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Experimental Study of Pressure Drop during Multiphase (Water, Air and Sand) Flow in Horizontal Pipes

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Abstract

Multiphase flow of air, water and sand through horizontal pipes has been studied experimentally and theoretically. In this study, a closed flow system is designed and constructed in order to measure the pressure gradient, using different liquid and gas flow rates, pipe diameter and sand concentration.

Experimental tests are carried out using different sand concentration 0, 1, 3 and 5 by weight percent of the water, using two pipe diameters (1.5" and 2"), in water-air system.

The effect of liquid and gas flow rates, sand concentration and pipe diameter had been experimentally investigated. It was found that the pressure drop increases with increasing liquid and gas flow rates, and decreases with increasing pipe diameter, also increasing of sand content result in an increase in pressure drop.

The experimental results are compared with the results obtained from of **(Wasp, et al., 1977)** density and viscosity definitions combined with No-slip-model, **(Lockhart & Martinelli, 1949)** separated model, **(Dukler, et al., 1964)** similarity model and **(Beggs & Brill., 1973)** Statistical analysis showed that the **(Beggs & Brill., 1973)** correlation gave good agreement with experimental data for 1.5" pipe diameter and **(Dukler, et al., 1964)** and **(Lockhart & Martinelli, 1949)** separated model for 2"pipe diameter.

Keywords: Pressure drop; Multiphase flow; Gas, liquid and solid; Horizontal pipes, flow.

Introduction

Multiphase flow is defined as the con-current movement of several phases (gas, liquid, and solid material), common examples are water droplets falling in air, gas bubbles rising in a liquid and solid particles transported by a fluid. The flowing of these phases are very complicated and taken different flow patterns (depending on the distribution of each phase). Multiphase flows are often classified according to the nature of the system: dispersed flows (particles or droplets in liquid or gas, bubbles in liquid), separated flows (annular flow in vertical pipes, stratified flow in horizontal pipes) and transitional flows, which are combination of the above two classes.

Multiphase flow occur in various fields, such as; petroleum, chemical and nuclear industries. In the petroleum industry, multiphase flow occurs during the production and transportation of oil and gas. Also, occurs in both well bore and flow lines, in horizontal, inclined, or vertical pipes. In oil field gathering system, multiphase mixture must be transported from the wells to the separation facilities. In offshore production, these lines can be of a substantial length before reaching separation facilities. In all of these applications, the prediction of pressure gradient is of great importance for designing purposes.

In petroleum engineering applications, the three most important hydrodynamic features are: flow pattern, liquid holdup, and the pressure drop. In order to accurately estimate the pressure drop and liquid holdup, it is necessary to know the actual flow pattern under the specific flow conditions.

Applications of multiphase flow correlations through horizontal or nearly horizontal pipes to the petroleum industry is the selection of proper design for the flow line (selection of the correct size) in order to minimize energy losses and raise the life time of the pipeline.

The main purpose of this study is to investigate experimentally, the effect of pipe diameter, liquid and gas flow rates, and solid material concentration on the pressure drop during the air, water and sand flow through horizontal pipes. Also, a comparative study presented between measured and calculated pressure drop using the combination method of **(Wasp, et al., 1977)** mixture density and viscosity definition with separated model of **(Lockhart & Martinelli, 1949)**, No-slip model, **(Beggs & Brill., 1973)** pressure drop correlation and **(Dukler, et al., 1964)** similarity method of calculation.

Theoritical Background:

Superficial velocity

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

$$V_{sL} = \frac{Q_L}{A} \tag{1}$$

$$V_{sg} = \frac{Q_g}{A} \tag{2}$$

The mixture velocity is given by the sum of the gas and liquid superficial velocities **(Chen, 2001; ALdewani, 2003)**:

$$V_m = V_{sL} + V_{sg} = \frac{Q_L + Q_g}{A} \tag{3}$$

Liquid holdup:

The characteristic of multiphase flow is the simultaneous flow of two or more phases of different densities and viscosities. The less dense and/ or less viscous phase tends to flow at a faster velocity. The difference in the insitu average velocities between the phases result in a very important phenomenon called the "slip" of one phase relative to the other, or the "holdup" of one phase relative to the other. Holdup can be defined as the fraction of the pipe volume occupied by a given phase. Let the cross sectional area occupied by liquid be (A_L); the remaining area (A_g) is occupied by gas. The liquid holdup and gas volume fraction are defined as **(Chen, 2001)**:

$$H_L = \frac{A_L}{A} \tag{4}$$

When insitu volume fraction is determined, we can calculate the average (insitu) velocity for each phase:

$$V_L = \frac{Q_L}{A_L} = \frac{V_{sL}}{H_L} \tag{5}$$

$$V_g = \frac{Q_g}{A_g} = \frac{V_{sg}}{(1-H_L)} \tag{6}$$

These are true average velocities of liquid and gas phases, which are larger than the superficial velocities **(Chen, 2001)**.

Fluid physical properties:

Correlation for the prediction of pressure losses requires estimating the values for the fluid physical properties that are usually not known using various empirical correlations. Average values for liquid phase surface tension, viscosity and density are usually used.

