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Two-phase flow pressure change subject to sudden contraction in small rectangular channels

Ing Youn Chen [a,*], Chih-Yung Tseng [a], Yur-Tsai Lin [b], Chi-Chuan Wang [c]

[a] *Mechanical Engineering Department, National Yunlin University of Science and Technology, Yunlin 640, Taiwan*
[b] *Mechanical Engineering Department, Yuan-Ze University, Taoyuan 320, Taiwan*
[c] *Energy and Environment Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan*

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ABSTRACT

This study investigates the pressure change and flow pattern subject to the influence of sudden contractions. The air and water mixture flows from small rectangular channels (2 × 4, 2 × 6, 4 × 4 and 4 × 6 mm, respectively) into a 2 mm diameter tube. The total mass flux (G) ranges from 100 to 700 kg/m^2 s with gas quality (x) being varied from 0.001 to 0.8. In general the contraction pressure change increases with the rise of mass flux, and gas quality but an unique deflection of contraction pressure change pertaining to liquid vena contracta at a very low gas quality is encountered at a very low gas quality in the 4 ± 6 mm test section. For a low gas quality, elongated bubble prevails after the contraction, yet the size of elongated bubbles is reduced when the aspect ratio is increased. Comparisons amid the pressure change data of this study and available literature data with the predictions of existing model/correlations indicate that none of them can accurately predict the data. It is found that the influence of surface tension and outlet tube size, or equivalently the Bond number plays a major role for the departure of various models/correlations. Among the models/correlations being examined, the homogeneous model shows a little better than the others. Hence by taking account the influences of gas quality, Bond number, Weber number and area contraction ratio into the homogeneous model, a modified homogeneous correlation is proposed that considerably improves the predictive ability over existing correlations with a mean deviation of 30% to all the data.

1. Introduction

Frictional performance arisen from singularities such as expansion and contraction are, as pointed out by Chalfi et al. (2008), among the least studies of two-phase system despite it is rather crucial in many applications such as chemical reactors, power generation units, oil wells and petrochemical plants. In these applications, the two-phase mixture can flow through the sudden area changes, the flow might form a separation region at the sharp corner and an irreversible pressure loss is induced. This singular loss often occurs in orifices, valves, practical pipeline connections and heat exchangers with round or rectangular configurations. In particular, the small and narrow channels are widely adopted in compact heat exchangers. One of the most common arrangements is plate-fin compact heat exchanger using rectangular channels with hydraulic diameters less than 5 mm and mass flux less than 350 kg/m^2 s (Wambsganss et al., 1992). Also, flow in small rectangular channels is an integral part of CPU cold plate using the liquid cooling with or without phase change (Chen et al., 2007).

The flow channel normally involves several geometrical singularities such as abrupt area changes (sudden enlargement, sudden contraction, valve or orifice). At an abrupt flow area change, eddy flow formed in the separation region which is a clear sign of the irreversibility for a large pressure loss. There had been some developed correlations applicable to the pressure change for the conventional tubes, however, very few investigations had reported this abrupt pressure change with respect to mini channels (Abdelall et al., 2005; Chen et al., 2007). Also, a detailed physical description of two-phase flow across the abrupt flow area change in smaller rectangular channels is still not available.

Two-phase flow across sudden contractions is considerably more complicated than sudden expansions. Many of the investigations had assumed the occurrence of the vena-contracta phenomenon with energy dissipation at the downstream of the contraction point. However, Schmidt and Friedel (1997) reported that a local pressure minimum was not detectable in the two-phase tests, thus the axial pressure profile and the shape of streamlines in two-phase flow are still unknown, and there is no evidence whether or not the profile is similar to single-phase flow. Further experimental investigations and theoretical analysis are needed, practically for small rectangular channels with sudden contractions.

* Corresponding author. Tel.: +886 55342601; fax: +886 55312062.
E-mail address: cheniy@yuntech.edu.tw (I.Y. Chen).

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2. Review of literature

The cross-sectional areas of the fluid inlet and outlet lines to the heat exchanger are normally smaller than the cross-sectional area of the fluid channels in the heat exchanger. If the change in channel cross-section is gradual, no flow separation occurs and the change of static pressure may effectively convert to the kinetic energy. However, if there has an abrupt flow area change, it would cause a significant loss.

