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Experimental Investigation of pressure drop in concurrent air-water flow

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Abstract:

Pressure drop measurements for horizontal stratified two-phase flow of air water have been performed in a channel with 5.33m length, 0.20m width, and 0.1m height. The gas and liquid Reynolds numbers were varied in the 54000-87000 and 13000-23000 ranges, respectively. A correlation was proposed for predicting pressure drop in horizontal stratified two phase flow. Predictions of the correlation proposed in this work were compared with experimental data and showed much better agreement compared to Friedel equation.

Keywords: Two-phase flow; Frictional pressure drop; Air-Water; Two-phase frictional multiplier

Nomenclature

		Greek symbols	
		χ	vapor quality
		ε	vapor void fraction
d_i	tube internal diameter	ρ	density (kg m^{-3})
E	parameter of Friedel	Φ_{Lo}	two-phase multiplier for liquid
F	parameter of Friedel	μ	only
f	friction factor		dynamic viscosity (N s m^{-2})
g	acceleration due to gravity (m s^{-2})	**Dimensional number**	
H	factor of Friedel		
L	tube length (m)		
$\dot{m}_{total}$	total mass velocity of liquid plus vapor	Fr	Froude number
P	pressure (Pa)	Re	Reynolds number
Δp_{total}	total pressure drop (Pa)	We	Weber number
Δp_{static}	static head pressure drop (Pa)	**Subscripts**	
Δp_{mom}	two-phase momentum pressure drop (Pa)		
Δp_{frict}	two-phase frictional pressure drop (Pa)	h	homogeneous
Δp_G	vapor-phase pressure drop (Pa)	L	liquid
Δp_L	liquid-phase pressure drop (Pa	Lo	liquid only (all flow as liquid)

1. Introduction

Simultaneous flow of two or more immiscible phases is termed as multiphase flow. The common class of multiphase flow is two phase flow such as gas-liquid, gas-solid, liquid-liquid and solid-solid flows. Gas-liquid flow is complex because of the existence of deformable interfaces and the fact that one of the phases is compressible.

The pressure drop in fluid systems is one of the fundamental parameters of interest to design engineers, for this reason two-phase pressure drop has been the subject of extensive research spanning many decades. Starting in the 1940s, researchers were concerned with developing predictive pressure drop models and correlations for mostly traditional industries such as steam and nuclear power generation, chemical and petroleum, etc.

Prediction of two-phase pressure drop in compact heat exchanger, direct expansion evaporators, nuclear reactor, condensers and two-phase refrigerant transfer lines is important for accurate design and optimization of refrigeration, air-conditioning and heat pump systems. The pressure drop in two-phase (i.e., gas-liquid) flow can be dramatically higher than pure liquid flow at the same overall mass flux, easily one or two orders of magnitude higher. Two phase multipliers have been used to account for this and provide a simple means of estimating the relative increase in pressure drop due to the presence of the gas phase.

A number of correlations and analyses have been developed to predict the two-phase multipliers for a variety of two-phase flows. The simplest analysis is perhaps the homogeneous approximation, where both phases are assumed to flow with the same average velocity. This approximation may be useful at high mass flux or high pressure, where the slip ratio (gas velocity to liquid velocity) is expected to be low, but in general the homogeneous model will under predict the actual pressure drop in real systems. Martinelli and Nelson (1948) [1] and Lockhart and Martinelli (1949) [2] were early proponents of a separated flow model, where each phase is assumed to flow at different average velocities. They developed a correlation which performed well for different fluids at low mass flux, but did not allow for sensitivity to mass flux. Baroczy (1968) [3] captured the mass flux effects as well as the effect of fluid property by fitting a large set of data taken in different fluids and at different flow rates; however the graphical form of his correlation did not len itself to easy application. Chisholm (1973) [4] combined the results of Lockhart and Martinelli and Baroczy with a new analysis to obtain an analytical expression for pressure drop which is more convenient to use than the Baroczy plots. Friedel (1979) [5] correlations were obtained from air-water and steam-water systems.