Density:

Density is defined as the fluid mass per unit volume **(Streeter & Wylie, 1985)**.

$$\rho = \frac{M}{V} \tag{7}$$

Density of water at standard condition is (1000kg/m^3).

Factors affecting density:

a. Effect of temperature on density:

The effect of temperature on the liquid density can be expressed by the following formula **(Szilas, 1975)**:

$$\rho_T = \rho_{60} - \alpha_T (T - 60) \tag{8}$$

b. Effect of pressure on density:

The effect of pressure on density can be expressed in the following formula **(Brill & Mukherjee, 1999)**.

$$\rho = \rho_r e^{C(P-\mathrm{Pr})} \tag{9}$$

c. Effect of solids concentration on density:

In practice, it is perhaps better to depend on the measurement of particle and fluid densities to define the density of a suspension for a given concentration, and use suspension density as a measure of concentration. The density of suspension in terms of its component densities is given by **(Wasp et al., 1977)**:

$$\rho_m = \frac{100}{\dfrac{C_w}{\rho_s} + \dfrac{100 - C_w}{\rho_L}} \tag{10}$$

Viscosity:

Viscosity is a measure of the relative ease or difficulty by which particle of fluid may be deformed **(King & Brater, 1976)**.

Factors affecting viscosity:

a. Effect of temperature on viscosity:

The effect of temperature on viscosity can be expressed in the following formula **(Chung et al., 1988)**.

$$\log\left(\frac{\mu_2}{\mu_1}\right) = 5705\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{11}$$

The above equation can only be used at pressure of (14.7 psia).

b. Effect of pressure on viscosity:

The effect of pressure on viscosity can be expressed in the following formula **(Chung et al., 1988)**.

$$\log\left(\frac{\mu_2}{\mu_1}\right) = A_T\left(\frac{p}{14.7} - 1\right) \tag{12}$$

$$A_T = 13.877 e^{\frac{4.633\gamma}{T^{2.17}}} \tag{13}$$

c. Effect of solid concentration on viscosity:

An important effect of the addition of solid particle to a fluid is its influence on the system viscosity. The presence of the particles invariably increase the suspension viscosity to a value greater than that of the fluid it self **(Wasp et al., 1977)**.

$$\mu_m = (1 + 2.5\phi)\mu_o \tag{14}$$

The above equation is true for dilute suspension and it is valid for concentration less than 1.0 percent of solid by volume **(Wasp et al., 1977)**.

Flow patterns:

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 the orientation and geometry of the pipe. Flow pattern map represent an attempt to define boundaries for the various flow regimes **(Kegel, nunn)**. Sketches of the various types are shown in **Fig.1**

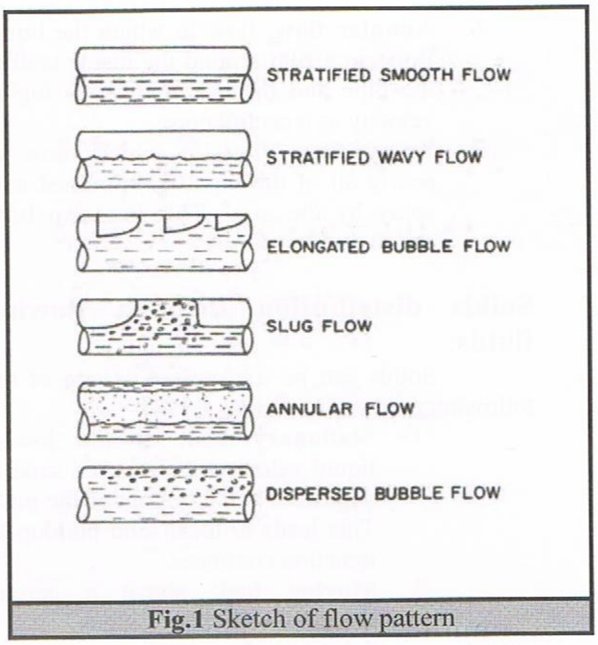

Fig.1 Sketch of flow pattern

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.; Arirachakaran et al., 1991; Surdasan et al., 1994; Ounang, 1995; Govier & Aziz, 1972; Kang & Jepson, 2002)**.

(Alves, 1954; Hewitt & Hall-Taylor, 1970), described these types as follows:

"Assuming a horizontal pipe with liquid flowing so as to fill the pipe and consider the type of flow that occur as gas is added in increasing amounts.

1. **Bubble flow**: flow in which bubbles of gas move along the upper part of the pipe at approximately the same velocity as the liquid. This type is some times called "froth flow" where the entire pipe is filled with froth similar to an emulsion.
2. **Plug flow**: flow in which alternate plugs of liquid and gas move along the upper part of the pipe.
3. **Stratified flow**: flow in which the liquid flows along the bottom of the pipe and the gas flows above. Over smooth gas-liquid interface.
4. **Wavy flow**: flow which is similar to stratified flow except that the gas moves at higher velocity and the interface is disturbed by waves traveling in the direction of flow.
5. **Slug flow**: flow in which a wave is picked up periodically by the more rapidly moving gas form a frothy slug, which passes through the pipe at a much greater velocity than the average liquid velocity.

