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Performance of an Orifice Meter Handling Two-Phase (Gas-Liquid) Flow

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KEYWORDS:
Two-phase flow; Orifice plate; Flow pattern; Orifice correction factor.

***Abstract*— The two-phase flow rate measurements remain a challenging task due its complexity. There are many factors that affect on the measurement process such as the properties of the two phases and the dryness fraction. In the current study, the two-phase flow through three orifice plates with different beta ratios (orifice diameter to pipe inner diameter ratio) of 0.7, 0.63, and 0.5 installed in a horizontal acrylic pipe with an inside diameter of 60 mm has been experimentally investigated to improve the accuracy of the two-phase mass flow rate measurements. The inlet superficial velocities of liquid and gas phases are rated from 0.8 to 2.4 m/s and from 0.0 to 0.79 m/s, respectively. Also, the average gas volume fraction is rated from 0.0 to 61%. The pressure drop through the three orifice plate was measured and the flow patterns were tackled before and after the orifice plate.**

The effect of the two-phase flow on the orifice correction factor is studied at different liquid and gas mass flow rate values for the three orifice plates with different beta ratios. Also, a new correlation was introduced for the two-phase correction factor through the three orifice plates.

I. INTRODUCTION

THE two-phase flow through singularities such as orifices, nozzles and venture-meters is encountered in many engineering applications such as chemical and mining transportation processes to measure the two-phase flow rates. Most of engineering systems have flow rate metering instruments, which mainly are affected by the properties of the two phases and the void fraction values. So, better understandings of the two-phase flow through systems are required to enhance the flow rate measurement accuracy and performance. In the present study, the orifice meter was selected due to its wide use in most engineering applications. The orifice meter is simple in design and construction, and is a limited maintenance metering device.

Monni et al. [1] investigated experimentally the annular two-phase flow through a venturi flow meter in a vertical upward pipe (80 mm inner diameter). The experiments were performed at air void fraction values up to 0.97 to simulate nuclear accident cases. The value of the two-phase pressure drop between the venturi flow meter inlet section and throat section, and between inlet section and outlet section were dependent on the two-phase flow parameters (phase velocities, void fraction and dryness fraction). Also, new correlations were proposed to relate the flow rate as a function of the two-phase pressure drop.

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Another new flow rate correlation was proposed by Zhang et al. [2] for diesel fuel-air mixture with void fraction values ranging from 15% to 83% flowed through a venture-meter, which was based on the homogeneous flow model [3]. The effect of the velocity ratio between liquid and gas phases was added to the correlation. The proposed correlation could predict both mixture and liquid flow rates with knowing the void fraction and the pressure drop across the venturi. Four types of flow patterns (bubbly, slug, wave and annular flow patterns) were observed. Coefficients used in their correlation were variable and based on the type of the flow regime, which reduced the root-mean-square errors.

Furthermore, Steven [4] investigated experimentally gas-liquid two-phase flow (with quality up to 50%) metering through horizontal venture-meter of 0.55 beta ratio. He presented some correlations for the discharge through orifice and venture-meter and compared their performance with other data. He proposed a new correlation which was limited with the flow rates and pressure conditions.

Hasan et al. [5] studied experimentally and numerically the bubbly water-gas two-phase flow through differential pressure venture-meter. The bubbly flow was assumed to be homogenous in which the slip ratio is unity. It was deduced, from the experimental results, that the homogenous model starts to lose its accuracy when the gas volume fraction increases beyond 17.48%, also the values of the drag coefficient (C_d) became unpredictable and the error increased to about 30%. They attributed it to the transition between slug and bubbly flow regimes.

Oliveira et al. [6] measured the air-water mass flow rate using a venturi and an orifice plate meter. The pipe inner diameter was 21 mm and the orifice beta ratio (β) was 0.5. The water flow rates were up to 4000 kg/h, air flow rate up to 50 kg/h and the void fraction ranging from 2% to 85%. Their results pointed out that the flow direction had no considerable effect on the flow meters in relation to the pressure drop in their experimental operating conditions.

Moreover, an experimental investigation for the steam-water mixture flow through standard sharp-edged orifices for the prediction of two-phase flow characteristics was presented by James [7]. The range of values of the dryness fraction in the experimental runs was from 1% to 56%. He investigated a correlation factor for a corrected dryness fraction for evaluating the density of two-phase used in the conventional single-phase orifice meter equation.

Alimonti et al. [8] investigated the characteristics of the two-phase flow through multiple orifice valves. Experiments were done using multiple orifice valves with three different sets of discs. Adjustments to two-phase multiplier equation constants were done for pipe flow to fit the experimental data. Furthermore, the computed frictional pressure drop was compared with that calculated using the modified two-phase multiplier equation and the experimental pressure drop, and a good agreement was obtained.

As it is clear from the above discussion, many previous studies concerned with the two-phase flow through venture-meters and orifice plates, but, to best author's knowledge, the effect of the orifice beta ratio on the two-phase flow characteristics has not been studied well. So, the aim of the present study is to investigate the behavior of the two-phase flow characteristics through three different sizes orifice plates. A new correction factor correlation (K_L), that is consistent with the present experimental data, will be deduced to increase the accuracy of the two-phase flow measurements.

II. THEORETICAL BACKGROUND

The flow obstruction methods (orifice, venture-meter and nozzle) are operating on the principal of creating a differential pressure drop by introducing a constriction in the duct. The created differential pressure is proportional to the fluid flow rate.

The mass flow rate for a single-phase flow rate through an orifice meter can be determined from the following equation;

$$\dot{m} = \frac{C_d}{\sqrt{1-\beta^4}} Y \varepsilon \frac{\pi}{4} d^2 \sqrt{2\Delta P \rho} \qquad (1)$$

where C_d, β, Y, ε, d, ΔP and ρ are the discharge coefficient, the ratio of the orifice diameter to the duct inner diameter, the compressibility, the thermal expansion, the internal orifice diameter, the differential pressure drop and the fluid density, respectively.

In the present study, the compressibility and thermal expansion are neglected. So, the value of the compressibility (Y) and thermal expansion factor (ε) are one.