Recently, there has been interest in understanding the pressure drop for refrigerant fluids, in particular for refrigerant systems where the coolant flows through small tubes or micro channels (Jung and Radermacher, 1989 [6]; Tran et al., 1996, 2000[7, 8]; Ould et al., 2002[9]; Garimella et al., 2003[10]).

The two-phase pressure drops for flows inside tubes are the sum of three contributions: the static pressure drop, the momentum pressure drop and the frictional pressure drop as:

$$\Delta P_{tot} = \Delta P_{static} + \Delta P_{mom} + \Delta P_{fric} \tag{1}$$

For a horizontal tube, $\Delta P_{static} = 0$ because of no change in static head, for calculating the ΔP_{fric} we have different correlations, two of them are famous. One is Friedel correlation and the other one is Lockhart and Martinelly correlation. Friedel correlation is not able to predict the pressure drop in low gas and liquid Reynolds numbers. Our aim in this paper is to propose a correlation being able to predict pressure drop in horizontal stratified two phase flow accurately.

Friedel correlation

This method is for vapor qualities from $0 \le x < 1$ and when the ratio of (μ_L/μ_G) is less than 1000:

$$\Delta P_{fric} = \Delta P_L \Phi^2{}_{L\circ} \tag{2}$$

Where Δp_L is calculated for the liquid-phase as:

$$\Delta P_L = 4 f_L \left(\frac{l}{D_i}\right) \dot{m}_{tot}^2 (1-x)^2 \left({}^{1}\!/\!{}_{2r_L} \right) \tag{3}$$

The liquid friction factor and liquid Reynolds number are obtained from

$$f=\frac{0.079}{\mathrm{Re}^{0.25}} \tag{4}$$

$$\mathrm{Re}=\frac{\dot{m}_{tot}d_i}{m} \tag{5}$$

Using the liquid dynamic viscosity m_L .Two-phase multiplier is correlated as:

$$\Phi^2_{L\circ}=E+\frac{3.24FH}{Fr_h^{0.045}We_L^{0.035}} \tag{6}$$

Where Fr_h, E, F and H are as follows:

$$Fr_h=\frac{\dot{m}^2_{tot}}{gD_i r^2_h} \tag{7}$$

$$E=(1-x)^2+x^2\left(\frac{r_L f_g}{r_g f_L}\right) \tag{8}$$

$$F=x^{0.78}(1-x)^{0.224} \tag{9}$$

$$H=\left(\frac{r_L}{r_g}\right)^{0.91}\left(\frac{m_g}{m_L}\right)^{0.19}\left(1-\frac{m_g}{m_L}\right)^{0.7} \tag{10}$$

The liquid Webber We_L is defined as:

$$We_L=\frac{\dot{m}^2_{tot}D_i}{s r_h} \tag{11}$$

And the homogeneous density r_h is used:

$$r_h=\left(\frac{x}{r_g}+\frac{(1-x)}{r_L}\right)^{-1} \tag{12}$$

Friedel’s method is typically that recommended when the ratio of ($\frac{m_L}{m_g}$) is less than 1000.

2. Apparatus

Experiments have been performed by an apparatus that its schematic view is represented in Figure 1. The test loop is composed of two vessels which are connected by a rectangular duct; the water leaving the duct is collected in vessel 2 and subsequently is pumped back into vessel 1. A globe valve was used to set the flow rate of water which was measured by a Rota meter. It also includes a fan and Pitot tube, an air fan was used for providing air flow and was connected to the duct with tubes and Pitot tube was used for measuring the velocity of air flow. A very sensitive pressure transducer was used for pressure measurements.