6. **Annular flow**: flow in which the liquid flows in a film around the inside wall of the pipe and the gas flows at a higher velocity as a central core.
7. **Spray flow**: flow in which most or nearly all of the liquid is entrained as a spray by the gas." This has also been called dispersed flow.

Solids distribution through flowing fluids:

Solids can be transported as one of the following modes **(Oudeman, 1993)**:

1. **Stationary bed**: at the lowest liquid velocity, the injected sand is deposited at the bottom of the pipe. This leads to local sand buildup as injection continues.
2. **Moving bed**: above a certain critical velocity (which is a function of pipe diameter, grain size and liquid and solid density and viscosity), the grain started to move initially as a dunes, at a higher velocities as continuous sand bed.
3. **Fully Suspended**: with increasing velocity, more particles are suspended in the fluid above the bed until, at some critical velocity, the bed vanishes and no particle moves along the bed bottom.

The maximum velocity at which all the particles are maintained in suspension is given by **(Oudeman, 1993)**:

$$V^{1.225} = 0.0251 * g * dp\left(\frac{\rho_m * D}{\mu}\right)^{0.775} * \frac{\rho_s - \rho_L}{\rho_L} \qquad 15$$

Two types of solid material distributions can be recognized **(Wasp et al., 1977)**

a) Homogeneous flow: the term given to systems in which the solids are uniformly distributed throughout the liquid media. It is encountered in slurries of high solid concentration and fine particle size. The presence of solid can have a significant effect on the system properties, usually resulting in a sharp increase in viscosity as compared to that of the carrier fluid.
b) Heterogeneous flow: solids are not evenly distributed and in horizontal flow, pronounced concentration gradients exist along the vertical axis of the pipe, even at high velocities. Particle inertial effect are significant, i.e. , the fluid and solid phase to a large extent retain their separated identities, and the increase in the system viscosity over that of the carrier liquid is usually quite small. Heterogeneous flow tends to be of lower solid concentration and have a large particle size than homogeneous flow.

Flow pattern map:

For a given system, with specified liquid and gas flow rates (Q_L & Q_g), a particular flow pattern is often displayed using a flow pattern map, which is a two- dimensional map depicting flow regime transition boundaries **(Chen, 2001)**.

The generation of flow pattern maps falls into two categories, one is the experimental flow pattern map, generated directly from experimental data. **Fig.2** illustrates a very commonly used experimental flow pattern map, which was generated from a large amount of experimental data. It is completely empirical and limited to data on which it is based. Mechanistic flow pattern map developed from the analysis of physical transition mechanisms, which are modeled by fundamental equations. **Fig.3** illustrates a mechanistic flow pattern map, also empirical correlations are still required in the mechanistic model for the model closure.

Pressure drop:

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

The prediction of pressure drop is complicated by the interdependence of the controlling variables, i.e., flow regime, flow rate of different phases and fluid properties. Because of these complexities, empirical correlations to predict pressure losses 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)**:

$$\left(\frac{d_p}{d_L}\right)_{total} = \left(\frac{d_p}{d_L}\right)_{friction} + \left(\frac{d_p}{d_L}\right)_{elevation} + \left(\frac{d_p}{d_L}\right)_{acceleration} \qquad 16$$

That is, the total pressure loss is the sum of the pressure drops caused by potential energy change (elevation), kinetic energy change (acceleration) and frictional losses.
Definition of each term in the total pressure drop equation of two- phase flow is given by **(Goyon et al., 1988; Barrufet et al., 1995)**:

$$\left(\frac{d_p}{d_L}\right)_{fric.} = \frac{f_{tp}\rho_{tp}V_{tp}^2}{2g_c d} \qquad 17$$

$$\left(\frac{d_p}{d_L}\right)_{ele.} = \frac{g}{g_c}\rho_{tp}\sin\theta \qquad 18$$

$$\left(\frac{d_p}{d_L}\right)_{acc.} = \frac{\rho_{tp}V_{tp}dV_{tp}}{g_c d_L} \qquad 19$$

