Pressure Drop of Gas-Liquid Two-Phase Flow in Inclined Pipelines

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Abstract

Two-phase flow of gas and liquid has been investigated through a pipe 3.40m long and 0.025m internal diameter oriented horizontally, vertically and at other three different inclination of $\Theta = 30^\circ$, $\Theta = 45^\circ$ and $\Theta = 60^\circ$. Five different systems were used. The air was used as a gas phase with water, ethanol, naphtha, light gas oil and carbon tetrachloride as liquid phases respectively.

The flow patterns were observed visually and compared with several different maps because most of the correlations require prior to knowledge of these flow patterns. The flow patterns observed were bubbly, plug, stratified, wavy and slug in horizontal flow and bubbly, plug (elongated Taylor bubbles), froth and ripply-annular in vertical flow and combinations of these flow regimes through the other three inclinations.

Graphical relations between total pressure gradient and void fraction with gas flow rate (0-18000 L/h) under different variables (liquid flow rate (298.8-1497.6 L/h), density (730-15000 Kg/m^3), viscosity (0.0005-0.00376 N.s/m^2), surface tension (23.0-71.2 mN/m) and finally the angle of inclination to horizontal), were studied and the effect of each variable was explained. It is found from this work that the total pressure drop will increase as the angle of inclination increases and it will decrease as the gas flow rate increases in inclined and vertical tubes only while at horizontal tubes the pressure drop will increase as the gas flow rate increases. During the experiment, the range of Reynold numbers used for the liquid and gas phases were (776.595-62250.0) and (0-155795.63) respectively. The Froude number ranges for liquid and gas phases were (0.1024-2.7556) and (0-408.84) respectively while the Eotvos number of the liquid was between 0.198 and 0.407.

The experimental data were compared with different correlations (Lockhart-Martinelli, Homogenous, API/AGA, Mamayev), the result was that, for pressure gradient API/AGA method gave the best prediction, while Mamayev correlation method gave good results for gas holdup or void

fraction. Statistical analysis was applied to select the best correlation which is in agreement with the system used.

Key words: Two-Phase(Gas-Liquid)flow, Inclined Pipelines, Pressure Drop

انخفاض الضغط لجريان مائعين (غاز وسائل) في الانابيب المائلة

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الخلاصة

تم في هذا البحث دراسة جريان طوري الغاز والسائل خلال أنبوب زجاجي طوله 3,40م وقطره الداخلي 0,025م وذلك بأستخدام خمسة أنظمة. حيث كان الهواء هو الطور الغازي مع استخدام خمسة سوائل مختلفة في خواصها الفيزياوية وهي الماء، الايناثول، زيت الغاز الخفيف، النافثا ورابع كلوريد الكربون.

كانت الدراسة في هذا البحث تنصب على دراسة الفقدان في الضغط عند جريان الطورين في أنبوب ذو انحناءات مختلفة ، لذلك تم توجيه الانبوب الى خمسة زوايا مختلفة وهي زاوية ٣٠^{o} ، 45^{o} ، 60^{o} بالاضافة الى الوضع الافقي والعمودي.

لقد تم ملاحظة نماذج الجريان المختلفة في جميع الانحناءات من خلال الأنبوب الزجاجي ، وقد تم مقارنتها مع خرائط الجريان المختلفة ولقد ظهرت خمسة نماذج جريان مختلفة في الوضع الافقي ، واربعة نماذج جريان في الوضع العمودي وثلاثة نماذج جريان في الوضع المائل حيث الزاوية تساوي 45^{o}، ولقد تم تحديد المناطق الانتقالية بينها.

في هذا البحث تم دراسة تأثير معدلات جريان الغاز على الفقدان في الضغط ومقدار نسبة الغاز المحتجز بالنسبة لعدد من المتغيرات مثل معدل جريان السائل ،كثافة السائل ولزوجته والشد السطحي ، وكذلك بالنسبة لدرجة ميلان الانبوب المستخدم في الدراسة.

من خلال هذا البحث لوحظ ان الفقدان الكلي في الضغط يتزايد مع زيادة حادة في الانحناءات القليلة ولكنها اقل حدة في الانحناءات الكبيرة، وقد لوحظ ايضاً أنه في حالة تدفق معدلات كبيرة من الغاز والسائل فأن تأثيرالميلان يكون قليلاً. وقد اظهرت النتائج ان الفقدان الكلي

في الضغط يتزايد مع تزايد كمية السائل المتدفق، اما بالنسبة للطور الغازي فأن الفقدان في الضغط يتناقص مع زيادة كمية الغاز المتدفق في الحالات المماثلة والعمودية فقط . ويتزايد في الحالات الافقية. أما بالنسبة لكمية الغاز المحتجز فأنها اقل ما تكون عند الزاوية 45^{o}، وأكثر ما تكون في الواقع الافقي.

وعند مقارنة النتائج العملية مع أربعة طرق لحساب الفقدان في الضغط وهي: (طريقة التجانس – طريقة لوكهارت – مارتنيللي – طريقة API /AGA – طريقة ماماييف)، وجد ان طريقة API /AGA كانت الافضل في ايجاد الفقدان في الضغط، بينما كانت طريقة ماماييف هي الافضل في ايجاد نسبة تواجد الغاز في الانبوب.

الكلمات الداله :جريان الطورين(غاز –سائل) انابيب مائله، فقدان الضغط

Nomenclature

C_G	Inlet, no slip, void fraction $[Q_G/ (Q_G+ Q_L)]$
D	Pipe diameter, (m)
E_O	Eotvos number $[g\rho D^2/\sigma]$
Fr	Froude number V^2/gD
H	Difference in height of mercury in the manometer (m)
P	Pressure (N/m^2)
Q_G	Gas flow rate (L/h)
Q_L	Liquid flow rate (L/h)
Re	Reynold number $(\rho VD/\mu)$
R_G	Gas holdup or void fraction
$R_{G\Theta}$	Gas holdup at any angle Θ
R_{GH}	Gas holdup at horizontal level $(\Theta = 0)$
V_{SG}	Superficial gas velocity (m/s)
V_{SL}	Superficial liquid velocity (m/s)
ΔP_M	Difference in pressure in the manometer $[N/m^2]$
ΔP_T	Total pressure drop over L $[N/m^2]$

σ	Surface tension (N/m)
ρ_{Hg}	Density of mercurey in the manometer (Kg/m^3)
ρ_L	Density of liquid (Kg/m^3)

Introduction

A phase is simply one of the states of matter that can be a gas, a liquid, or a solid. Multiphase flow is the simultaneous flow of several phases, as concurrent or countercurrent flow (15).

Multiphase flow in pipes is defined as the cocurrent or countercurrent simultaneous movement of the gases and immiscible liquids in pipes (1).

Interaction between the phases and the coexistence of liquid and gas phases which have different velocities makes it very difficult and complicated to describe the hydrodynamic behavior because of the creation of a wide variety of flow regimes (7)

Despite the numerous theoretical and experimental investigations on gas-liquid pipe flow, no reliable pressure drop and void fraction correlation are available, mainly as a result of the large number of variables involved (2).

The multiphase flow can be divided into three categories (4, 14):

1- Horizontal flow.

