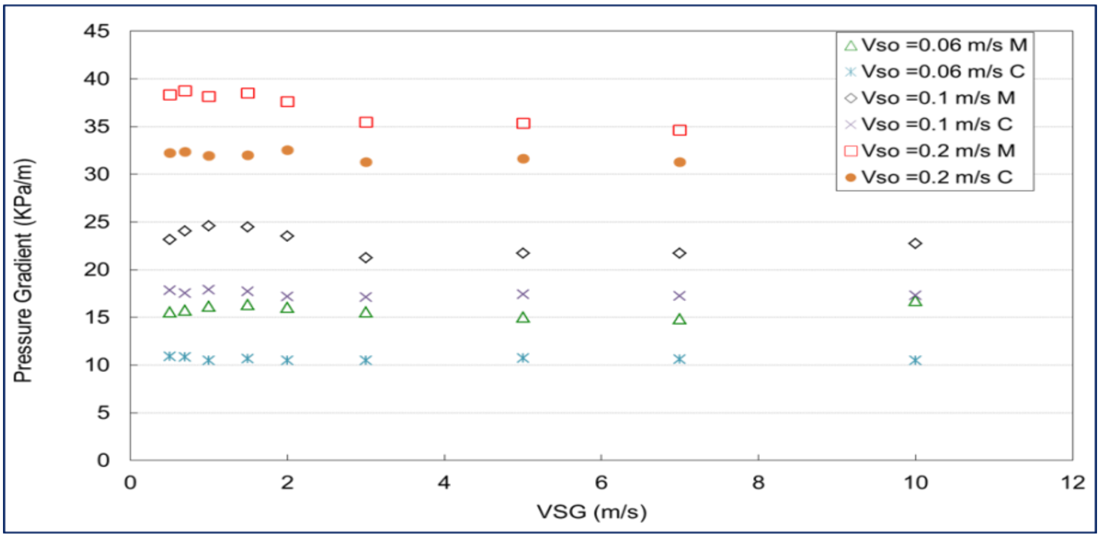


Figure (4): Pressure gradients measured in 1 inch oil-air tests.

5- Comparative study:

The predicted value of the pressure drop (Δp), using the presented methods (combination of Beggs & Brill, Lockhart & Martinelli, Muller & Heck and Dukler et.al) are evaluated against measured pressure drops, statistical analysis which is a scale of agreement between calculated and measured results also, its assist the comparative study and introduce results more objectively.

Several attempts were also made to validate published pressure drop correlations for air-oil system against the experimental data from Cranfield university by using viscous oil. most of available pressure drop correlations have not been validated against air-liquid system with viscous liquids. **M** letter is the mark of measured pressure while **C** is the calculated pressure.



Figure(5): Pressure gradients comparison in 1 inch oil-air tests.