In the case of the two-phase flow, a new correction factor (K_L) is introduced to the previous equation to calculate the two-phase mass flow rate;

$$\dot{m}_{(TP)} = \frac{C_d}{\sqrt{1-\beta^4}} \frac{\pi}{4} d^2 K_L \sqrt{2\Delta P \rho} \qquad (2)$$

The value of the correction factor (K_L) is dependent on the dryness fraction (x), the void fraction (α) and the two fluids properties. Various correlations were developed to investigate the value of the factor K_L.

Based on the homogenous model, which assumes that the two-phase flow with the same velocity (no slip velocity between the two phases), K_L can be calculated according to the following equation, [6];

$$K_L = \sqrt{\frac{1}{x\left(\frac{\rho_L}{\rho_G} - 1\right) + 1}} \qquad (3)$$

Furthermore, other correlation was deduced by Chisholm [9];

$$K_L = \left(\frac{1}{1-x}\right)\left[1 + \left(\frac{\frac{1}{S}\sqrt{\frac{\rho_L}{\rho_G}} + S\sqrt{\frac{\rho_G}{\rho_L}}}{\left(\frac{1-x}{x}\right)\sqrt{\frac{\rho_G}{\rho_L}}}\right) + \left(\frac{1}{\left(\frac{1-x}{x}\right)^2 \frac{\rho_G}{\rho_L}}\right)\right]^{-0.5} \qquad (4)$$

where S is the slip ratio (the ratio between the gas phase velocity and the liquid phase velocity).

Zhang et al. [10] proposed a correlation to investigate the value of the correction factor (K_L) at low dryness fraction values (x < 1%) for air-water two-phase flow through an orifice plate;

$$K_L = \left\{\left[x^{\left(1.25+0.25x^{1/3}\right)}\right]\left(\frac{\rho_L}{\rho_G}-1\right)+1\right\}^{-0.5} \qquad (5)$$

III. EXPERIMENTAL TEST SYSTEM

A. Flow system description

The experimental test facility shown in schematic Fig. 1, which was firstly used in Mansour et al. [11], was used in the present work. The test section extended up to 66D length at which different beta ratio orifice plates were installed at its middle section with the same 60 mm inner diameter acrylic pipe (Fig. 2). These sharp edged orifice plates were constructed according to ISO 5167 [12]. The present test facility is capable to generate different two-phase flow patterns (plug, slug, bubbly, stratified, wavy, and annular flows). The dry air flow rate was measured by utilizing a rotameter (±2% accuracy). It was mixed with a main water stream through two inlets placed at the wall of the mixing section. The two inlets located at the same horizontal plane as shown in Fig. 2(a). Water was circulated from a 1000-liter storage tank, which was opened to atmosphere through a straight pipe and mixing section using a centrifugal pump with a 2-kW power (Type COM500/15/A). The flow rate of water was measured using a turbine flow meter (Type FT-40C1U3-LEA-3) with ±0.25% accuracy. The differential pressure across the orifice plate was determined using mercury-water U-tube manometer, Fig. 2(b). Mercury of specific gravity (S.G) of 13.6 was used as the working fluid of the manometer.

A T6i Canon camera with the Sumire Prime CN-E50mm T1.3 FP X lens, which has a focal length of 50 mm, was used to record and capture the gas-liquid flow patterns at different flow conditions upstream and downstream of the orifice plate. The camera gives 1080p @ 30 fps and 1/4000 to 30 sec shutter speeds.

B. Test procedure

Firstly, the liquid phase only circulates across the bypass loop. The control valve is then opened cautiously to let the liquid phase to flow in the test section. The desired liquid flow rate is regulated by both control and bypass valves. The water flow rate is measured by utilizing the turbine flow meter. The air flow rate is monitored and measured by utilizing a rotameter and regulated at the desired flow rate by the air pressure regulator.

The air flow is directed to the mixing section through hoses and the two-phase flow is achieved with the required liquid and gas flow rates. The differential pressure across the orifice plate is measured using a mercury-water U-tube manometer to calculate the mixture flow rate.

Images and videos are captured using a digital camera to record the various flow patterns. For different cases of the two-phase flow, the above procedure has to be repeated with changing both the air and water mass flow rates. The uncertainties of water and air flow rate meters are 0.2% and 1.0%, respectively. Other uncertainties of the different parameters are estimated and listed in Table 1.

TABLE 1
UNCERTAINTY PARAMETERS

Parameter	**Uncertainty value**
Differential pressure mercury U-tube manometer	2.5%
Two-phase correction factor (K_L)	2.7%

IV. RESULTS AND DISCUSSION

The two-phase flow characteristics through three orifice plates with different beta ratios of 0.5, 0.63, and 0.7 were studied experimentally at liquid Reynolds number range from 5.4E+4 to 9.6E+4 and at gas Reynolds number range from 0 to 9.8E+3. The two-phase flow patterns were captured upstream and downstream the orifice plate to show the effects of singularities on it at different gas volume fraction values. Also, the pressure drop across the orifice plate was measured to estimate the two-phase mass flow rate. Finally, the two-phase correction factor, K_L, at different air volume fraction values was investigated.

A. Flow patterns

In the current study, different flow patterns were depicted experimentally at different inlet flow conditions. Bubbly, slug, plug and core flow patterns were observed upstream the orifice plate while only bubbly-slug flow pattern was observed downstream as illustrated in Fig. 3. The flow patterns were recorded after the flow reached the fully developed region for both upstream and downstream cases. In the fully developed region, the air was fully immigrated to the upper wall due to the buoyancy effect. It is clear from the figure that the air slugs collapsed after the orifice plate. At the orifice hole, the two phases flowed with a high mixing momentum exchange between them due to the orifice plate geometry, which sharply forces the air to move from the upper wall to flow through the orifice in the pipe center. The two-phase flow was mostly homogenous and continued homogenous at the pipe core due to the inertia, which was acquired previously. At a distance of 25D for most small air volume fraction cases, the air phase tends to move again to the upper wall of the pipe to transform into bubbly-slug flow as shown in Fig. 3.