2- Inclined flow (upward and downward)

3- Vertical flow (upward and downward)

The flow models which have been developed can be classified (5, 10).

1-Homogenous flow model

Here the two-phase flow is assumed to be equivalent to a single phase flow having pseudo properties.

2- Separated flow model

Here the two-phases of the flow are considered to be artificially segregated.

3- Drift flux model

Here the two-phase flow is considered as separated flow model in which attention is focused on relative motion between phases

4- Flow pattern model

Here the two-phase is considered to be arranged in one of three or four definite geometries (flow regimes) [16].

The basic factors which affect the gas-liquid flow are the liquid and gas flow rates, the geometry of the test section, the physical properties of the phases and the angle of inclination [13].

The most important measure is the total pressure drop which is equal the summation of frictional pressure drop, kinetic energy pressure drop (acceleration term) and potential pressure drop (gravitational or hydrostatic head).

The aim of this work is to study the effect of flow patterns and the angle of inclination on the pressure drop of gas-liquid two-phase flow of five liquid systems with air as the gas phase.

Experimental Work

Schematic diagram of the experimental apparatus used in this study as in Fig. (1). By this apparatus, a study is made to know the effect of physical properties, flow patterns, and angle of inclination on the two-phase gas-liquid systems pressure drop.

Experimental Apparatus

Test Section

The test section was made of glass pipe (QVF) of 0.025 m, I.D, 3.40 m long, with the equivalent length of fitting joined with it; the total length is then 4.5m. The pipe lines are supported on steel frames and instrumented, lifted manually so that the fluid flows at five inclinations, ($\Theta = 0^{\circ}$, $\Theta = 30^{\circ}$, $\Theta = 45^{\circ}$, $\Theta = 60^{\circ}$, $\Theta = 90^{\circ}$).

Ball, check and gate valves, pressure gauges, flow meters were all used in the experiment, Figs. (1)

Gas and Liquid System

Air (Table 1) was used as the gas phase with five liquids systems used. Air is supplied from a compressor and flows through a rotameter to an air/liquid mixer, passing through a check valve. A calibrated gas rotameter was used to measure air flow rate. The specifications of the compressor are

Power 550 watt, maximum pressure 1600 kN/m^2, rotational speed 1450 r.p.m.

The liquid system was stored in two tanks (0.75* 0.75 * 0.75) m^3 connected in series. The liquid was circulated through the test section, using a centrifugal pump.

The specifications of the pump are Maximum flow rate = 17600 L/hr, power: 80, 110, 125 watt, rotational speed: 1200: 1700: 2300 r.p.m.

The five liquid systems used in the experiment are Water, ethanol, light gas oil, naphtha and carbon tetrachloride. All the physical properties are listed in tables (2, 3).

Gas Liquid Mixing System

In the experiment, the gas and liquid phase flowed simultaneously, so the two phase entered separately through a U-shaped glass tube of 0.2m long followed by a pipe of 0.25m long in order to have good mixing between the two phases. All the pipes used in the experiment are glass of type QVF. This mixing zone section was located before the test section, as shown in Fig. (1).

Liquid flow rate was measured by using a rotameter which was calibrated as shown in Fig. (2) and checked by using a stop watch and a graduated cylinder to accumulate a certain volume of liquid at a given period of time. The entrance length for the two phases flow is 0.5 meter which is enough in the case of two phase flow because the gas phase has a great effect in destroying the boundary layer not like the single phase flow which needs more entrance length in the range of (50-100) times the diameter of the pipe [5, 6].

Void fraction was measured by measuring liquid fraction several times for the same run and then the average value was calculated, the percent error was ± 10%, by using two quick-closing ball valves.

For the cases of different inclinations including vertical situation, the void fraction was measured by calculating the portion of the tube not filled with liquid, by using a metering scale put on the tube between the two-ball valves (BV2 & BV3)

The pressure drop was measured by using a mercury manometer which was filled with the liquid used in each run. The difference in height between the two levels was recorded.

The pressure drop was then calculated by using the equation

$\Delta P_M = (\rho_{Hg}-\rho_L)\, gH$ ……… (1)

Experimental Procedure

The experimental steps which were undertaken are:

1- The test section was firstly, directed perfectly in horizontal position.

2- The liquid flow rate (water, ethanol, naphtha, light gas oil, and carbon tetrachloride) was set on a certain value by using a rotameter (calibrated for each kind of liquid used) with a gate valve (1in) to control the flow of liquid in to the test section.

3- The gas flow rate was set on a certain value (starting from low to high values) by using a check valves which controls the flow of gas.

4- After reaching steady-state condition, the midpoint pressure was recorded by the pressure gauge and pressure difference by manometer.

5- For measuring liquid and consequently gas holdup, both ball valves (BV2 & BV3) were closed simultaneously. This step was repeated several times and the liquid fraction reading were averaged.

6- For the same value of liquid flow rate, the gas flow rate was increased and steps (3, 4, and 5) were repeated.

7- The liquid flow rate was changed and steps (2-6) were repeated.

8- The angle of inclination of the test section will be changed from $\Theta = 0^\circ$ to $\Theta = 30^\circ$, $\Theta = 45^\circ$, $\Theta = 60^\circ$ and $\Theta = 90^\circ$ in each inclination, all the step from (2-7) were repeated.

Results and discussion

Five systems were used in the experimental work and were represented by (2000) data points. The operating flow rates in (L/h) of water are (600, 800, 1000, 1200), of ethanol (650, 850, 1100), of naphtha (700, 942, 1150), of gas oil (630, 830, 1077) and of carbon tetrachloride (450, 600, 750). The test section used was oriented at five angles which were $\Theta = 0^\circ$, 30°, 45°, 60° and 90°. The operating conditions were atmospheric pressure at room temperature of 30˚C .The air flowrate was in the range of (0-18000L\h).

Flow Patterns

Flow patterns were observed visually through the glass transparent test section during the experimental work, and different photos were taken for different flow patterns by the use of camera, see Fig (3).

These observed actions of flow patterns were recorded (Table 4) and compared with different flow pattern maps, where 85% of the points were rightly predicted. Differences may be because of the liquid used is this work are not the same as liquids used in plotting the map, sometimes due to the differences in operating conditions and the lack of accuracy.

For horizontal flow Mandhane et al. flow pattern map [(11)], Fig. (4) is found to fit our data where 90% of the data points are in good agreement with our map. Five regimes were observed with the range of variables used, these regimes were bubbly, plug, slug, stratified and wavy. Transition zones were also observed between these regimes.

For vertical flow, the experimental results were compared with the Govier, Radford, and Dunn [(8)] flow pattern maps in Fig. (5). They were in a good agreement with these maps since 90% of the data points were correctly represented in the map. Four flow regimes were obtained for the different systems used. These regimes were bubbly, plug, froth and ripple (wavy layer of liquid on the wall). It can be noticed that the stratified and wavy flow regimes disappeared here in vertical flow, and the bubble, slug, and froth regimes are the predominant ones.