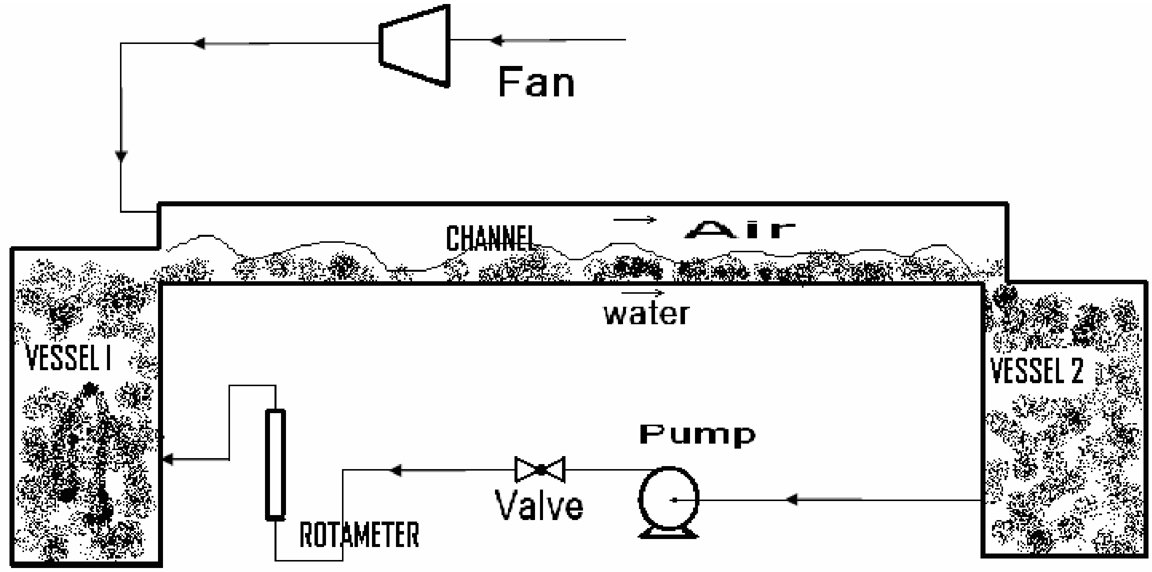


Figure1: Schematic of the test loop

3. Experiments

Pressure drop was measured for 3 different air flow rates and 4 different water flow rates, and 3 different water heights in channel and also 3pressure drop was measured in the dry duct(in fact this 3experiments show the pressure drop with out the effect of water). The total number of experiments was 48. At first when the duct was completely dry, the fan was turned on. The air velocity and pressure drop were measured by Pitot tube and pressure transducer, respectively. The pump was turned on then to flow water in the duct. After regulating the water height by moving the weir in desire level and waiting enough for becoming steady state, the air velocity and pressure drop were measured. The result of experiment is shown in table 1.

4. Results

In field of pressure drop determination, knowing the friction factor is so important because the main contribution of the pressure drop is frictional pressure drop. Friction factor is related to the Reynolds number and roughness of the surface. In air-water flow, roughness of the surface is related to the waves that are produced by flowing gas that moves over the liquid surface. So there must be relationship between flow rate of air and flow rate of water and wave amplitude and wave period, If air flow rate increases then the amplitude of the waves will increase (in other word there is direct relationship between wave amplitude and air flow rate). It is definitely clear that increase in amplitude and frequency of waves are equal to increase in roughness of the air-water surface. According to the above sentences if the roughness of surfaces increases, the friction factor increases and it means that the frictional pressure drop increases. Effect of wave amplitude increase on frictional pressure drop is shown in Figure 2 for 3 different liquid heights.