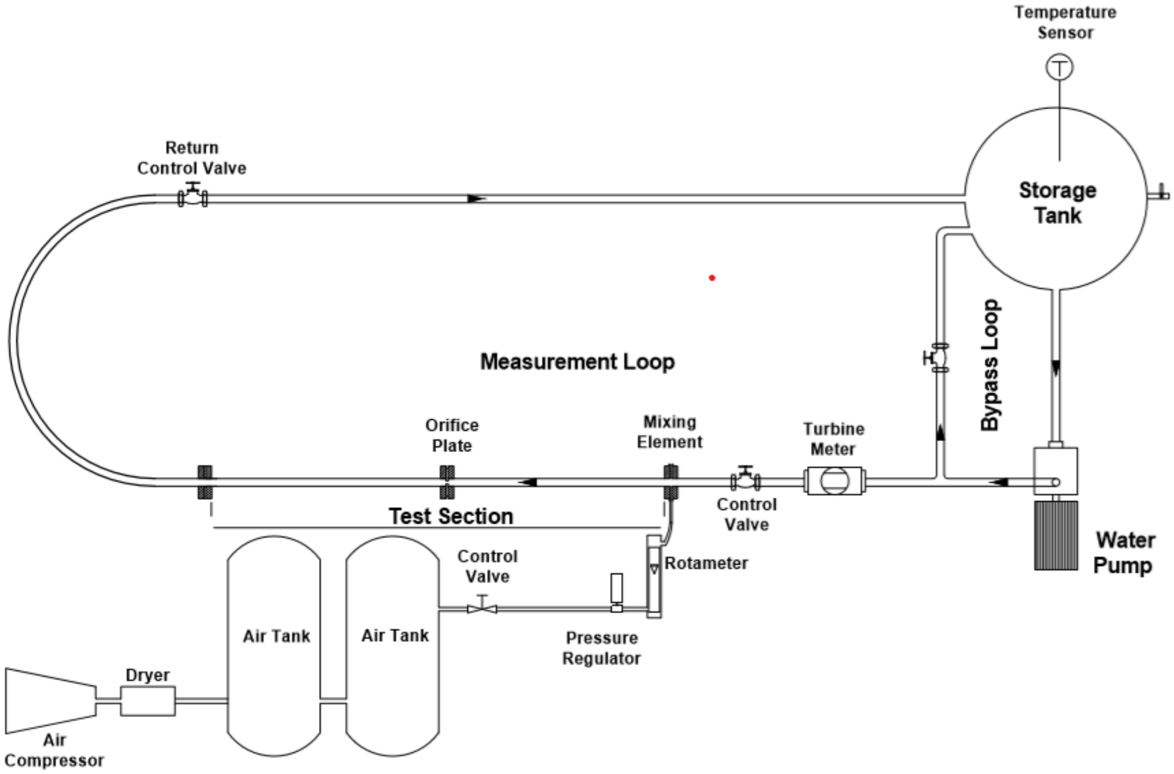
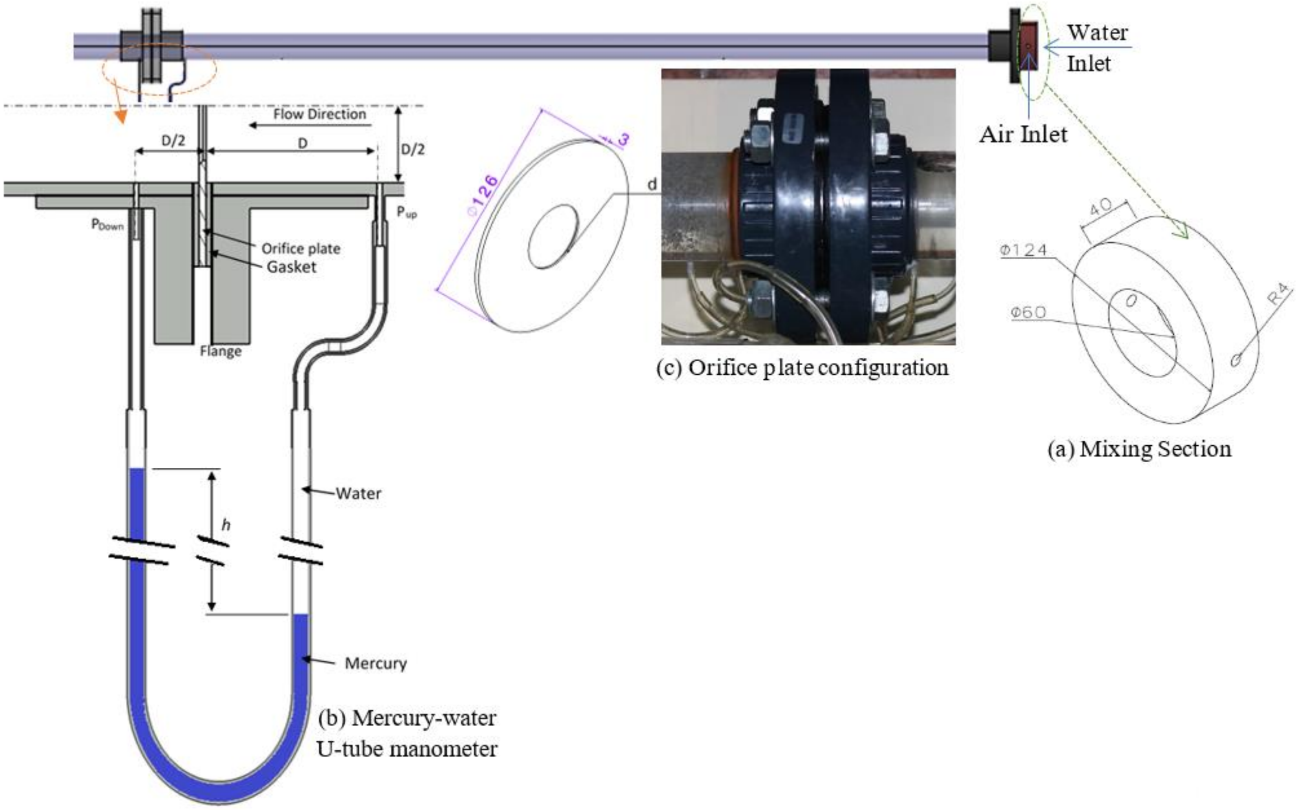


Fig. 1. Experimental test rig.