For inclined flow, $\Theta = 45^o$, Fig. (6) the Gould et al.[(12)] flow pattern map of air–water system was used to compare our data with it. There are few flow pattern maps for inclined flow in literature, so our data were compared only with the Gould et al. map. Only 70% of the points were been in good agreement with the map, because the region of "both-phases continuous" (which is equivalent to the stratified flow regime) that appears in the map was not observed in this study, so three flow regimes were observed for inclined flow at $\Theta = 45^o$, they were bubble, plug and froth flow regimes.

The upward inclination causes intermittent flow (elongated bubble and slug) to take place over a much wider range of flow conditions and causes the stratified flow to disappear since by starting to increase the angle of inclination from horizontal, the regime of stratified flow starts to shrink into smaller region, and then for higher inclination of 30^o and more, the stratified flow is not observed and is replaced by slug flow region.

Void Fraction

The void fraction of (air-gas oil) as an example is represented in Fig. (7) which show the effect of variation of the void fraction with gas flow rate for five

systems at different inclinations. Void fraction was affected by gas and liquid flow rates and angle of inclination.

It can easily be seen that by increasing the gas flow rate, the void fraction (gas holdup) will increase, and by increasing the liquid flow rates, the void fraction will decrease.

From our experimental data, simple empirical relations of void fraction with gas and liquid flow rates were summarized as in Fig. (7):-

for bubbly flow (with 10% error)

$R_G = 0.8\ C_G$ …….. (2)

for slug flow (with 12% error)

$R_G = 0.75\ C_G$ …….. (3)

Angle of Inclination

It can be seen from Fig. (8) that for the same gas and liquid flow rates of a system, the void fraction will decrease first by increasing the inclination from $\Theta = 0^o$ to $\Theta = 45^o$, and then it starts to increase by increase the inclination from $\Theta = 45^o$, to $\Theta = 90^o$ because of the vertical and horizontal components of the force of gravity and the difference in densities between the air and the other liquids. So, it is noticed that the void fraction will have a minimum value at the interval around $\Theta = 45^o$, (maximum liquid holdup), causing the total pressure drop to increase. And also it is noticed that it will be maximum at the horizontal position.

About 75% of the experimental data exhibit good agreement with Beggs [3] correlation, which report greater sensitivity of the void fraction with the angle of inculcation.

From this work empirical relation was found to relate the void fraction with the angle of inclination (with the error percent of 12%) in the form of:-

$R_{G\Theta} = R_{GH} - 0.1 \sin (1.9\ \Theta)$ …… (4)

Pressure Gradient

The main parameter affection the pressures drop is:

Liquid Flow Rate

Fig. (9) shows the experimental values of the two-phase pressure gradient versus the gas flow rate with the liquid flow rate as a parameter. It is clear that the

pressure drop increases with increasing liquid flow rate; because liquid velocity will increase causing wall shear force to increase in the two-phase flow as in the single phase liquid flow.

Gas Flow Rate

Increasing gas flow rate will increase the total pressure drop in horizontal tubes only as seen in Fig. (9) because the gas phase travels faster than the liquid phase, so slippage will occur causing interfacial friction force between the two phases in addition to the wall shear force. Also increasing the gas velocity will increase the mixture velocity, and consequently the frictional shear stress at the wall increases, causing frictional pressure drop to increase.

For situations, other than horizontal ($\Theta = 30^o, 45^o, 60^o, 90^o$), it is noticed that increasing the gas flow rate will decrease the total pressure drop as seen in Figs. (10 to 13). When adding gas to liquid the mixture will be lightened, and the density of the mixture will be less, so the gravitational pressure will decrease causing a noticeable decrease in total pressure drop. So, at higher inclinations the highest total pressure losses are recorded for the lower gas flow rates.

From this study it is found that the total presser drop in inclined and vertical tubes is inversely proportional to the Froude number of gas phase but for horizontal tubes it is directly proportional to Froud number.

ΔP_T is proportional with $(FR_G)^{-1}$ for inclined and vertical tubes

ΔP_T is proportional with (FR_G) for horizontal tubes

Liquid Density

It can be easily seen that increasing the density of the liquid used, the total pressure drop will increase, Fig. (14) as the liquid density increase a higher momentum friction will be required to transport the liquid causing the frictional pressure drop to increase, and also by increasing the liquid density, the mixture density will increase causing the gravitational pressure drop to increase, and hence the total pressure drop.

Liquid Viscosity

As seen from Fig. (15) increasing the liquid viscosity increases the frictional pressure drop. Viscosity of a liquid is a measure of the internal frication of that liquid, so by increasing viscosity, the internal friction will increase causing an increase of the mixture friction.

Liquid Surface Tension

Fig. (16) shows the effect of surface tension variations on pressure gradient. It is seen that by increasing the surface tension of the liquid, the pressure drop will decrease. This is because liquid of small surface tension have curved interfaces with the gas phase, leading to the formation of spherical bubbles, which will increase the surface contact area between the phases and consequently increase the pressure drop. Also the small surface tension increase roughness of the interfaces causing an increase in pressure drop.

From experimental work, it was shown that the surface tension is inversely proportional to pressure gradient. In spite of its importance, the surface tension effect is not in Lockhart-Martinelli correlation.

Angle of Inclination

The most important factor which affects the total pressure drop is the elevation of the test section. Because increasing angle of inclination in the upward flow will increase the hydrostatic head, or the potential energy of the mixture, causing a high increase in total pressure drop.

Fig. (17) shows the effect of inclination on pressure gradient which is that by increasing the angle of inclination the pressure drop increases.

It can be noticed that the total pressure drop increases sharply at small inclination, but at higher inclination the rate of increase of pressure drop is less.

At the vertical situation ($\Theta = 90^o$), the total pressure drop is not increasing sharply as the previous angles, in spite of the maximum hydrostatic head. The reason is that the frictional pressure drop increases continuously by increasing the inclination and then starts to decrease to lower values at vertical and near vertical flow. This decrease in friction term will almost cancel the effect of increases in the gravitational term, so the total pressure drop will not increase sharply at vertical and near vertical positions [(4)].

These negative frictional pressure losses are due to the fact that the water film immediate to the wall is forced to move downwards against the flow by the rising gas slug whilst that near the interface will travel upwards, naturally as the superficial liquid velocity is increased, this effect will be eliminated.

For inclined flow and for low V_{SL}, V_{SG} the gravitational component predominate the total pressure loss, but as the liquid and gas flow rate increases, the pressure drop behavior is independent on the inclination and frictional term of the total pressure drop is dominated. So at high liquid and gas flow rate, the effect of inclination on the total pressure drop will be small, where:

$$\Delta P_T = \Delta P_{friction} + \Delta P_{acceleration} + \Delta P_{potential} \qquad \text{……. (5)}$$

Conclusions

1- For horizontal flow, five flow regimes were obtained (bubbly, plug, stratified, wavy and slug). The experimental data were compared with the flow pattern map of Mandhane et al., which showed good agreement with the experimental data, since 90% of the data points were correctly fitted in this map.

For inclined flow, Gould et al. map for 45^o up flow, was the only one to compare the data with. It was in good agreement for 70% of the data points. Three flow regimens were obtained at the inclination of 45^o (bubbly, plug and slug).

2- The void fraction has a minimum value at $\Theta = 45^o$, and has its maximum value at the horizontal flow.