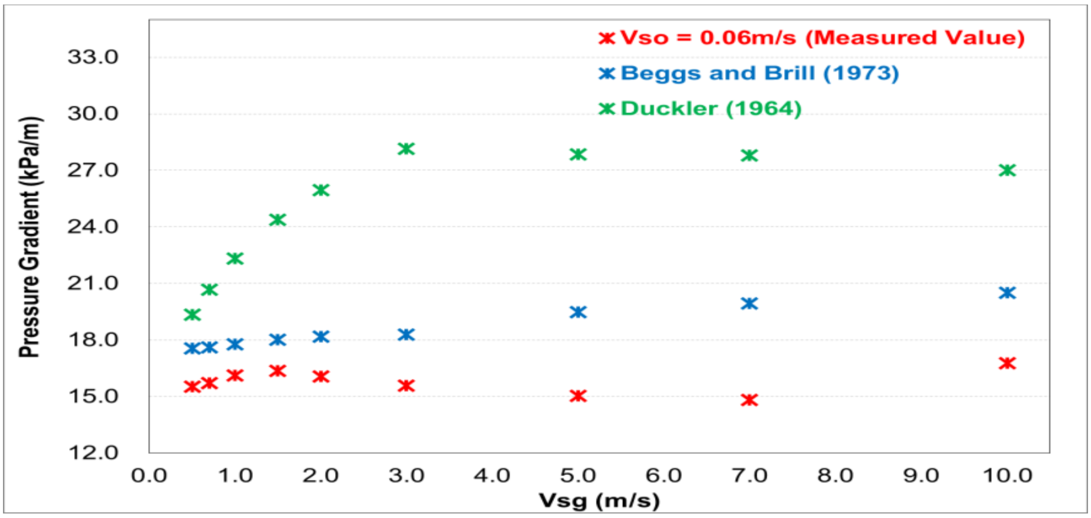
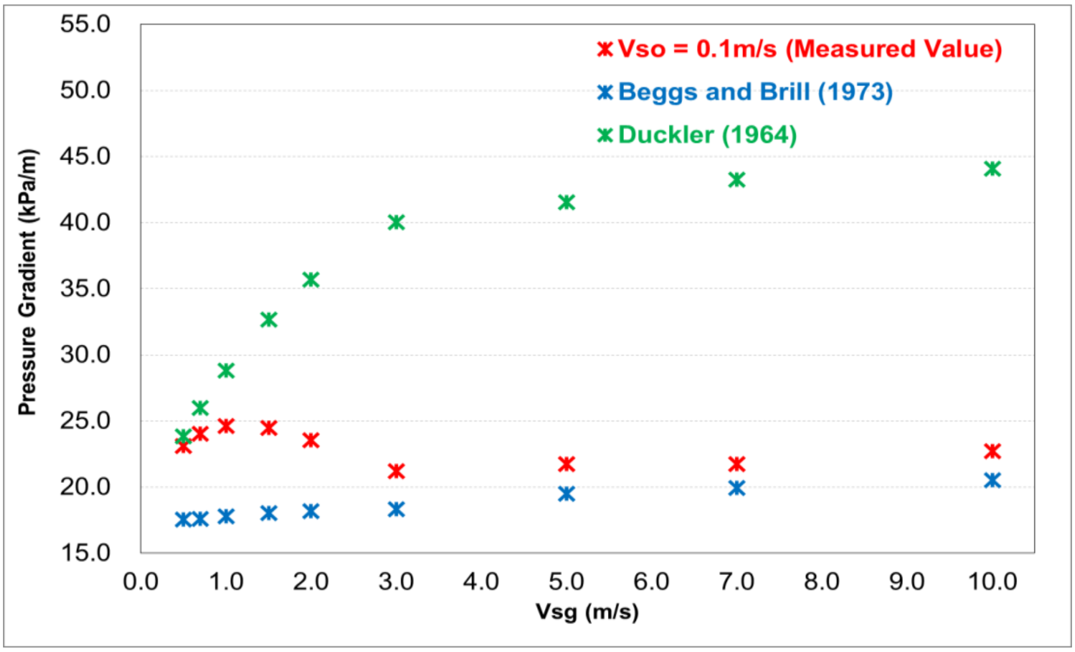
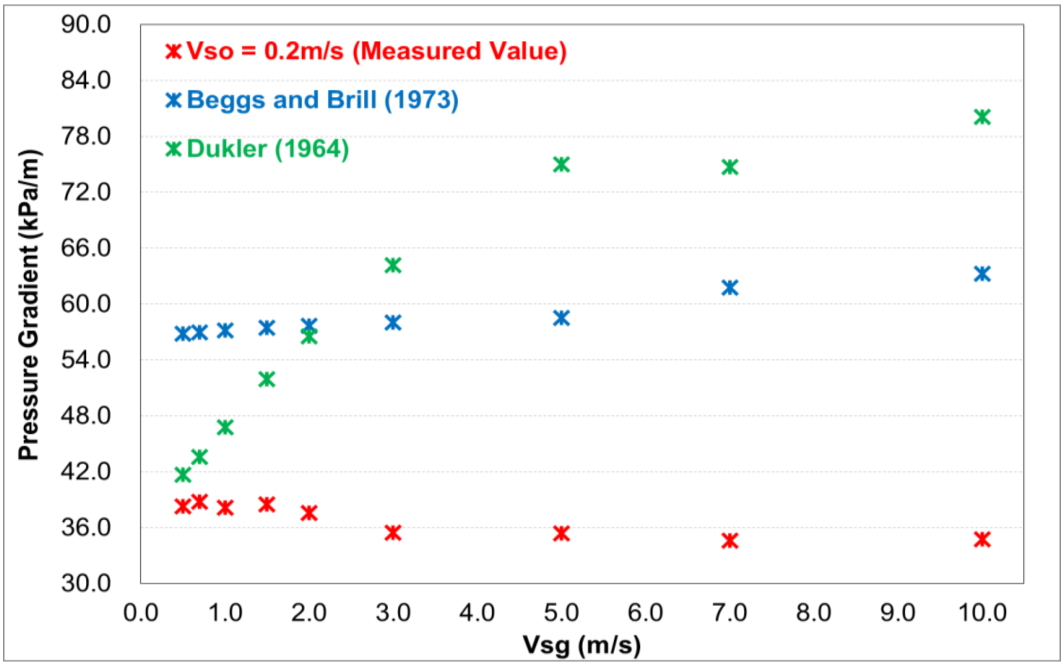