2.1. Single-phase loss coefficient

For single-phase flow through the contraction area, the flow separates from the inner wall and eddy zones are developed just at the front of transitional cross-section. The contracted flow forms itself into a small jet flow pattern with the narrowest cross-section of the jet being called vena-contracta which is located immediately after the transition cross-section. In the contracted flow region the static pressure decreases rapidly than the fully developed flow at the upstream and downstream. After the ventral-contracta, the pressure gradually increases and reaches its maximum, and then merges into the fully developed pressure gradient line at the downstream.

Chisholm (1983) combined the static pressure drop to the vena contracta and the pressure recovery downstream of the vena contracta to give the total static pressure drop at the contraction (ΔP_{cl}):

$$\Delta P_{cl} = \left(\frac{G^2}{2\rho L}\right)\left[\frac{1}{(\rho_A C_C)^2} - 1 - \frac{2(C_C^{-1}-1)}{\sigma_A^2}\right] \quad (1)$$

where σ_A is the passage cross-section area ratio and $0 < \sigma_A < 1$, ρ_L is the liquid density and mass flux (G) is calculated based on the smaller cross-sectional area of the outlet tube. The contraction coefficient (C_C) correlated by Chisholm (1983) is given as follows:

$$C_C = \frac{1}{\left[0.639(1-\sigma_A)^{0.5} + 1\right]} \quad (2)$$

2.2. Two-phase pressure change across sudden contraction

Geiger (1964) measured pressure drops for steam–water mixtures flowing through sudden contraction with area ratios (σ_A) of 0.398, 0.253, and 0.144. His test conditions are summarized in Table 1. The data were compared with the homogeneous model, momentum equation and mechanical energy equation across the contractions. The homogeneous model gave the best predictions of the data.

McGee (1966) had also measured the steam–water mixtures flowing through sudden contraction using the same test rig as Geiger (1964), but with different test sections and conditions ($\sigma_A = 0.608, 0.546$). His test conditions are also listed in Table 1. The predictions by homogeneous model against the test data were fairly accepted. The predictions by the momentum and mechanical energy equations were much lower than the test data. This deviation is believed due to the assumption of no mechanical energy loss for the acceleration of the fluids at the downstream of the contraction.

For two-phase flow, the change in static pressure at a sudden contraction can be estimated using a homogeneous flow model as recommended by Collier and Thome (1994):

$$\Delta P_c = \left(\frac{G^2}{2\rho L}\right)\left[\left(C_C^{-1}-1\right)^2 + (1-\sigma_A^2)\right]\left[1 + x\left(\frac{\rho L}{\rho G}-1\right)\right] \quad (3)$$

where x is the gas quality and ρ_G is the gas density.

Chisholm (1983) introduced a constant B coefficient for flow through a discrete interval in evaluating the contraction pressure change:

$$\Delta P_c = \Delta P_{cl}\left[1 + \left(\frac{\rho L}{\rho G}-1\right)(Bx(1-x)+x^2)\right] \quad (4)$$

$$B = \frac{\left\{\frac{1}{K_O}\left(\frac{1}{(\sigma_A C_C)^2}-1\right) - \frac{2}{(K_O C_C \sigma_A^2)} + \frac{2}{(\sigma_A^2 K_O^{0.28})}\right\}}{\frac{1}{(\sigma_A C_C)^2} - 1 - \frac{2}{C_C\sigma_A^2} + \frac{2}{\sigma_A^2}} \quad (5)$$

where ΔP_{cl} is the contraction pressure drop for total flow assumed liquid across the same sudden contraction, and K_O is given as

$$K_O = \begin{cases} \left(1 + x\left(\frac{\rho_L}{\rho_G}-1\right)\right)^{0.5} & \text{for } X > 1 \\ \left(\frac{\rho_L}{\rho_G}\right)^{0.25} & \text{for } X \leqslant 1 \end{cases} \quad (6)$$

where X is the Martinelli parameter.

Based on the momentum and mass transfer balance, Schmidt and Friedel (1997) developed a new pressure drop model for sudden contraction which incorporates all of the relevant boundary conditions. In this model all the relevant physical parameters were also included in their sudden expansion paper (1996). The model predicts several experimental data sets from 8 test sections with different physical properties. The comparison of the model and their test results is fair with 80% of the data sets being predicted within ±30%. The test conditions of water–air data for the test section with 72.2 mm inlet diameter and 17.2 mm outlet diameter conducted at 25 °C and 5 bar shown in Fig. 4 of Schmidt and Friedel (1997) are listed in Table 1. This data set is used for the comparison in this study.