Analytical relation, of the void fraction with the inclination and with gas and liquid flow rates were found from this work.

$R_{G\Theta} = R_{GH} - 0.1 \sin(1.9\ \Theta)$

$R_G = 0.8\ C_G$ (bubbly flow)

$R_G = 0.75\ C_G$ (slug flow)

3- the total pressure drop is noticed to increase by increasing the inclination with different rates, since at small inclination the increasing rate is higher than the rate at larger inclination (near vertical).

4- From experimental results, it is found that the pressure drop is directly proportional to the density and viscosity of the liquid but it is inversely proportional to the liquid surface tension.

5- Increasing liquid flow rate will increase the total pressure drop in all situations. But increasing gas flow rate will increase the total pressure drop in horizontal flows only.

6- For inclined flow and for low VSL, VSG the gravitational component predominate the total pressure loss, but as the liquid and gas flow rate increases, the pressure drop behavior is independent on the inclination, and frictional term of the total pressure drop is dominating. So at high liquid and gas flow rate, the effect of inclination on the total pressure drop will be small.

7- By comparing the experimental data of the present work with (Lockhart–Martinelli, API/AGA, Homogenous and Mamayev) methods, it is noticed that API method was the best to predict the pressure drop values and Mamayev correlation was the best to predict the void fraction data.

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Table 1 shows physical properties of air

Temperture	**30 ^oC**
Density (Kg/m^3)	**1.165**
Absolute viscosity ($N.S/m^2$)	**1.890 (10^{-5})**
Kinematic viscosity (m^2/s)	**1.56 (10^{-5})**
Average molecular weight	**28.96**
Specific gravity	**1.0**

Table 2 shows physical properties of liquid used

	Density ρ Kg/m^3	**Viscosity** 10^3 μ $N.S/m^2$	**Surface tension** 10^2 σ N/M
Water	**995.65**	**0.801**	**7.12**
Ethyl alcohol	**780**	**1.0**	**2.15**
Carbon tetrachloride	**1500**	**0.843**	**2.54**
Naphtha	**730**	**0.5**	**2.3**
Light gas oil	**810**	**3.76**	**2.8**
Mercury	**13521.36**	**1.5**	**51.39**

Table 3 shows range of variables

Item	**Range**
ρ_L	**730-1500 Kg/m^3**
ρ_G	**1.165-11.65 Kg/m^3**
μ_L	**0.0005-0.00376 $N.S/m^2$**

$\theta = 0^o$	**Bubble flow**	**Plug flow**	**Stratified flow**	**Stratified-slug**	**slug**
$\theta = 30^o$	**Bubble flow**	**Plug flow**	**Plug-slug flow**	**Slug**	**Slug**
$\theta = 45^o$	**Bubble flow**	**Plug flow**	**Plug-slug flow**	**Slug**	**Slug**
$\theta = 60^o$	**Bubble flow**	**bubble flow**	**Slug-flow**	**Slug - froth**	**Froth**
$\theta = 90^o$	**Bubble flow**	**bubble flow**	**Slug-flow**	**Slug - froth**	**Froth**

μ_G	**$1.89 * 10^{-5}$ N.S/m^2**
Q_L	**$8.3 * 10^{-5}$ - $4.16 * 10^{-4}$ m^3/s equal to 298.8 - 1497.6 L/h**
Q_G	**0.0 - $5.0 * 10^{-3}$ m^3/s equal to 0.0 - 18000 L/h**
σ	**23.0 - 71.2 mN/m**
V_{SL}	**0.16 - 0.83 m/s**
V_{SG}	**0.0 - 10.11 m/s**
R_G	**0.005 - 0.62 dimensionless**
θ	**0^o - 90^o degrees**

Table 4 shows the effect of changing inclinations on changing flow patterns of air-gas oil system for different liquid and gas flow rates.

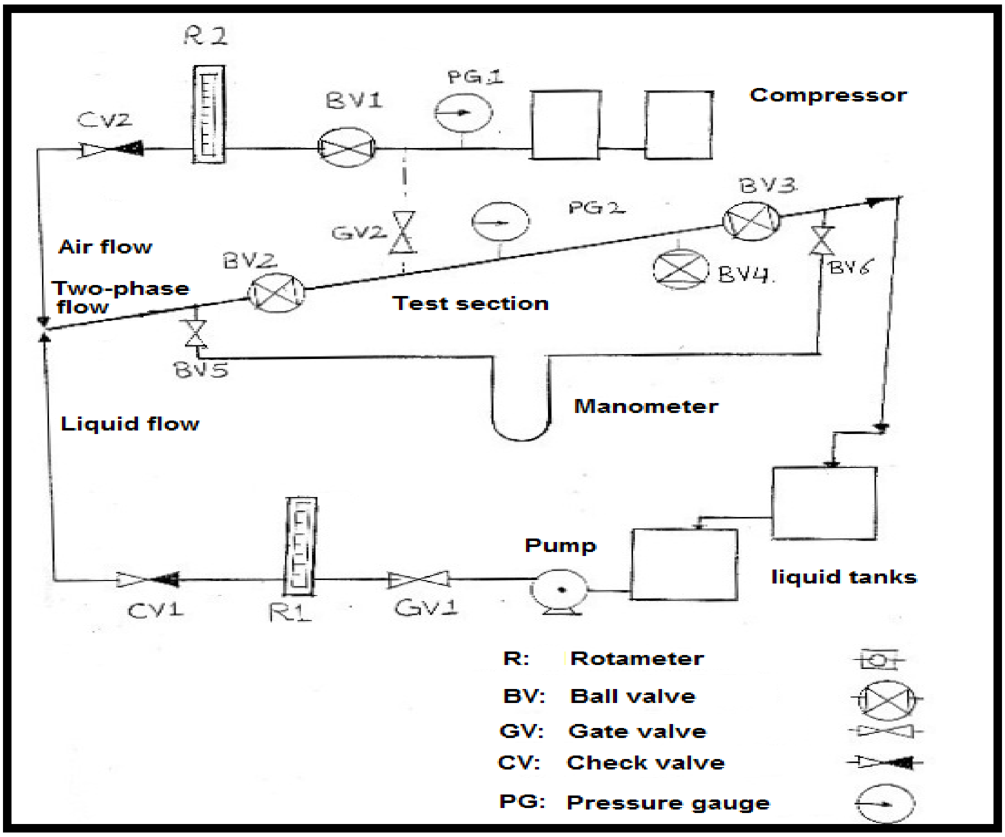

Fig. 1 Schematic diagram of the test section.