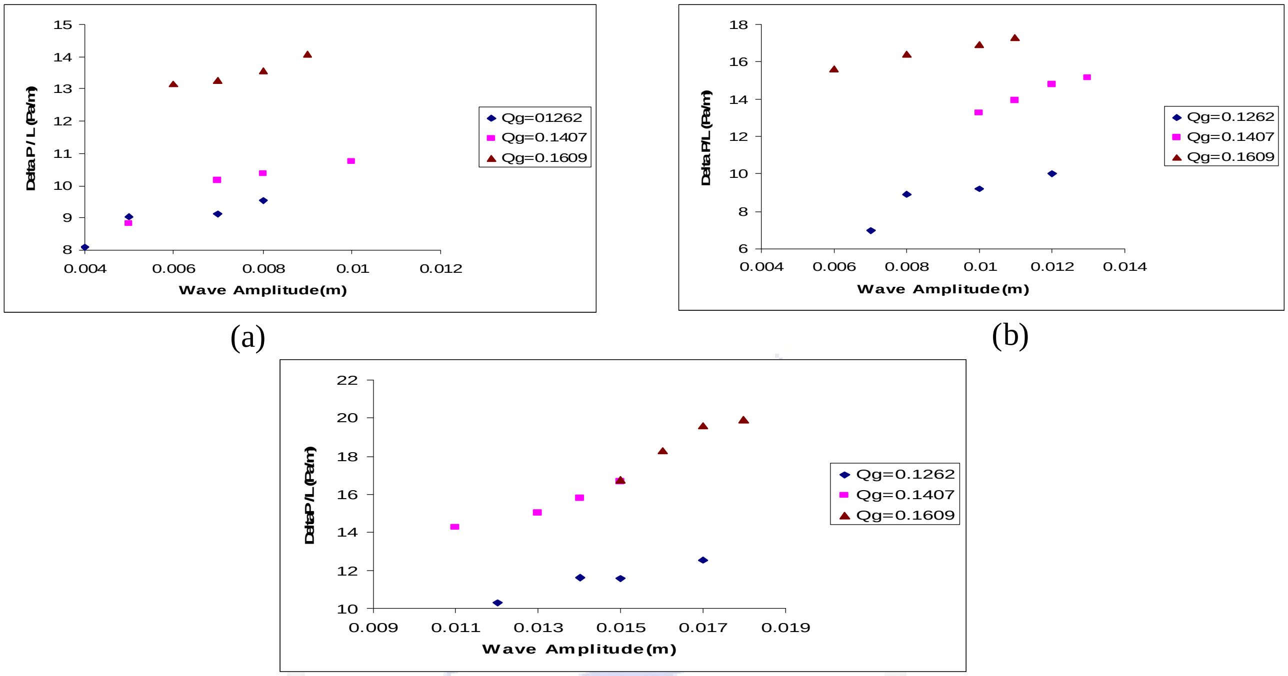
Table 1: Experiments' Results

Air Flow Rate(m^3/sec)	Water Height (cm)	Water Flow Rate(m^3/sec)	Pressure Drop in Channel (Pa)	Air Flow Rate(m^3/sec)	Water Height (cm)	Water Flow Rate(m^3/sec)	Pressure Drop in Channel (Pa)
0.1262	2	0	14.1	0.1407	2	0	14.15
		0.01136	16.2			0.01136	17.65
		0.01514	18.1			0.01514	20.35
		0.01893	18.25			0.01893	20.75
		0.02271	19.1			0.02271	21.5
	3	0	7.65		3	0	24.35
		0.01136	13.9			0.01136	26.5
		0.01514	17.75			0.01514	27.85
		0.01893	18.4			0.01893	29.55
		0.02271	20.05			0.02271	30.35
	4	0	19.6		4	0	25
		0.01136	20.6			0.01136	28.5
		0.01514	23.25			0.01514	30.05
		0.01893	23.15			0.01893	31.55
		0.02271	25.05			0.02271	33.3
0.1609	2	0	22.6				
		0.01136	26.35				
		0.01514	26.55	Pressure drop in dry duct			
		0.01893	27.15				
		0.02271	28.15				
	3	0	29.9				
		0.01136	31.25	0.1262	0	0	3.55
		0.01514	32.8				
		0.01893	33.85	0.1407	0	0	6.5
		0.02271	34.55				
	4	0	24.25	0.1609	0	0	9.25
		0.01136	33.5				
		0.01514	36.55				
		0.01893	39.25				
		0.02271	39.85				

At constant air flow rate and water height, the amount of water flow rate effects on pressure drop. Increasing of water flow rate in constant water height increases the pressure drop. The waves those are produced on the water surface are the main cause of this fact, because increase in water flow rate has same effect on the amplitude as air flow rate does, and both of them cause to increase of water amplitude and it is equal to increase in surface roughness.

Figure 3 shows the effect of increasing water flow rate on pressure drop. At constant flow rate of air and water, there is a direct relationship between variation of water height and pressure drop.

Increase in water height cause the increase of pressure drop, it also represents that pressure drop increases by increasing the water flow rate. These facts are correct for the other gas flow rates.