(b) Mercury-water U-tube manometer

(c) Orifice plate configuration

(a) Mixing Section

Fig. 2. Test section.

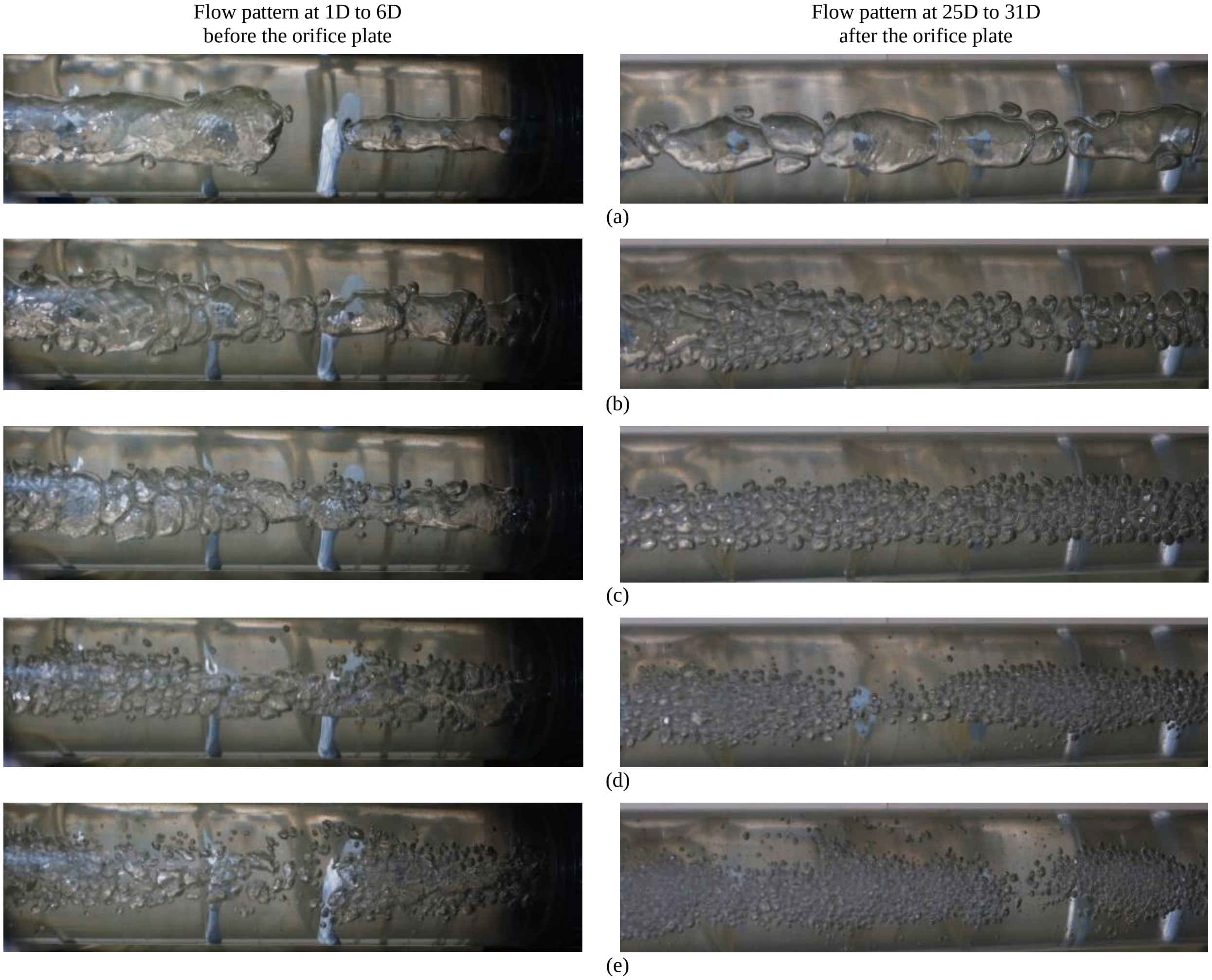


Fig. 3. Plane view of flow pattern before and after orifice plate with 0.7 beta ratio at fixed air superficial velocity of J_G = 0.039 m/s and different water superficial water velocity J_L cases: (a) J_L = 0.897 m/s, (b) J_L = 1.215 m/s, (c) J_L = 1.351 m/s, (d) J_L = 1.604 m/s, (e) J_L = 1.893 m/s.

B. *Two-phase pressure drop across the orifice plate*

The value of the gas volume fraction has a great effect on the two-phase pressure drop through the orifice plate. The pressure drop of the two-phase flow was measured experimentally across three different orifice plates with beta ratios of 0.5, 0.636, and 0.7 and gas volume fraction values up to 50% to study the effects of both beta ratio and the gas volume fraction. Each orifice plate was inserted between two PVC flanges with guiding of four screw drivers as illustrated in Figure 2(c). A transparent hoses with 2 mm inside diameter was inserted up to the main pipe inner surface at axial distance D upstream the orifice plate and at D/2 axial distance downstream the orifice plate to measure the differential pressure through the orifice plate as shown in Figure 2(c).

The pressure drop across the three orifice plates were measured using a mercury manometer. The average value of the height of the manometer was synchronized with the two-phase initially preset flow rates. At high liquid mass flow rates, the gas volume fraction could not be increased more than 19% in order to get stable reading values of the manometer head. Figures 4-6 show the variation of the pressure drop through the three orifice plates with the gas flow rate at different liquid mass flow rate values. For the orifice plates with beta ratios of 0.5 and 0.636, the pressure drop decreased with increasing the gas mass flow rate or decreasing the liquid mass flow rate.