Figure (6): Comparison Between the Experimental Results and Pressure Drop Empirical Correlations at V_{so} = 0.06 m/s.



Figure(7): Comparison Between the Experimental Results and Pressure Drop Empirical Correlations at V_{so} = 0.1 m/s.



Figure(8): Comparison Between the Experimental Results and Pressure Drop Empirical Correlations at V_{so} = 0.2 m/s.

Figs.6 to 8 represent the values of the experimental average pressure drop and the values obtained by (Beggs & Brill.,1973) and (Dukler., 1964) pressure drop empirical correlations. All figures show that the Beggs and Brill method are the nearest to the experimental results.

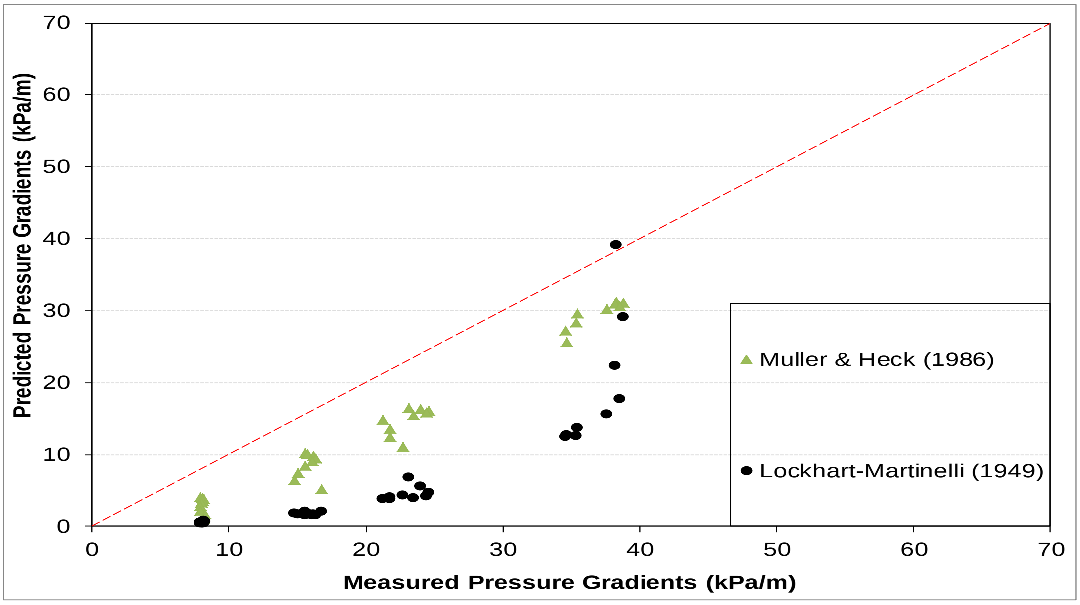


Figure (9): Measured pressure gradients versus those predicted by (Lockhart-Martinelli., 1949) and (Müller & Heck., 1986)

The statistical analysis based on the total pressure gradient for the entire test section, it is found that the Beggs & Brill gave the best results of agreement for 1 inchpipe. Also we can see that measured pressure drop usually little than the calculated one.

6- Conclusions:

An experimental and theoretical study on the pressure drop in a horizontal multiphase flow of oil and air with different liquid and gas flow rates were conducted leading to the following conclusions:

- The pressure gradients increase with increasing of liquid and gas flow rates.
- From a comparative study, it is found that Beggs & Brill gave the best results for small pipe diameter.
- The pressure gradients for oil-air flows at all the testing points are higher than those for single phase oil flow at the same V_{so}.

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