Table 1
Available data for two-phase flow across sudden contraction.

Researchers	Geiger (1964) 3 tubes	McGee (1966) 2 tubes	Abdelall et al. (2005) 1 tubes	Present data 4 tubes	Schmidt and Friedel (1997) 1 tube
Mass flux (kg/m^2 s)	Max: 6538 Min: 705	Max: 1973 Min: 542	Max: 4679 Min: 2092	Max: 5358 Min: 226	Max: 4000 Min: 500
Quality	Max: 0.265 Min: 0.001	Max: 0.323 Min: 0.004	Max: 0.0168 Min: 0.0019	Max: 0.8027 Min: 0.0008	Max: 0.9 Min: 0.005
Working fluid	Steam–water at 194–241 °C	Steam–water at 141–195 °C	Air–water at 25 °C	Air–water At 25 °C	Air–water at 25 °C, 5 bar
Hydraulic diameter, D_h (mm)	① 9.70–25.53 ② 12.88–25.53 ③ 16.10–25.53	① 8.64–11.68 ② 11.68–14.99	① 0.84–1.6	① 2–2.67 ② 2–4 ③ 2–3 ④ 2–4.8	① 17.2–72.2
Contraction ratio	① 0.398 ② 0.253 ③ 0.144	① 0.608 ②0.546	① 0.2756	① 0.3927 ② 0.2618 ③ 0.1963 ④ 0.1309	① 0.0568
Bo	Max: 71.6 Min: 20.4	Max: 30.7 Min: 13.4	0.0953	Max: 0.55 Min: 0.53	39.025
We	Max: 95831 Min: 774	Max: 12016 Min: 332	Max: 1723 Min: 251	Max: 79031 Min: 3.94	Max: 18694 Min: 261
Test points	211	44	26	156	77
Mean deviation by homogenous model	21%	73%	223%	861%	50%

Abdelall et al. (2005) investigated air–water pressure drops caused by abrupt flow area expansion and contraction in a very small test section. The large and small tube diameters were 1.6 and 0.84 mm, respectively. Their test conditions are also listed in Table 1. The data of two-phase flow pressure change across the sudden contraction were found significantly lower than the predictions of the homogeneous model. It might be attributed to the significant velocity slip at the vicinity of the flow area change. With the assumption of an ideal annular flow regime, the velocity slip ratio was given by Zivi (1964) as:

$$S = \frac{u_G}{u_L} = \frac{(1-\alpha)\rho_L x}{[(1-x)\rho_G \alpha]} = \left(\frac{\rho_L}{\rho_G}\right)^{\frac{1}{3}} \quad (7)$$

where u_G and u_L are the actual gas and liquid velocities of gas and liquid phases, respectively. Since the void fraction (α) is involved in the calculation of the two-phase pressure drop at the sudden contraction in Abdelall et al. correlation, the above slip ratio equation was thus used to calculate the void fraction. The proposed slip flow model with vena-contracta coefficient (C_C) resulted in relatively close agreement with a mean deviation of 16.41% between their 26 point data and predictions, but the mean deviation is 32.76% for the full liquid Reynolds number less than 2600.

Based on the same test facility of Abdelall et al. (2005), Chalfi et al. (2008) recently reported more data for single-phase and two-phase flow pressure drops caused by flow area expansion and contraction using air and water. Their new data falls within an even lower all liquid Reynolds number ($Re_{LO} < 1020$) than that of Abdelall et al.'s, 2005 data ($1754 < Re_{LO} < 3924$). For flow contraction, the one-dimensional slip flow model along with the slip ratio expression (Eq. (7)) agreed with the new data well, provided that no vena-contracta ($C_C = 1$) was considered. The results showed that the homogeneous model over predicted the pressure drop very significantly everywhere, typically by a factor of five. The slip flow model with vena-contracta (C_C) also over predicted the data consistently, typically by a factor of two. However, for the data with higher all liquid Reynolds number, the one-dimensional slip flow model with vena-contracta gave better agreement than that with slip flow model without vena-contracta (Abdelall et al., 2005).

From the foregoing review of the two-phase pressure change across the sudden contraction, most of the investigations are related to the abrupt area change for the upstream and downstream having round tube configurations Since the singular configuration variation from rectangular to round channel is very common in practice, thereby it is the objective of this study to provide newly test data regarding to the influence from rectangular to round singularity. In addition, flow visualization experiment is also carried out to link with certain special pressure drop phenomenon. Since most of the proposed correlations/model is only applicable to their own database, the effort of this study is to provide a physical modification of the existing model that is capable of handling a much larger database.