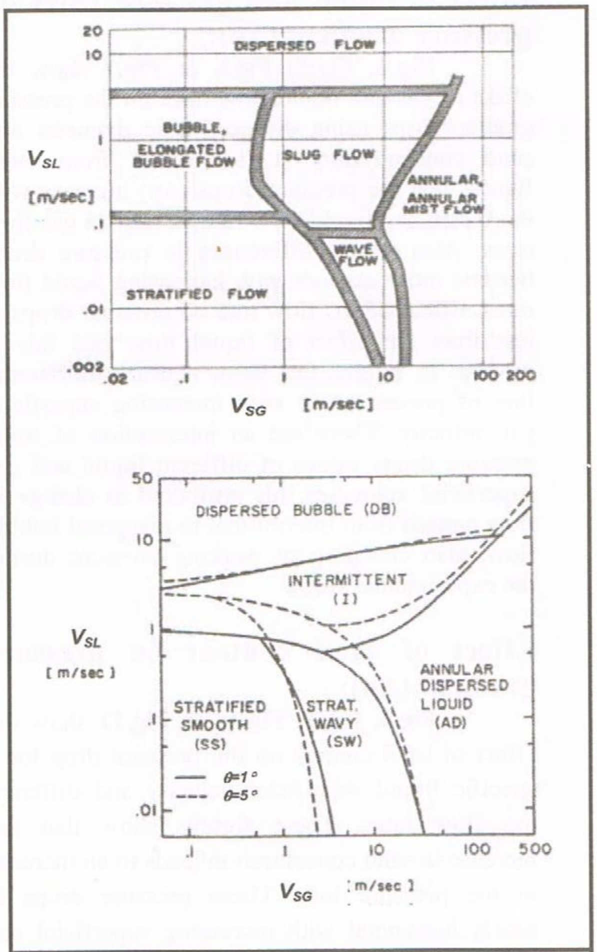

Fig.3 Mechanistic flow pattern map (Taitel et al. (1976))

Multiphase Flow through Restrictions:

Multiphase flow through restrictions may be classified into one of the following **(Taitel & Dukler, 1976)**:

1. **Critical flow**: this occurs when the fluid flows through the choke at velocities greater than that of sound in that fluid. To satisfy this condition in oil field work the upstream pressure must approximately twice the downstream pressure.
2. **Sub-critical** flow: this occurs when the velocity of the fluid is less than the velocity of sound in that fluid.

Pressure drop through restrictions or any other fittings can be calculated by adding the equivalent length of the straight pipe. **(Crane, 1957)**, determined experimentally the equivalent lengths of many standard valves and fittings.

Experimental Work

The experimental work in the present research involves measurement of the effect of gas and liquid flow rate, sand concentration and pipe diameter on the pressure drop during multiphase flow of air, water and sand through a horizontal pipe.

Air, water and sand used as the component of multiphase mixture under test for reasons of availability and comparatively low costs; also, for the reasons of non-inflammable (fire hazards) and non-toxic (safety), also, the availability of measuring devices. There is no mass transfer between phases, the density of water assumed to be constant and equal (1000 Kg/m^3), the viscosity of water assumed to be constant and equal (1cp.), surface tension of air/water was taken to be constant at ($72*10^3$N/m), also, the specific gravity of sand was known (2.634) and the grain diameter is less than or equal 2.5mm, gas density is taken to be constant and equal (1Kg/m^3), gas viscosity at 8bar, 15°C is taken to be equal (0.0182cp.). There is no interaction between phases such as solids dissolving in the liquid or the liquid being absorbed by the solids due to the difference in chemical composition of used material.

Test procedure:

The following steps were followed in order to operate the experimental system:

a) Filling the supply tank with a sufficient quantity of water (100 liter) (0.1 m^3).
b) Operating the air compressor to store enough amount of air (120 liter) (0.12m^3).
c) Circulating the water and added sand in a small circulating system to prevent the sand deposition at the bottom and keep it homogeneously distributed within the water.
d) Fixing the reading of water flow rate at a specific value, using a ball valve situated at the entrance of the flow meter.
e) Recording the value using the flow meter reading.
f) Adjusting the air flow rate unit at a specific value, by using a check valve situated at the upstream of the rotameter.
g) Recording the air flow rate using the rotameter reading.
h) Recording the pressure drop through the test section using the reading of transmitter.
i) Repeating the previous steps from (d) to (h) using different water, air flow rate.
j) Change the sand concentration using 0%, 1%, 3% and 5% of the total weight of water and repeating the previous steps from (d) to (i).
k) Repeating all the previous work using a different pipe diameter.

Range of experiments:

Temperature = (12-14) °C

Operating pressure = 6-8 bar

Water flow rate = 5-20 m^3/hr

Air flow rate = 1-10 m^3/hr

Sand content = 0, 1, 3 and 5% of weight of the liquid phase.

Results And Discussions

In this work, the effect of liquid and gas flow rates, pipe diameter and sand content on the pressure drop have been studied experimentally. The experimental tests have been performed using three phase flow (air, water and sand) in pipes having 1.5" and 2" diameter with sand content ranged from 0-5% of weight of the liquid phase through horizontal pipe. The maximum velocity at which all the particles are maintained in suspension is given by eq.(15):

$$V^{1.225} = 0.0251 * g * dp * \left(\frac{\rho_m * D}{\mu} \right) * \frac{\rho_s - \rho_L}{\rho_L}$$

For 2 inch pipe diameter

$$V^{1.225} = 0.0251 * 32.174 * \frac{2.5}{1000} * \left(\frac{1000 * 2 * 0.0254}{1} \right) * \left(\frac{2634 - 1000}{1000} \right) = 0.17 m/\sec$$

For 1.5 inch pipe diameter

$$V^{1.225} = 0.0251 * 32.174 * \frac{2.5}{1000} * \left(\frac{1000 * 1.5 * .0254}{1} \right) * \left(\frac{2634 - 1000}{1000} \right) = 0.12 m/\sec$$

Minimum velocities used during experiment are 1.22 for 1.5 inch pipe diameter and 0.695 for 2 inch pipe diameter. Thus all sand particles that carried out by the fluid are kept in suspension.