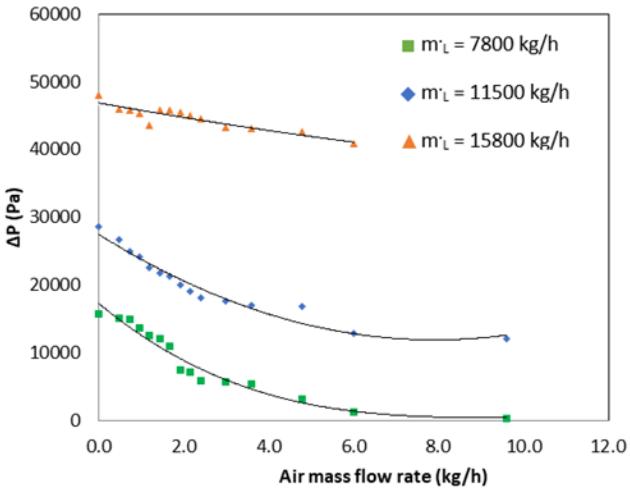


Fig. 4. Pressure drop across orifice plate with β = 0.5 against air mass flow rate at different liquid mass flow rates.

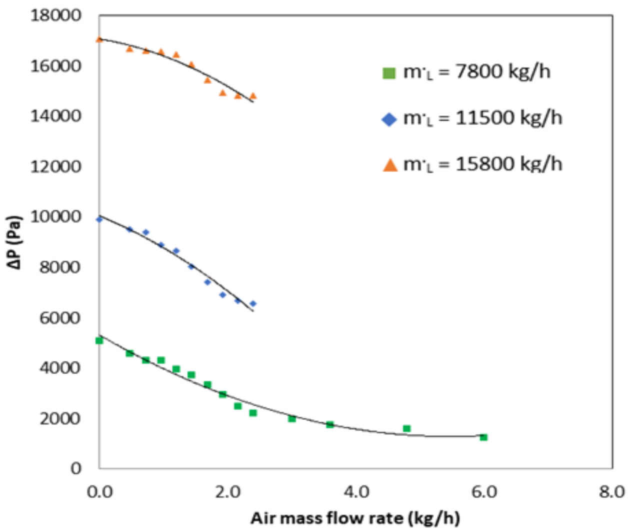


Fig. 5. Pressure drop across orifice plate with β = 0.636 against air mass flow rate at different liquid mass flow rates.

On the other hand, for the orifice plate with beta ratio of 0.7, the pressure drop through the orifice plate increases slightly or remains approximately constant with increasing the gas mass flow rate due to the high beta ratio for that orifice plate as in Fig. 6.

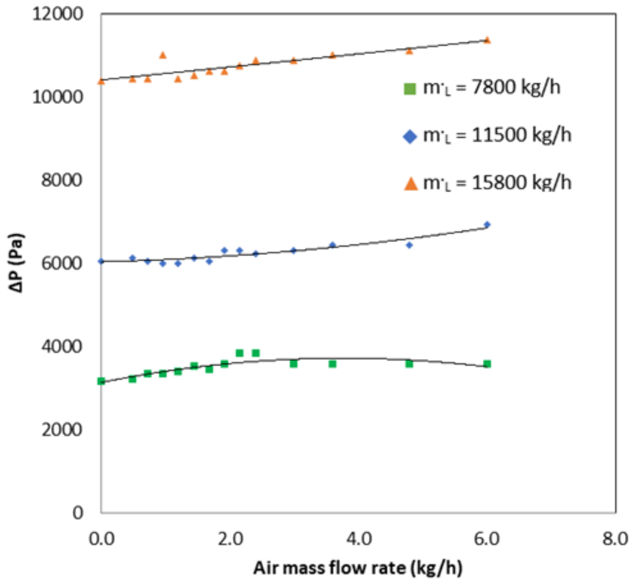


Fig. 6. Pressure drop across orifice plate with β = 0.7 against air mass flow rate at different liquid mass flow rates.

To study the effect of the orifice beta ratio on the two-phase pressure drop behavior, the three different orifices were tested at different gas and liquid mass flow rates as illustrated in Fig. 7(a, b and c). The pressure drop behavior is quite similar across the two orifice plates with the smallest beta ratio values where the pressure drop decreases sharply at low air mass flow rate values and the decreasing rate reduced at higher gas mass flow rate values.

Figure 8 summarizes all the above cases, where the pressure drop across orifice plate is plotted against the gas and liquid mass flow rates for the three orifice plates in a three-dimensional graph.

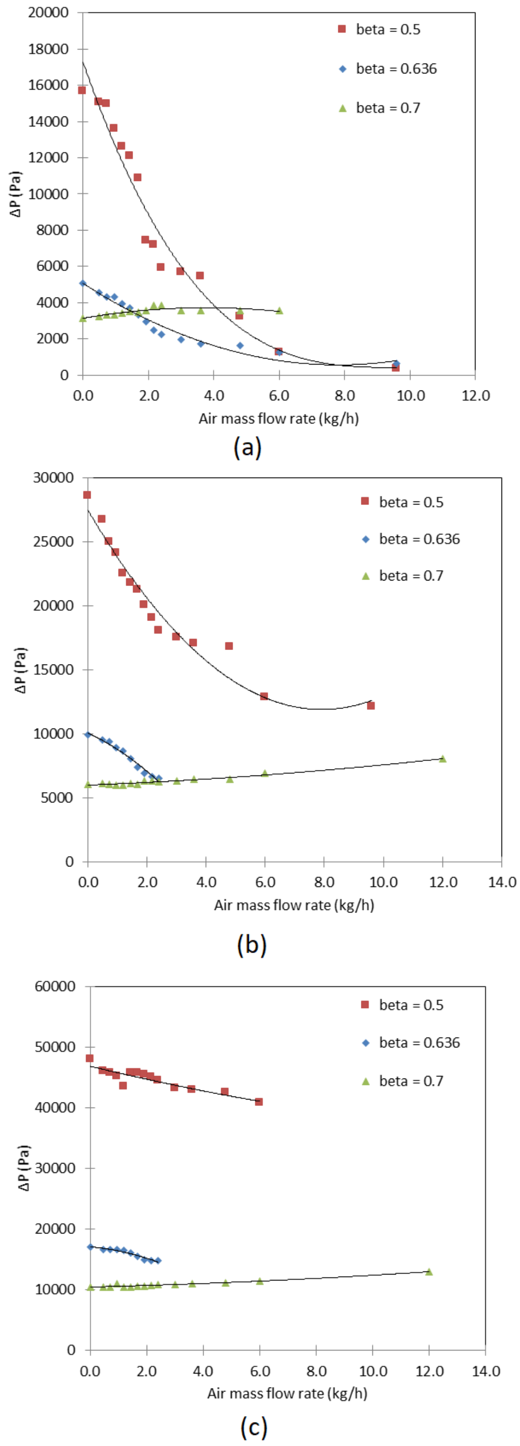


Fig. 7. Pressure drop across orifice plate with β = 0.5, 0.636, and 0.7 against air mass flow rate at different liquid mass flow rates cases:
(a) $\dot{m}_L$= 7800 kg/h, (b) $\dot{m}_L$ = 11500 kg/h, (c) $\dot{m}_L$ = 15800 kg/h.