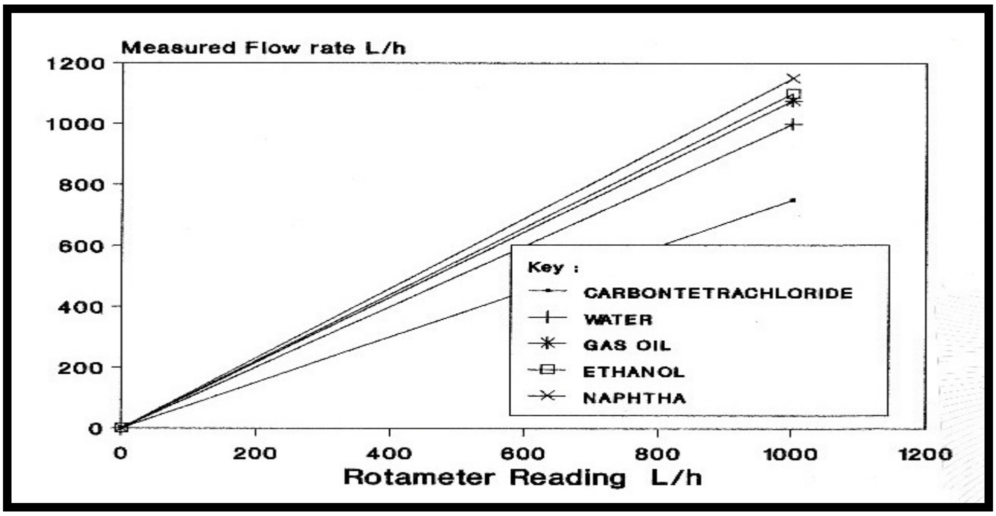

Fig. 2 Calibration of the rotameter.

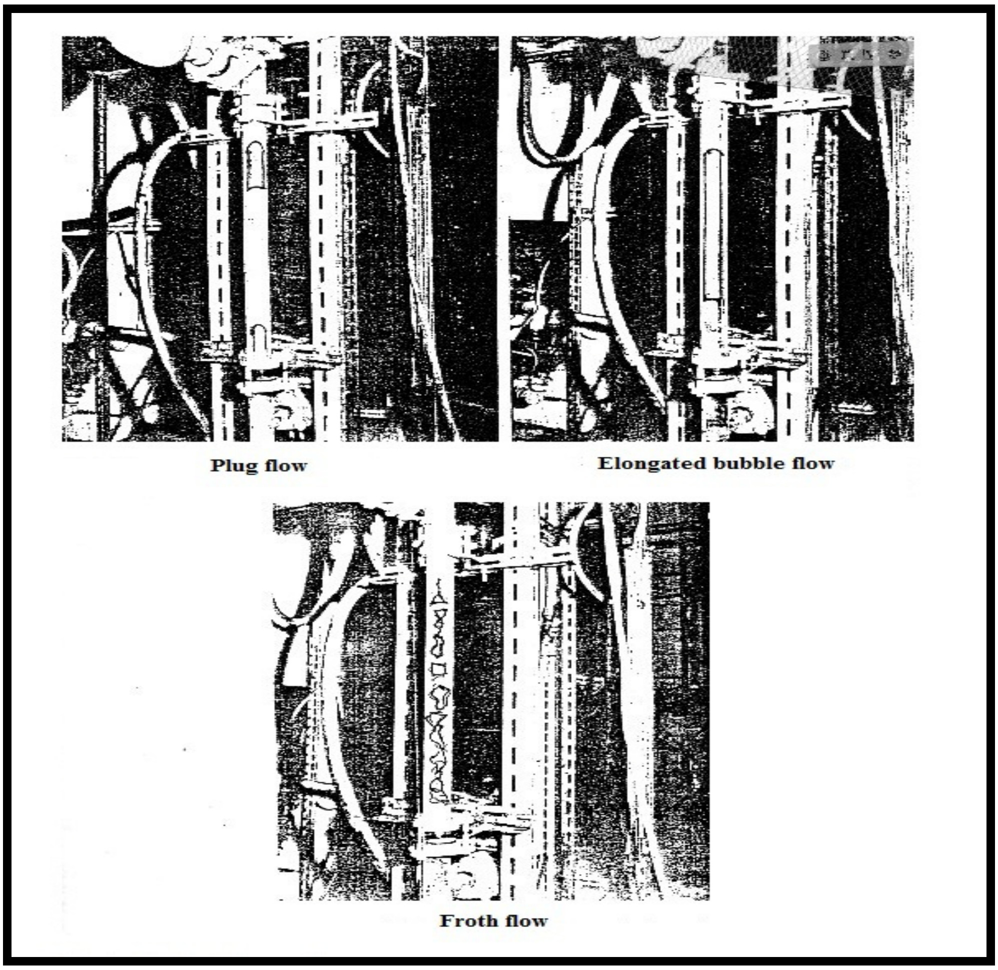

Fig. 3 Vertical flow patterns.

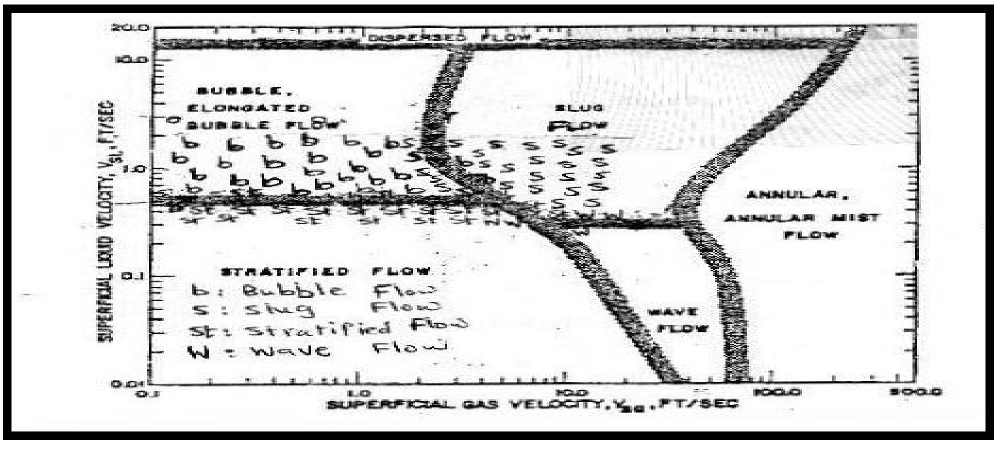

Fig. 4 Comparison of experimental data with Mandhane et al. Map for horizontal flow.

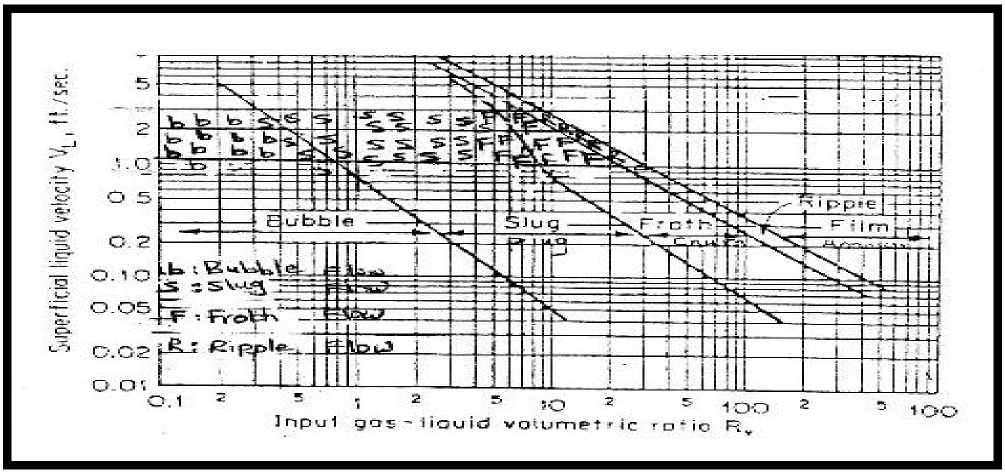

Fig. 5 Comparison of experimental data with Govier, Radford and Dunn' s vertical flow pattern map.