Effect of liquid and gas flow rates on pressure gradient (Δp):

Fig.4, Fig.5, Fig.6 & **Fig.7** show the effect of gas and liquid flow rates on the pressure gradient (Δp) using different pipe diameter and sand concentration. It is obvious from these figures that the pressure drops (Δp) increase with the increasing liquid flow rate as well as gas flow rates. Also, these differences in pressure drops became more obvious with increasing liquid flow rates. Effect of gas flow rate on pressure drops is less than the effect of liquid flow rate this is obvious in figures that show a nearly horizontal line of pressure loss with increasing superficial gas velocity. There are an intersection of some pressure drops values of different liquid and gas superficial velocities this attributed to change in flow pattern from intermittent to dispersed bubble flow, also changing in working pressure during the experimental work.

Effect of sand content on pressure gradient (Δp):

Fig.8, Fig.9, Fig.10 & **Fig.11** show the effect of sand content on the pressure drop for a specific liquid superficial velocity and different gas flow rates. These figures show that the increase in sand concentration leads to an increase in the pressure loss. These pressure drops is nearly horizontal with increasing superficial gas velocity because of little effect of gas flow rate on pressure drop compared with the effect of liquid flow rates, the effect become more obvious as liquid flow rates increased, it can also be seen that at some flow rates of liquid and gas the pressure losses of different sand content be close to each other, this is because it lies on the transition zone between intermittent and dispersed flow patterns , also it attributed to difference in working pressure (6-8 Bar).

Effect of pipe diameter on pressure gradient (Δp):

Fig.12, **Fig.13**, **Fig.14** & **Fig.15** show clearly the effect of pipe diameter on pressure losses. These figures show obviously that the pressure gradients decrease with increasing pipe diameter and vise versa. The effect of pipe diameter on pressure gradient become clearer with increasing of liquid flow rates, also these differences between the two pipe pressure drops become more obvious and clearly separated. Effect of gas flow rate on the pressure losses is more obvious here than any previous figures. In figure **Fig.14** & **Fig.15** the pressure drop of 2 inch pipe diameter increase until it intercepted with the measured pressure drop of 1.5 inch pipe diameter this intersection happen at low liquid flow rates and high gas flow rate with increasing sand content in the system these closures of the measured pressure losses of different pipe diameter vanish with increasing of liquid flow rates this is attributed to the fact that at low liquid flow rates and high gas flow rate the flow pattern will be stratified (separated flow), a sudden increase in pressure gradient is expected within such velocities.

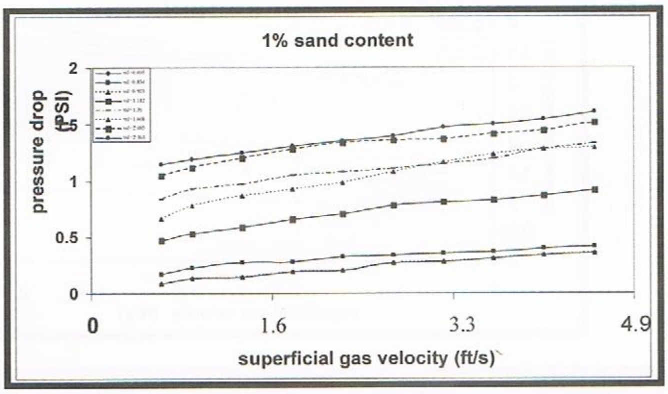

Fig.4 Effect of gas & liquid superficial velocity (2" pipe diameter, 1% sand)

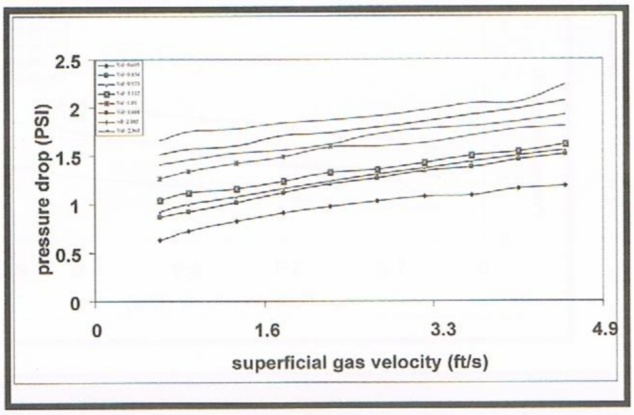

Fig.5 Effect of gas & liquid superficial velocity (2" pipe diameter, 5% sand)