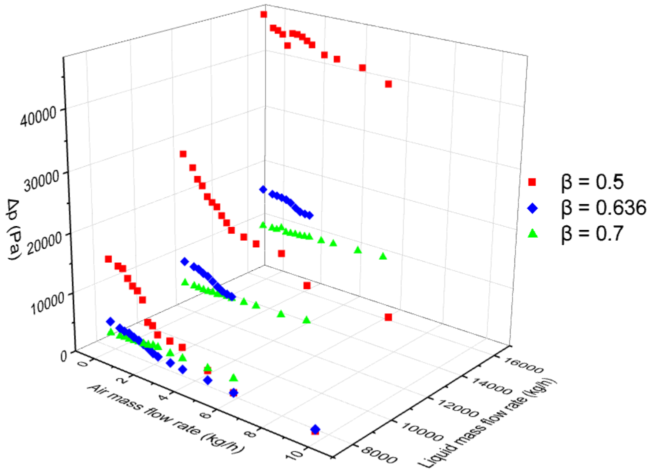


Fig. 8. Pressure drop across orifice plate against air mass flow rate and liquid mass flow rates for different beta ratio orifice plates.

C. Two-phase correction factor

For the two-phase flow, a parameter (K_L) has been introduced into the mass flow rate equation (Eq. (2)). As discussed before, some suggested correlations have been proposed to investigate the behavior of the parameter K_L for different cases. The parameter K_L was calculated from the present experimental results and compared with that calculated by the homogenous flow model, Chisholm correlation [9] and Zhang et al. [10] correlations for the three orifice plates at different gas and liquid mass flow rates to investigate both the effect of air volume fraction variation and beta ratio on these correlations.

Figure 9(a, b and c) shows the variation of parameter K_L for the two-phase flow through the orifice plate with beta ratio of 0.5. At a liquid flow rate of 7800 kg/h (relatively low liquid flow rate), the models results agree with the present experimental data until air volume fraction of 15%. Most of these models were investigated for the two-phase flow with low dryness fraction values. So, the differences between the present data and the results of these models increased for air volume fraction values more than 15% as shown in Fig. 9 (a). At high air volume fraction values, the flow pattern at the orifice entrance was slug, which produced pulses to the differential pressure through the relatively small orifice beta ratio of 0.5.

Furthermore, at a liquid flow rate of 11500 kg/h (moderate liquid flow rate), the behavior of the experimental K_L parameter is relatively close to that obtained by Zhang et al. [10] as depicted in Figure 9(b). At high liquid mass flow rate, the two-phase flow pattern was bubbly and the behavior of the experimental K_L parameter is approximately the same as that deduced from Zhang et al. [10] model as shown in Figure 9(c).

The experimental K_L parameter for the orifice plate with $\beta = 0.636$ at relatively low liquid mass flow rate has mostly the same behavior as that investigated for the orifice plate with $\beta = 0.5$ as shown in Figure 10 (a, b, c). On the contrary, for other moderate and higher mass liquid flow rate, the experimental K_L parameter is located in between of homogenous model, Chisholm correlation [9] and Zhang et al. [10] correlations as illustrated in Fig. 10(b, c).

For orifice plate with larger beta ratio of 0.7 with pulsation in two-phase flow through the orifice bore, the experimental K_L parameter values is located between the homogenous model, Chisholm correlation [9] and Zhang et al. [10] correlations as shown in Figure 11(a, b, c) for all liquid mass flow rates.

D. **New K_L correlation**

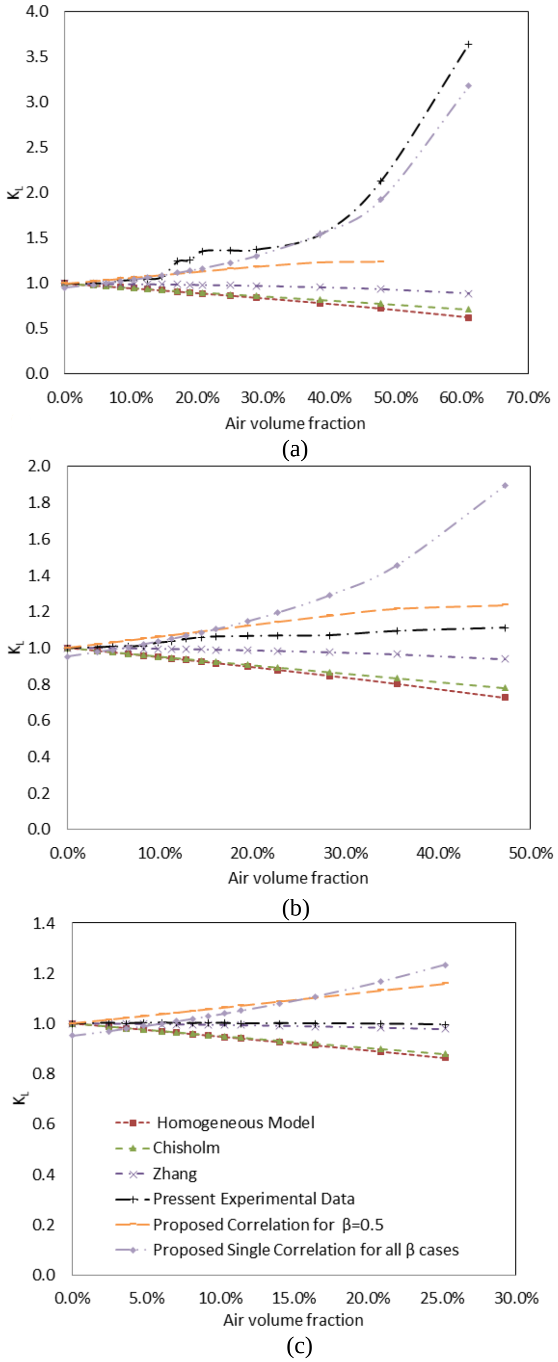
All experimental data of 121 sample cases, which are shown in Figs. 9-11, were used as one data set to establish a single relation depending on regression models to predict the K_L parameter as a function of beta ratio, dryness fraction, and the two-phase density ratio using the Data Fit software package as illustrated in equation (6) in Table 2. The deduced correlation failed to predict the value of K_L correctly as the relative error between the data of that correlation and the experimental data reached 42%. As shown in Figs. 9-11, the behavior of the parameter K_L is different for the three different plates. K_L increases with increasing the gas volume fraction for the orifice plates with beta ratio 0.5 and 0.636 while it decreases with increasing the gas volume fraction for the orifice with beta ratio of 0.7.