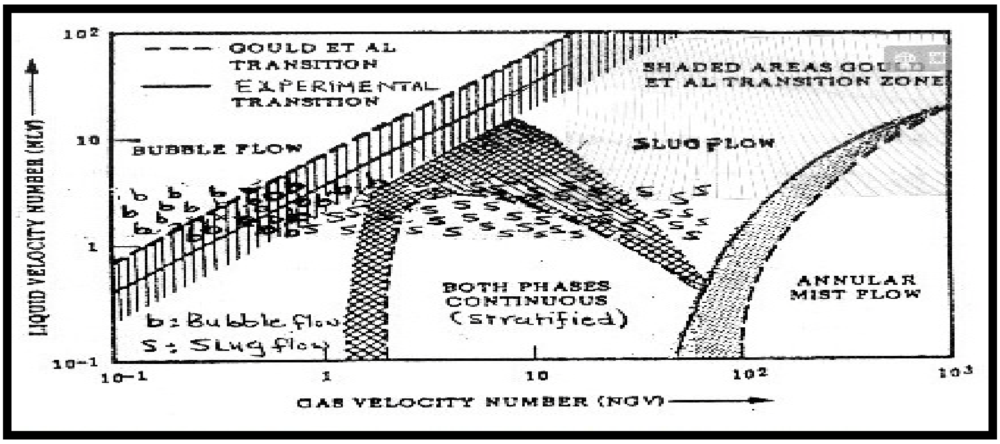

Fig. 6 Comparison of experimental data with Gould et al. map-45^o upflow.

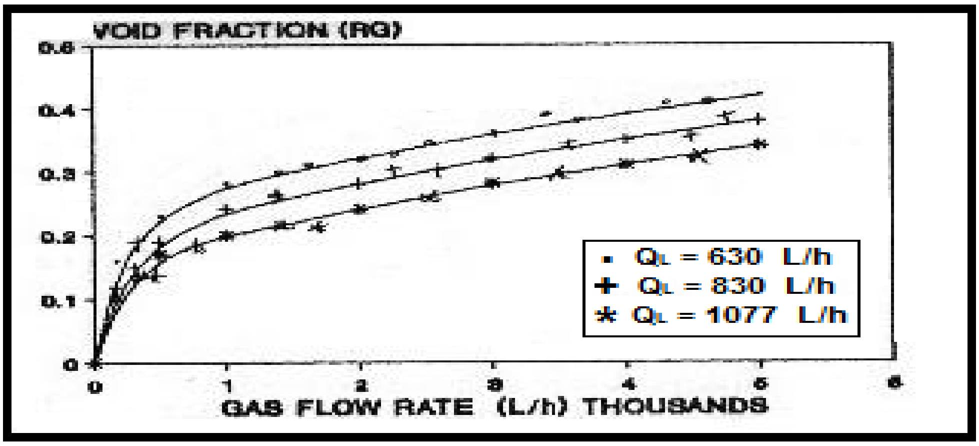

Fig. 7 Void fraction vs. gas flow rate of (air-gas oil) system at ϴ= 0^o.

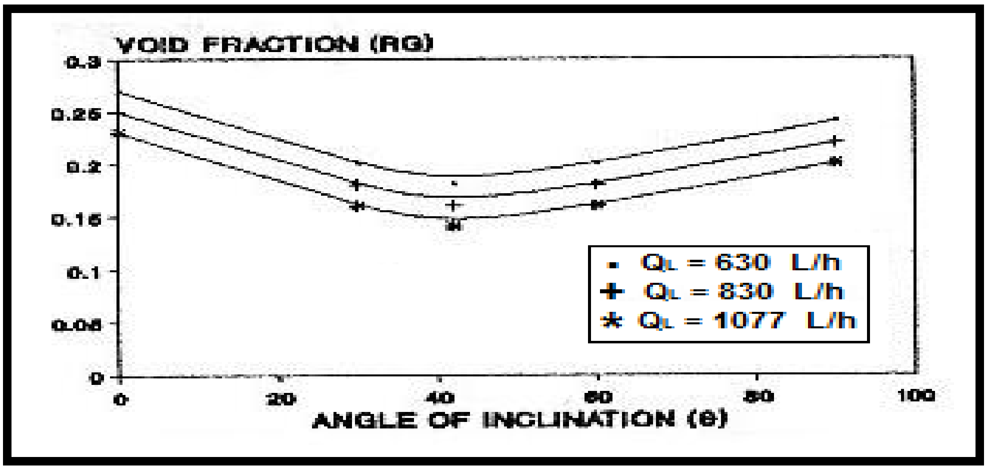

Fig. 8 Void fraction vs. inclination for (air-gas oil) system at Q_G = 1000 L/h.

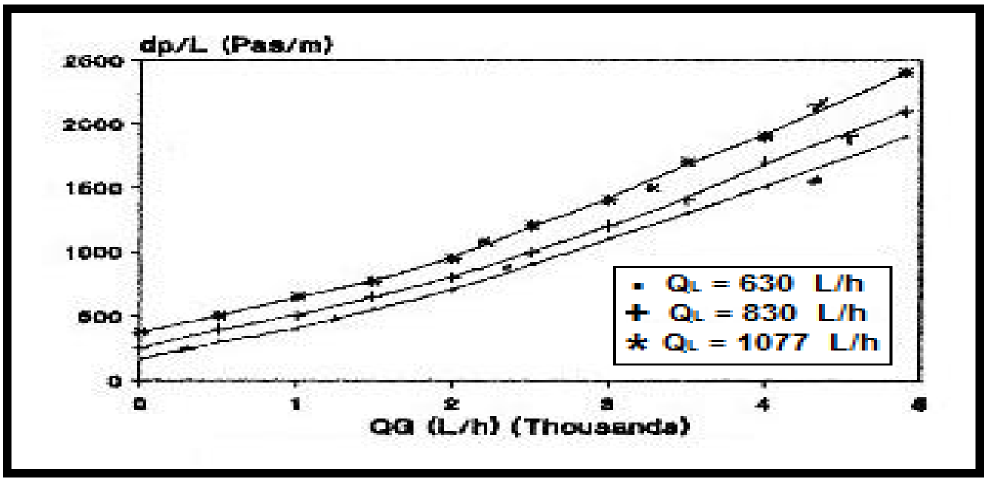

Fig. 9 Pressure gradient vs. gas flow rate (air-gas oil) system at Θ = 0°.