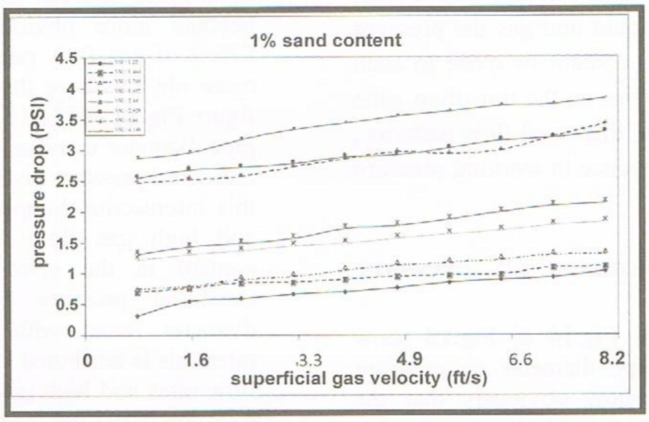

Fig.6 Effect of gas & liquid superficial velocity (1.5" pipe diameter, 1% sand)

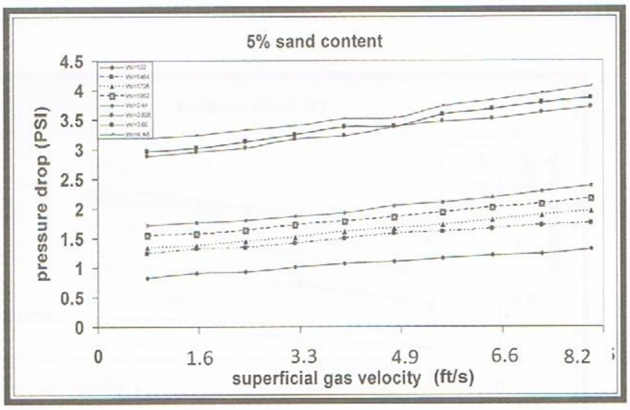

Fig.7 Effect of gas & liquid superficial velocity (1.5" pipe diameter, 5% sand)

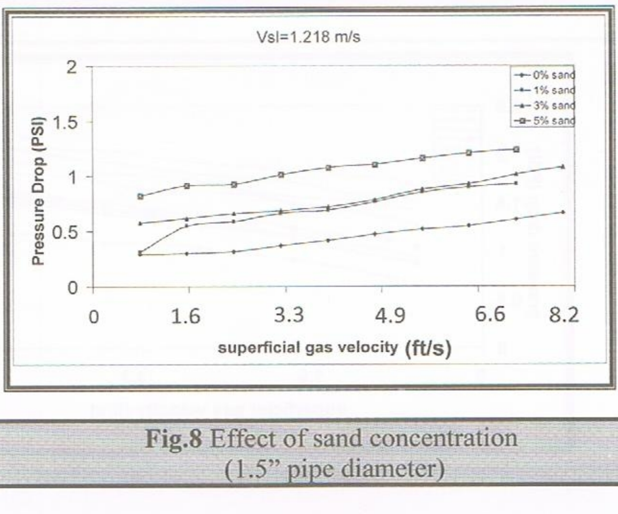

Fig.8 Effect of sand concentration (1.5" pipe diameter)

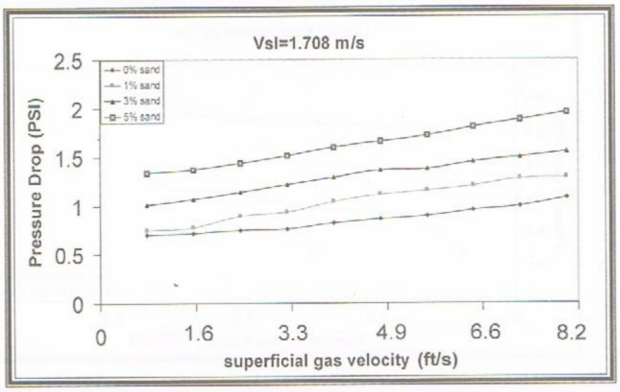

Fig.9 Effect of sand concentration (1.5" pipe diameter)

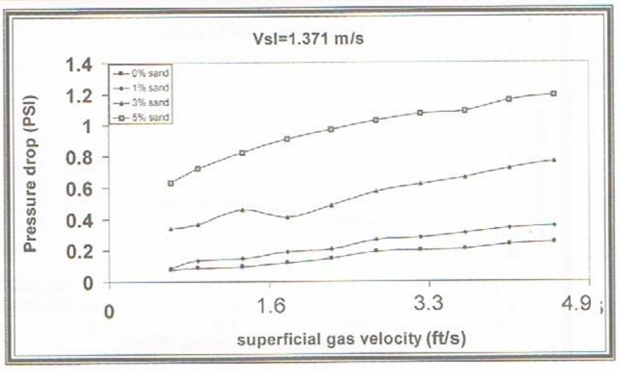

Fig.10 Effect of sand concentration (2" pipe diameter)