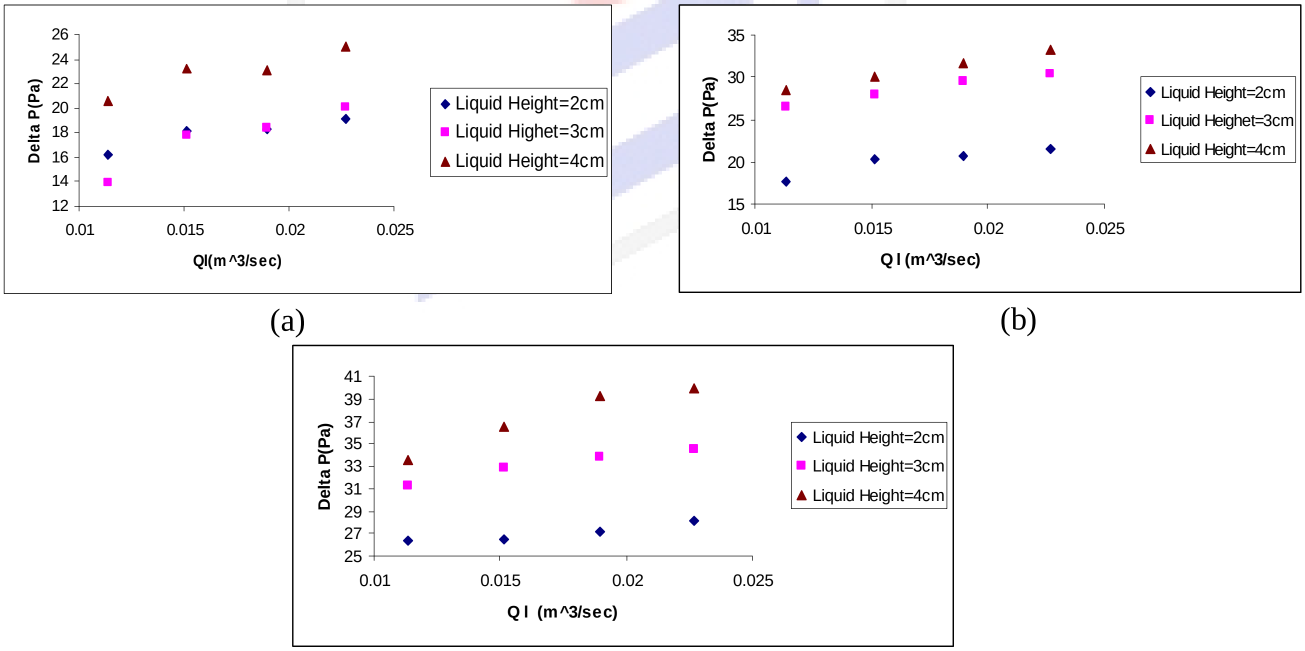


(a) (b)

(c)

Figure 2: Variation of experimental pressure drop with wave amplitude for 3 different liquid heights.

(a: Liquid Height=2 cm, b: liquid Height=3 cm, c: Liquid Height=4 cm)