Therefore, the data for each orifice plate were used to deduce a separate relation for each orifice to increase the accuracy of K_L prediction. The relation in that case is only a function of dryness fraction and two-phase density ratio as in equations (7-9) in Table 2. The error is calculated with the following equation:

$$Error = \frac{K_{L(Correlation)} - K_{L\,(Experimental)}}{K_{L(Experimental)}}$$

TABLE 2
PROPOSED K_L CORRELATIONS

Case	Equation	Sample size	Min. to max. error
One equation model	$K_L = e^{(a\beta + bx + c\frac{\rho_L}{\rho_G} + d)}$ (6) *where:* *a = -0.437299909* *b = 640.3644511* *c = 1201653531* *d = -9.99E+11*	121	-14% to 42%
$\beta = 0.5$	$K_L = -311.8(\frac{\rho_L}{\rho_G})x^2 + 499.3x + 1$ (7)	42	-20% to 16%
$\beta = 0.636$	$K_L = 637(\frac{\rho_L}{\rho_G})x^2 + 200.15x + 1$ (8)	35	-10% to 10%
$\beta = 0.7$	$K_L = 192.6(\frac{\rho_L}{\rho_G})x^2 - 201.77x + 1$ (9)	42	-3% to 6%

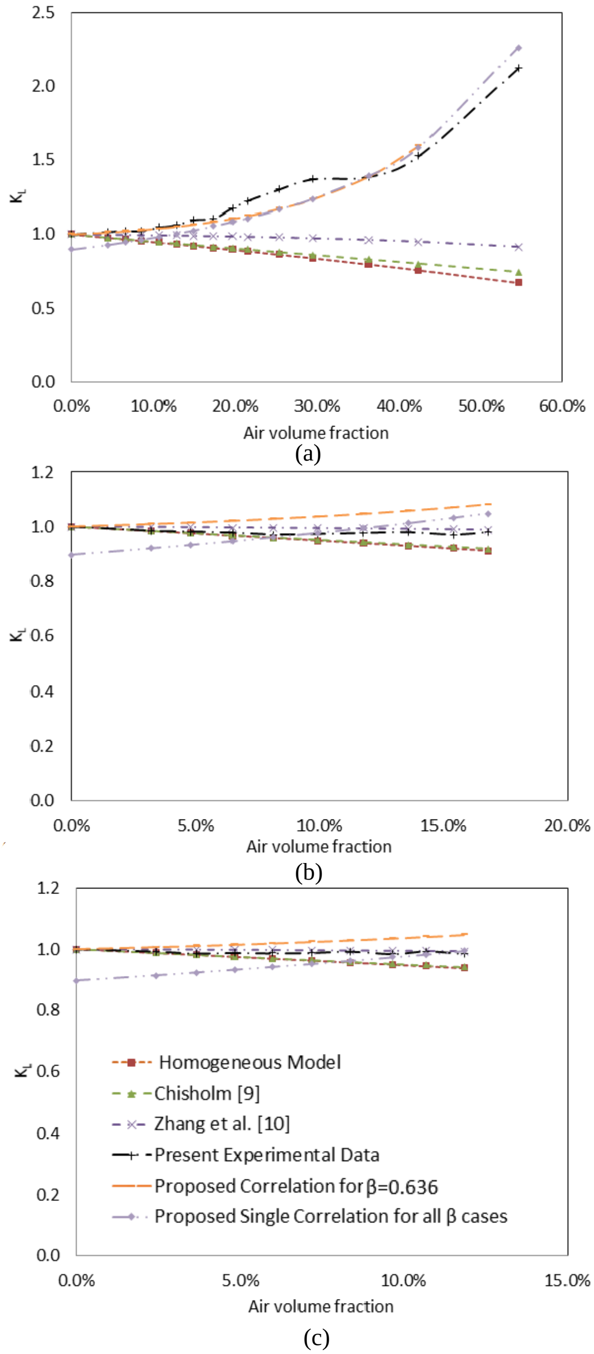


(a)

(b)

(c)

Fig. 9. Correction factor, K_L, versus air volume fraction for orifice with β = 0.5 at different liquid mass flow rates: (a) $\dot{m}_L$ = 7800 kg/h, (b) $\dot{m}_L$ = 11500 kg/h, (c) $\dot{m}_L$ = 15800 kg/h.