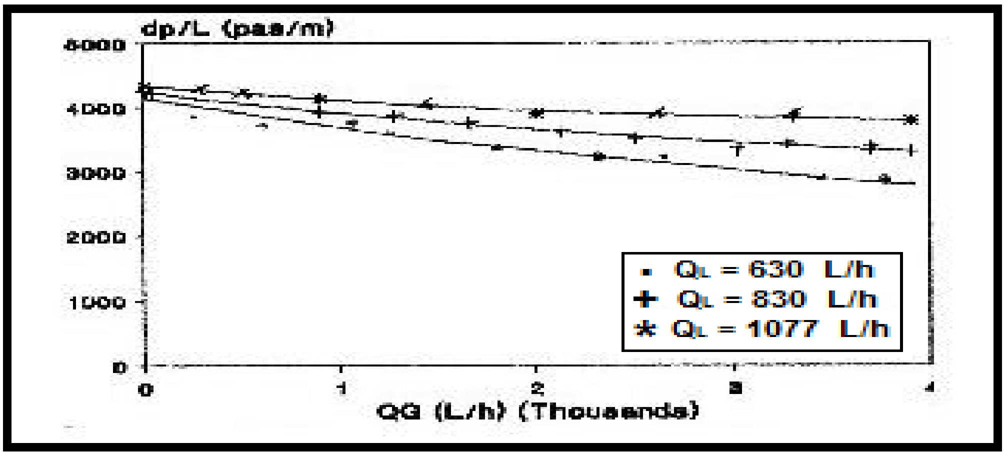

Fig. 10 Pressure gradient vs. gas flow rate (air-gas oil) system at Θ = 30°.

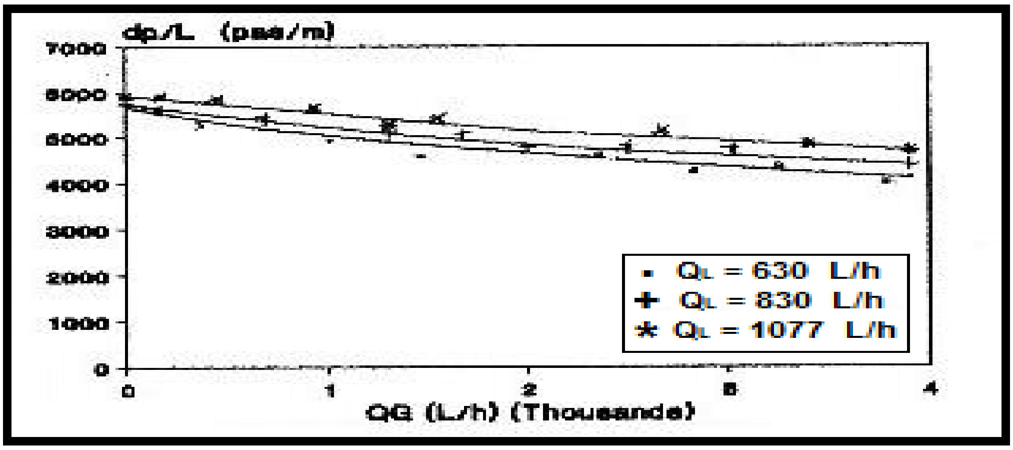

Fig. 11 Pressure gradient vs. gas flow rate (air-gas oil) system at Θ = 45°.

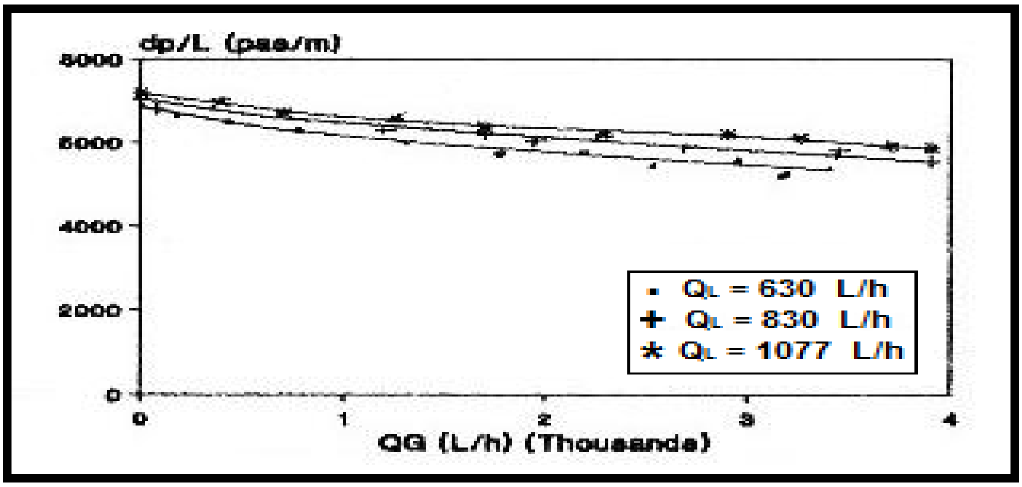

Fig. 12 Pressure gradient vs. gas flow rate (air-gas oil) system at Θ = 60°.

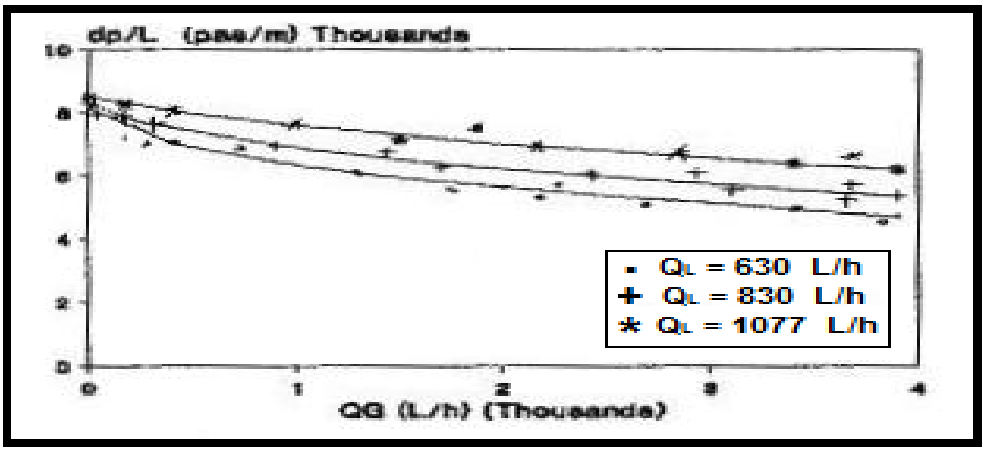

Fig. 13 Pressure gradient vs. gas flow rate (air-gas oil) system at Θ = 90°.

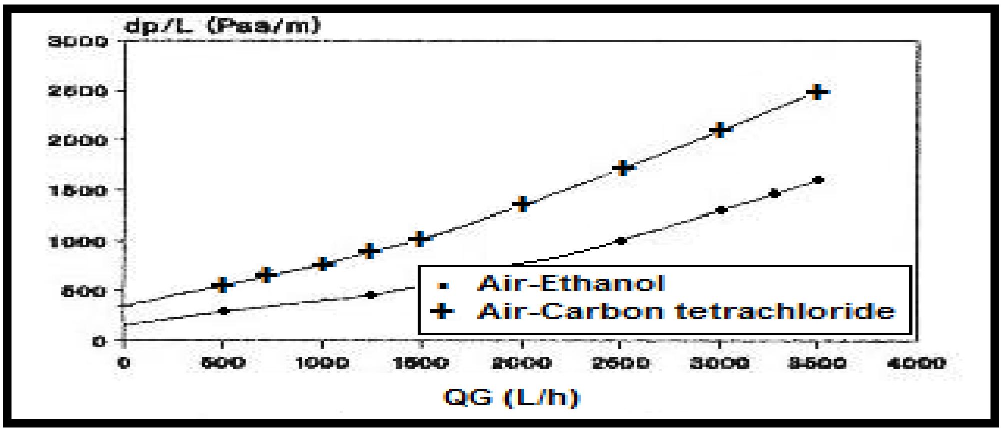

Fig. 14 Effect of liquid density on pressure gradient vs. gas flow rate for (A-E), (A-C) system (QL = 760 L/h).