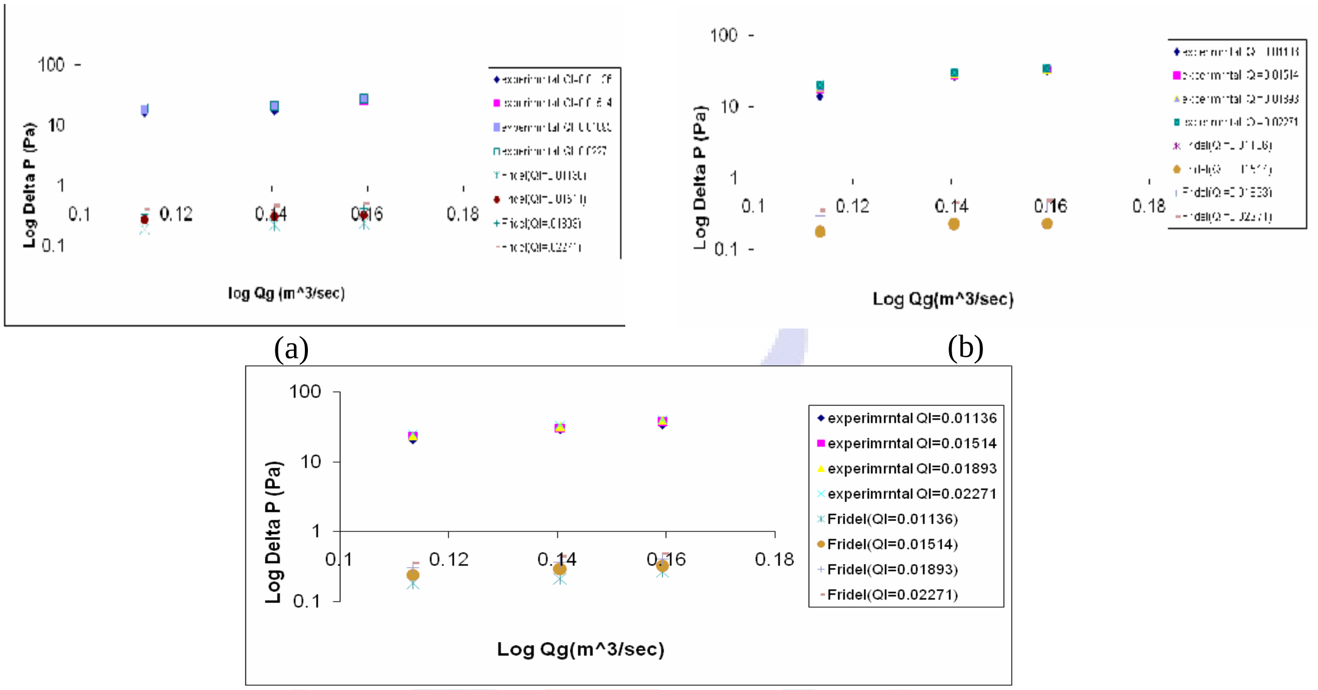
(a) (b)

(c)

Figure 3: Variation of experimental pressure drop with water flow rate (m^3/sec) for 3 different water heights.

(a: Qg=0.1262(m^3/sec), b: Qg=0.1407(m^3/sec), c: Qg=0.1609(m^3/sec))

Friedel correlation is popular for calculating frictional pressure drop in stratified two phase flow, this sentences does not mean that Friedel correlation always has a good precision for predicting the frictional pressure drop. Figure 4 represents that frictional pressure drops that are calculated by the Friedel correlation do not support experimental data.



(a) (b)

(c)

Figure 4: Comparison of Experimental data at different liquid heights with Fridel correlation results.
(a: Liquid Height=2cm, b: Liquid Height=3cm, c: Liquid Height=4cm)

Friedel correlation does not provide accurate predictions at low Reynolds numbers. Therefore, 48 experiments at low Reynolds numbers were performed to produce enough data to modify Friedel equation parameters .Two different assumptions were used to modify Friedel parameters:

1. In equation (6), constant number and powers of Fr_h and We_L were supposed to be unknown.
2. In equation (6), constant number and powers of Fr_h, We_L, F and H were supposed to be unknown.

48 experimental data at low Reynolds number and least square errors method were used to modify Friedel equation parameters and the results are represented below:

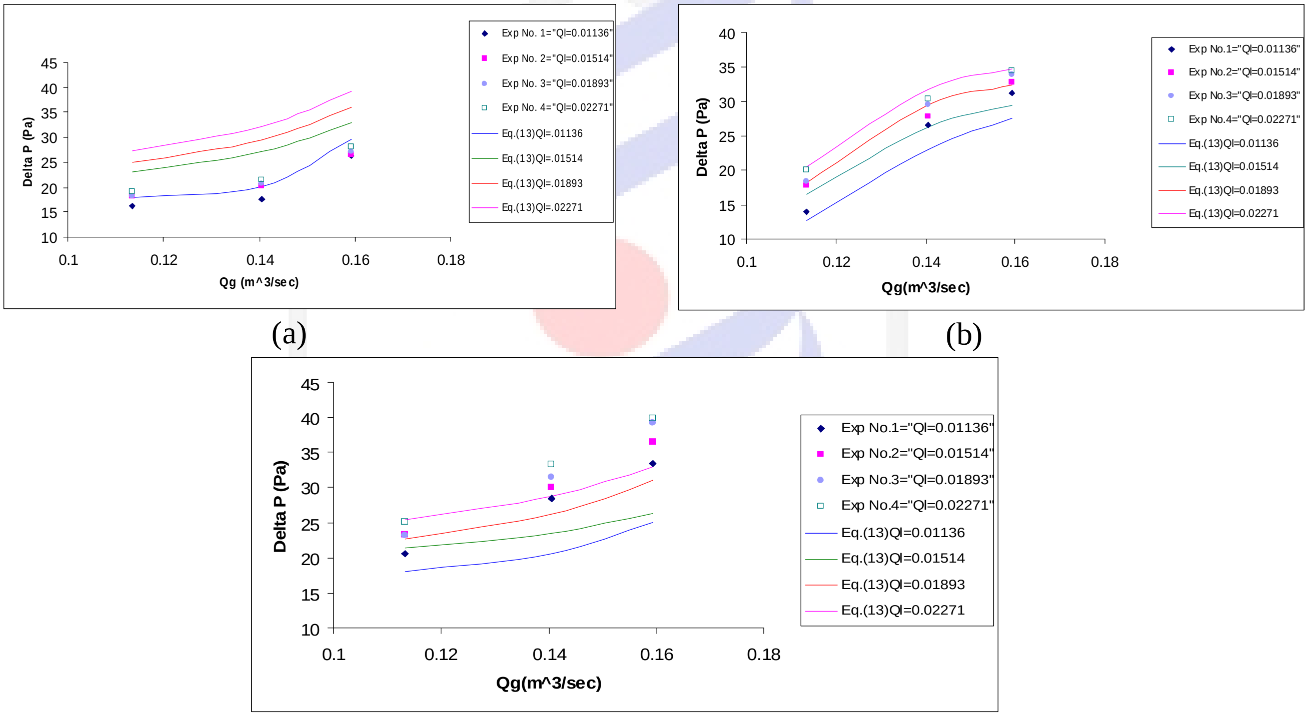
$$\Phi_{L\circ}^{2} = E + \frac{3.057 FHFr_h^{0.01314}}{We_L^{0.7412}} \tag{13}$$

$$\Phi_{L\circ}^{2} = E + \frac{9.86 * e^{-30} F^{2.067} H^{14.312} Fr_h^{0.4239}}{We_L^{0.0463}} \tag{14}$$

Both of these modified Friedel equations show good agreement with experimental data but equation (14) does not have physical meaning because $9.86 * e^{-30}$ is very small and also $H^{14.312}$ is a large number, so it is clear that the results make an incorrect equation, and as a result equation (14) is an useless equation. Predictions of the correlation (13) are compared with typical experimental data in Figure 5.

5. Conclusion

As Figure 5 shows pressure drop increases by increasing gas flow rate. The rate of increase decreases at greater gas Reynolds numbers. With due attention figure 4, represent that frictional pressure drops that are calculated by the Friedel correlation do not support experimental data in this range of gas and liquid Reynolds. Proposed correlation shows good agreement with experimental data. As the experimental data on table 1 represent, when the duct is dry, the pressure drop is less than the time that the flow of water exists in the duct, the reason of this events is related to the roughness and velocity of air. When water exists in the duct and air passes through it, the wave amplitude acts like extra roughness of the surface and increases pressure drop, but when the duct is dry the roughness of surface is related to the roughness of the surface that air is passing through it and this roughness is so smaller than the roughness that waves produce. The existence of water flow in the duct effects on the amount of air velocity, when the water flow exists in the duct, the air velocity is greater than the time that the duct is dry. Air velocity have direct influence on the pressure drop so if the air velocity increase, the pressure drop will increase too.



(a)

(b)

(c)

Figure 5: Comparison of Experimental data with correlations (13)
(a: Liquid Height=2cm, b: Liquid Height=3cm, c: Liquid Height=4cm)

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