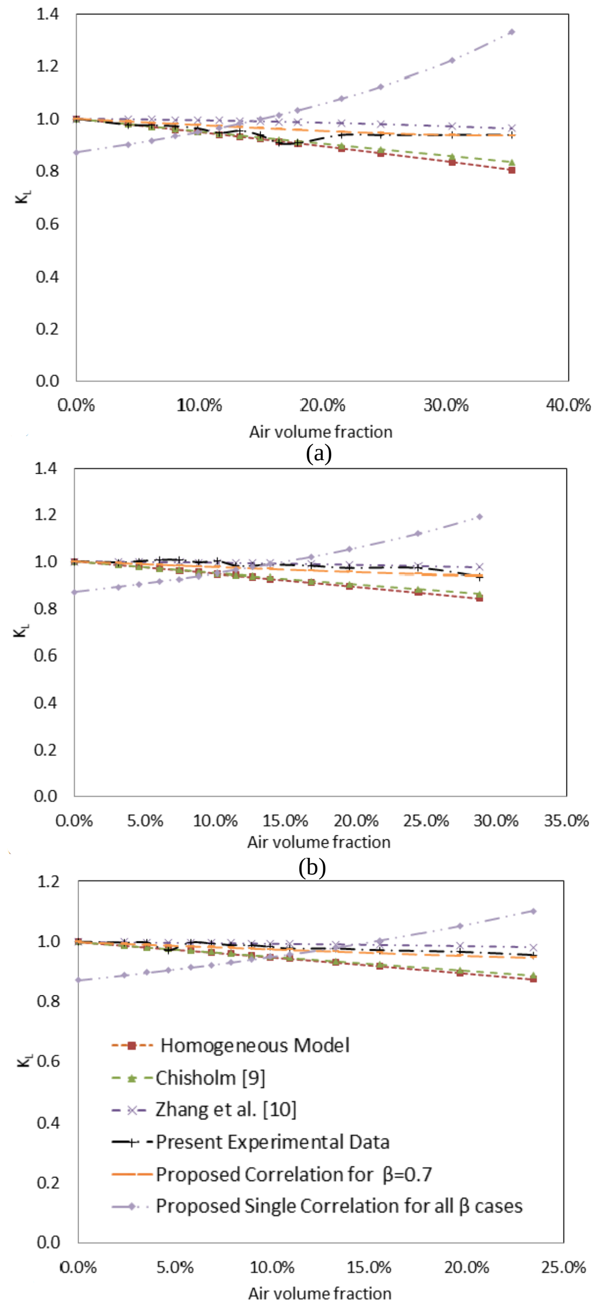


(a)

(b)

(c)

Fig. 10. Correction factor, K_L, versus air volume fraction for orifice with β = 0.636 at different liquid mass flow rates: (a) $\dot{m}_L$ = 7800 kg/h, (b) $\dot{m}_L$ = 11500 kg/h, (c) $\dot{m}_L$ = 15800 kg/h.



(c)

Fig. 11. Correction factor, K_L, versus air volume fraction for orifice with β = 0.7 at different liquid mass flow rates: (a) $\dot{m}_L$ = 7800 kg/h, (b) $\dot{m}_L$ = 11500 kg/h, (c) $\dot{m}_L$ = 15800 kg/h.

V. CONCLUSIONS

The hydrodynamic characteristics of air-water two-phase flow through three orifice plates with different beta ratios inserted in acrylic round horizontal pipe with 60 mm inner diameter were investigated experimentally. Based on the results acquired from the experimental investigations, the next conclusions can be obtained:

- Flow patterns at the inlet and outlet of the orifice plate were observed at different flow conditions. The air slugs collapsed after the orifice hole and slug flow pattern converted to smaller slug or bubbly flow pattern.
- The effect of orifice beta ratio on the two-phase pressure drop across the orifice was examined and it is found that the behavior is different for the orifice with large beta ratio.
- New correlations were proposed to predict the K_L parameter to predict the two-phase flow measurement more accurate predictions of two-phase flow measurement through different orifice plate. It is found that the error increased when using a single K_L correlation for the different beta ratio size orifices to reach to 42%.
- The experimental results presented in the current work improve the present knowledge and realization of gas-liquid two-phase flow through orifice plates. The present experimental data can be used to optimize the performance of existing orifice plate metering systems and to improve the design of new installations.

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NOMENCLATURE

C_d	Orifice discharge coefficient, [-]
d	Orifice diameter, [m]
D	Diameter, [m]
g	Acceleration of gravity, [m/s^2]
J	Superficial velocity, [m/s]
K_L	Two-phase correction factor
$\dot{m}_L$	Liquid mass flow rate, [-]
n	Coefficient - Zhang et al. [2]
P	Pressure, [Pa]
Re	Reynolds number, [-]
x	Dryness fraction
Y	Compressibility, [-]
Greek symbols	
ΔP	Differential pressure across the orifice plate, [Pa]
ε	Expansibility factor, [-]
μ	Dynamic viscosity, [Pa.s]
ρ	Density of the fluid at all points in the fluid, [kg/m^3]
Subscripts	
G	Gas phase
L	Liquid phase
TP	Two-phase

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Title Arabic:
أداء قرص ذو فوهة يتعامل مع سريان ثنائي الطور (غاز - سائل)

Arabic Abstract:

قياسات معدل التدفق ثنائي الطور (غاز - سائل) ذات أهمية خاصة في العديد من التطبيقات الهندسية رغم صعوبتها و تعقيدها. هناك العديد من العوامل التي تؤثر على عملية القياس مثل خصائص الطورين و نسبة الجفاف. في هذا البحث ، تم دراسة التدفق ثنائي الطور عملياً خلال ثلاث أقراص فوهية بنسب بيتا مختلفة (نسبة قطر فتحة القرص إلى قطر الأنبوب) هي 0.5 و 0.63 و 0.7 مثبتة في أنبوب أفقي دائري مصنوع من الأكريليك بقطر داخلي 60 مم و ذلك لتحسين دقة قياس معدل التدفق الكتلي ثنائي الطور. تتراوح مدى السرعات السطحية المستخدمة في هذه الدراسة للغاز والسائل من 0.8 إلى 2.4 م/ث ومن 0.0 إلى 0.79 م/ث على التوالي ، ويتفاوت متوسط نسبة حجم سريان الغاز إلى حجم السريان الكلي للسريان ثنائي الطور من 0.0 إلى 61٪. تم قياس انخفاض الضغط خلال الأقراص الفوهية الثلاثة ، كما تم تتبع أنماط التدفق قبل وبعد القرص الفوهي. تمت دراسة تأثير التدفق ثنائي الطور على معامل تصحيح الفوهة عند قيم مختلفة للسريان الكتلي للسائل والغاز خلال الأقراص الفوهية الثلاثة ذات نسب بيتا المختلفة. أيضاً ، تم اقتراح ارتباط جديد لمعامل التصحيح للسريان ثنائي الطور خلال نفس الأقراص الفوهية.