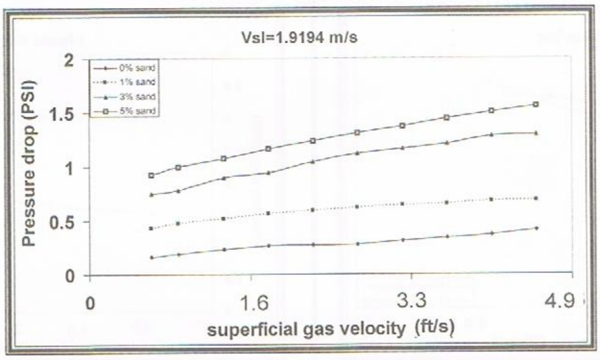

Fig.11 Effect of sand concentration (2" pipe diameter)

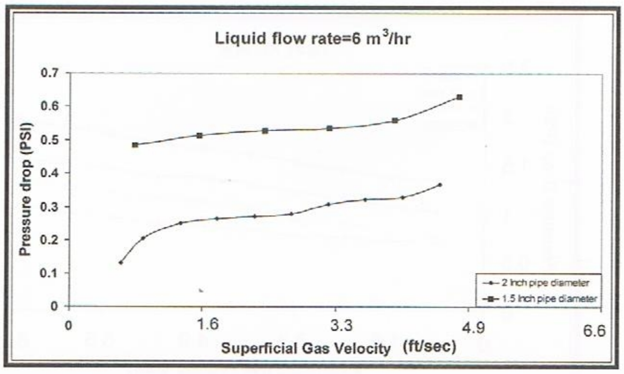

Fig.12 Effect of pipe diameter
(1.5" pipe diameter)

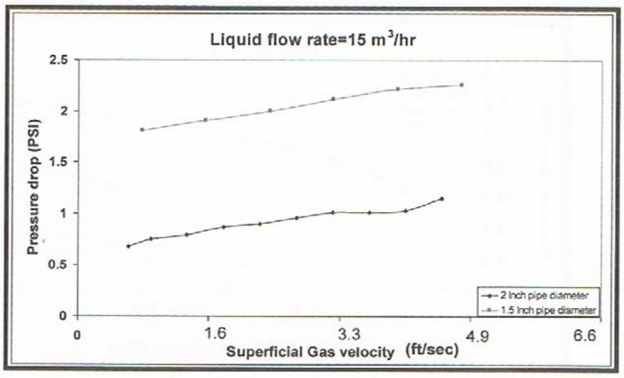

Fig.13 Effect of pipe diameter
(1.5" pipe diameter)

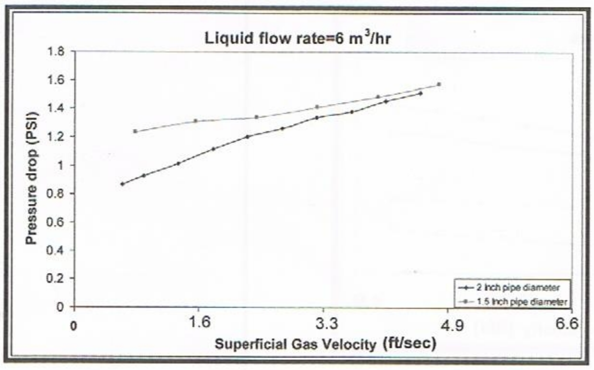

Fig.14 Effect of pipe diameter
(2" pipe diameter)

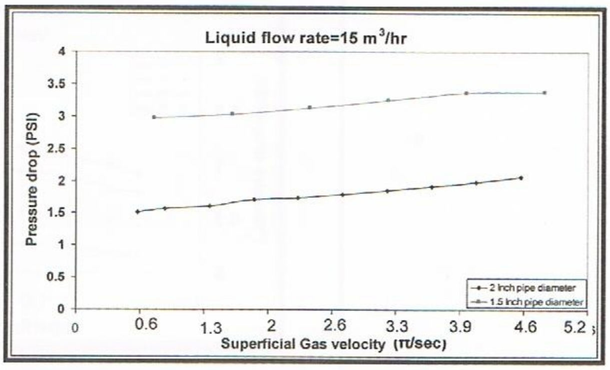

Fig.15 Effect of pipe diameter
(2" pipe diameter)

Comparative study:

The predicted value of the pressure drop (Δp), using the presented methods (combination of Wasp et. al. [(36)] and Lockhart & Martinelli[(1)], Beggs and Brill [(13)] , No-slip model [(31)], and Dukler et.al [(58)]) are evaluated against measured pressure drops, statistical analysis are present, which is a scale of agreement between calculated and measured results, also, its assist the comparative study and introduce results more objectively. Two statistical parameters are used in the present work; these parameters are the Average percent error (APE) & Average absolute percent error (AAPE),

$$\text{Percent Error (PE)} = \frac{\text{Calculated value} - \text{measured value}}{\text{Measured value}} * 100$$

$$\text{Average Percent Error (PE)} = \frac{1}{n}\sum_{i=1}^{n} PE$$

$$\text{Average Absolute Percent Error (AAPE)} = \frac{1}{n}\sum_{i=1}^{n} |PE|$$

The statistical analysis based on the total pressure gradient for the entire test section, it is found that the combination of wasp et al. [(36)] and Beggs & Brill [(13)] gave the better results of agreement for 1.5" pipe for all sand concentrations, followed by the No-slip model, other methods gave the worst analysis compared with these two methods.