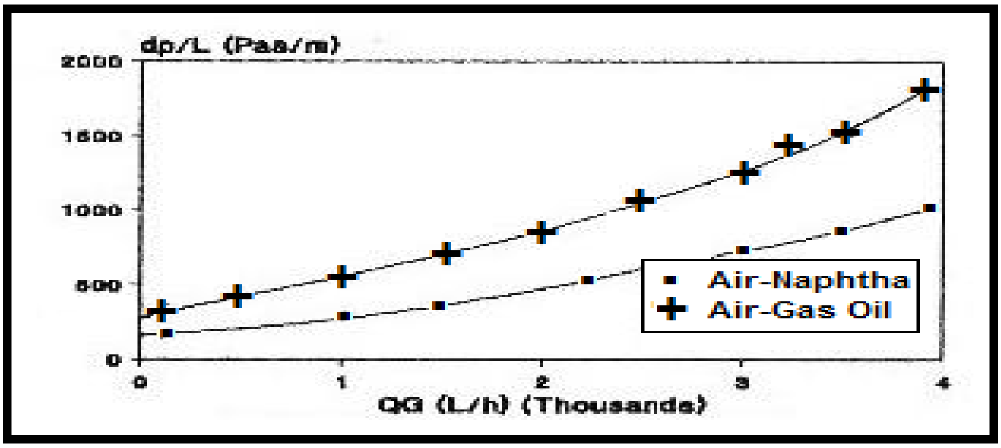

Fig. 15 Effect of liquid viscosity on pressure gradient vs. gas flow rate for (A-N), (A-G) system (QL = 950 L/h).

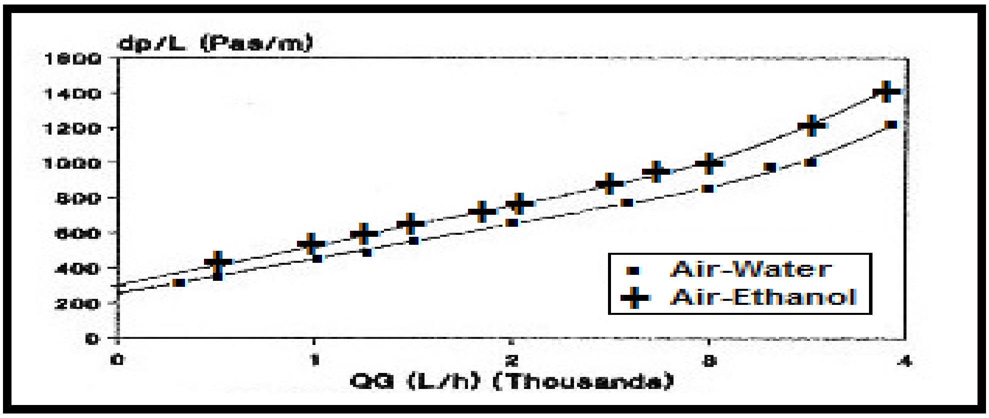

Fig. 16 Effect of liquid surface tension on pressure gradient vs. gas flow rate for (A-W), (A-E) system (QL = 1000 L/h).

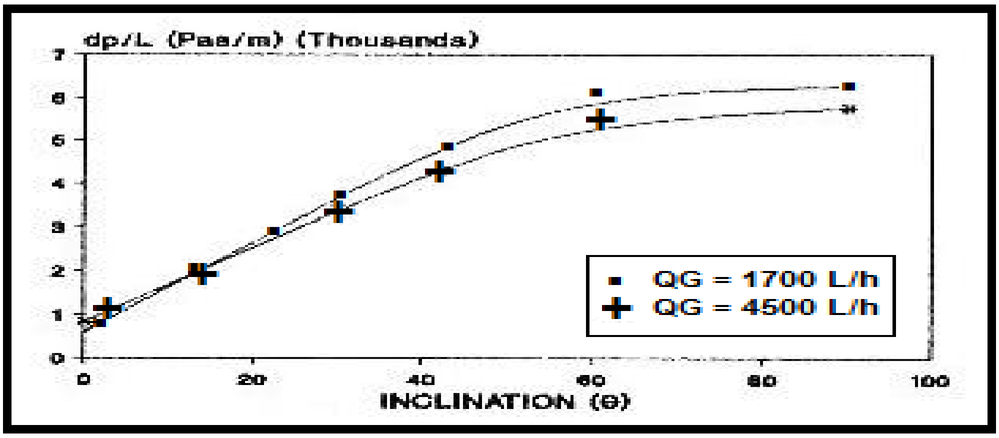

Fig.17 Pressure gradient vs. inclination of (air-gas oil) system at QL= 830 L/h.

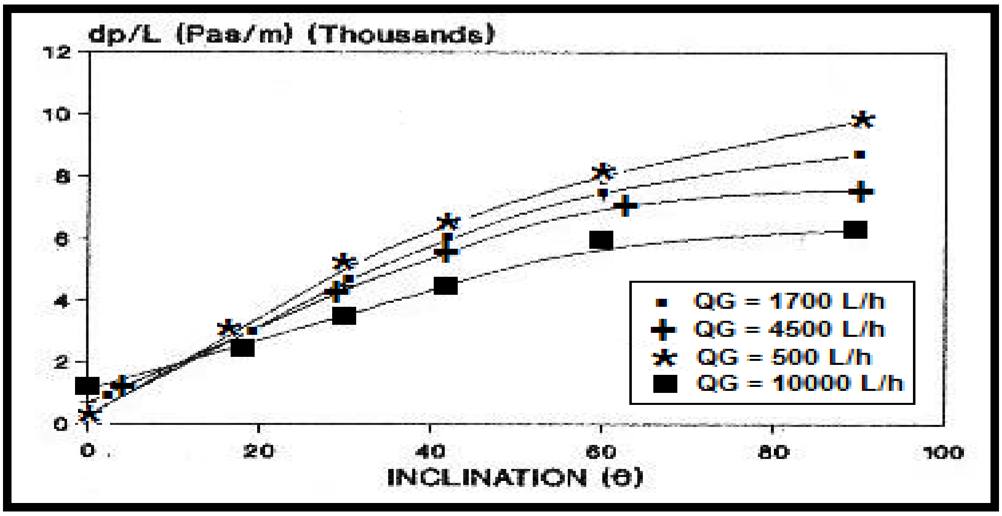

Fig.18 Pressure gradient vs inclination of (air-gas oil) system at QL=1000 L/h.