For 2" pipe diameter the combination of wasp et al. [(35)] and Dukler [(58)] and Lockhart & Martinelli[(1)], gave the better statistical values of pressure gradient, here the Beggs & Brill [(13)] and the No-slip model representing the worst methods. Also we can see that measured pressure drop usually little than the calculated one, this is due to neglecting many forces done by the solid phase during calculation method of pressure losses and taking only the effect of sand concentration on the density and viscosity of the liquid phase.

Conclusions:

An experimental and theoretical study on the pressure drop in a horizontal multiphase flow of air, water and sand, different liquid and gas flow rates and different sand concentration was conducted leading to the following conclusions:

1. The pressure drop decrease with increasing pipe diameter.
2. Adding the sand to the system leads to high pressure loss in pipe.
3. Increasing sand concentration in the system resulting in formidable problems, such as: valve sticking, partial blockage of the line connecting the pipe with transmitter, affecting the pump efficiency and also, a small amount of sand depositing in the inlet of one way valve resulting an entering of the liquid phase into the air system.
4. The pressure gradient increase with increasing the liquid and gas flow rates.
5. The effect of gas and liquid rates on the pressure drop becomes more obvious with increasing sand content.
6. From a comparative study, we found that the presented method gave good results for small pipe diameter and low sand concentration, but as the pipe diameter increase and sand concentration increase the deviation is more obvious. Thus, presented method can be used for prediction of pressure drop of little sand concentration.

Recommendations:

The present work is only a first step toward the development of various studies for gas-liquid and solids material flows through the pipes. Basing on the observation for the present work, the following recommendations are suggested:

1. Using the same system with changing the sand grain size and show the effect of grain size on the pressure losses through the pipe.
2. Studying the effect of liquid and gas flow rates for different pipe inclination.
3. Studying the entire factor effecting on the pressure drop that used during the present work but for a vertical pipes.
4. Working with different liquids and show the effect of liquid properties on the pressure gradient.
5. Using a transparent test section to observe the flow regime.
6. Using another method for the calculation method of pressure drop.

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Nomenclature

A : Pipe cross sectional area, in^2
A_T : Constant depend on temperature,
C : Compressibility factor, psi^{-1}
C_L : Liquid volume fraction
C_g : Gas volume fraction
C_w : Solid concentration, % weight
D : Pipe diameter, in
F : Friction factor
g : Acceleration of gravity, ft/sec^2
H_L : Liquid holdup
H_g : Gas void fraction
M : Mass, lb
P : Pressure, psi
Q : Flow rate, ft^3/hr
T : Temperature, °F
V : Volume, ft^3: Velocity, ft/sec

Greek letters

α_T : Temperature coefficient, $lb/ft^3/°F$
Δp : Pressure drop, psi
γ : Specific gravity
μ : Viscosity, cp
ρ : Density, lb/ft^3

Superscript and Subscripts

g : Gas phase
L : Liquid phase
m : Mixture
o : Suspending media
s : Solid phase
TP : Two-phase

دراسة عملية لهبوط الضغط لجريان متعدد الأطوار (ماء, هواء,رمل) في أنبوب أفقي

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الخلاصة:

تم دراسة الجريان متعدد الأطوار للهواء ,الماء والمواد صلبة(الرمل)خلال الانابيب مختبرياً ونظرياً. في هذه الدراسة تم استخدام منظومة دوران مغلقة مصممة ومنشئة من اجل قياس خسارة الضغط ,وذلك باستخدام معدلات جريان ماء وغاز مختلفة ,أقطار أنبوب مختلفة وتراكيز مواد صلبة مختلفة.

تم انجاز التجارب المختبرية باستخدام أربع تراكيز مختلفة للمواد الصلبة 0, 1, 3, 5%)من الوزن الكلي للسائل (باستخدام أنبوبين ذات أقطار مختلفة 1.5, 2)انج (لمنظومة ماء وهواء.

تم دراسة تأثير معدلات جريان السائل والغاز ,تركيز المواد الصلبة و تأثير قطر الأنبوب على خسارة الضغط ,ووجد زيادة في خسارة الضغط نتيجة لزيادة معدلات جريان السائل والغاز ,كذلك زيادة في خسارة الضغط عند زيادة تركيز المواد الصلبة المضافة زيادة واضحة بالإضافة إلى نقصان في خسارة الضغط عند ازدياد قطر الأنبوب.

تم مقارنة النتائج المختبرية التي تم الحصول عليها مع القيم المحسوبة من معادلات خسارة الضغط .وجد انه الطريقة المطورة لبيكس و بريل مع طريقة واسب وجماعته قد اعطتنا قيم جيدة لخسارات الضغط للأنابيب ذات القطر 1.5 انج ,بينما طريقة لوكهارت ومارتنلي وكذلك دكلر وجماعته مع طريقة واسب قد أعطتنا نتائج جيدة لخسارات الضغط بالنسبة للأنابيب الكبيرة 2انج.