3. Experimental setup

The test rig shown in Fig. 1 is designed to conduct tests with air–water mixtures. Air is supplied from an air-compressor and then stored in a compressed-air storage tank. Airflow through a pressure reducer, and depending on the mass flux range, is measured by three Aalborg® mass flow meters for different ranges of flow rates. The water flow loop consists of a variable speed gear pump that delivers water. A mixer provides better uniformity of the air and water mixture. An enlarged view of mixer is shown as the round perspex tub in Fig. 1. The detail of this mixer had been described by Chen et al. (2001) in two-phase flow pressure drop tests in small tubes. Since the data for two-phase pressure drop in the rectangular channels were taken simultaneously with the

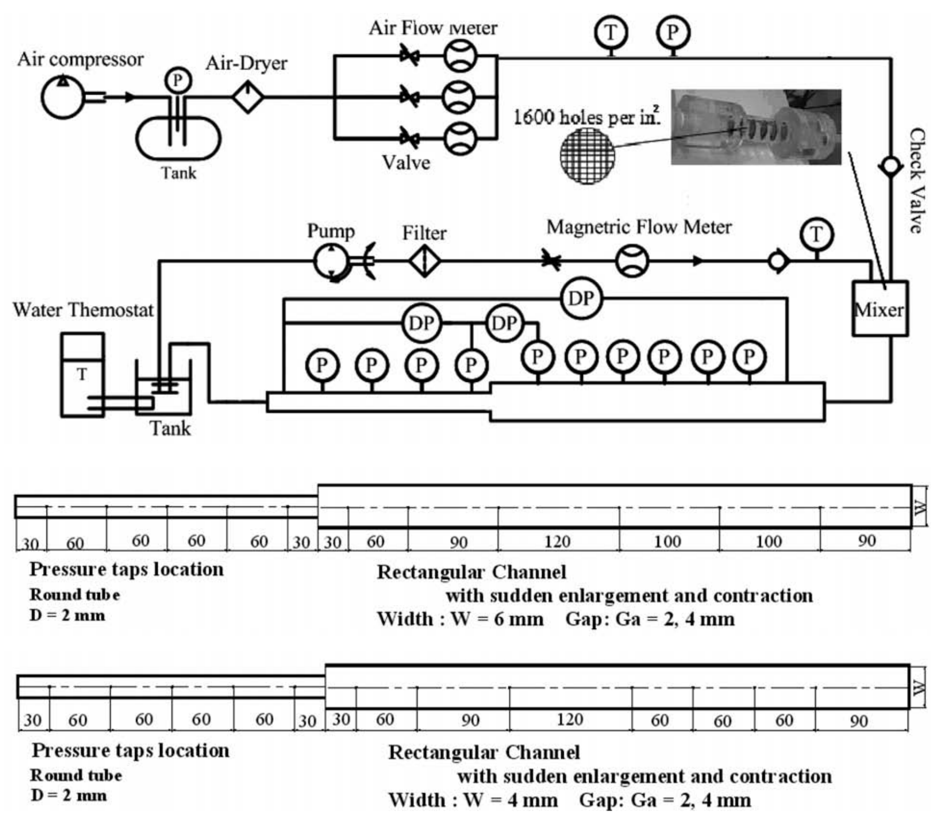

Fig. 1. Schematic of test rig and test section showing pressure taps.

sudden contraction tests, the mass flux is based on the cross-sectional area of rectangular channels. The total mass flux density (G) of air and water flow rate is ranged from 100 to 700 kg/m^2 s with gas quality (x) being varied from 0.001 to 0.8. However, in order to compare the obtained contraction data with the available correlations, the mass flux (G) is then changed to the base of the smaller cross-sectional area of the outlet round tube. The inlet temperatures of air and water are near 25 °C. The pressure measured just after the contraction position is in the range of 101–350 kPa. The pressure drops of the air–water mixtures are measured by three YOKOGAWA EJ110 differential pressure transducers having an adjustable span of 1300 to 13,000 Pa. Resolution of this pressure differential transducer is 0.3% of the measurements. The drilled holes of the pressure taps are perpendicular to the test sections with a diameter of 0.5 mm. Pressure measurements are made in nine locations along the inlet tube and along the rectangular channel of the test sections as shown in Fig. 1. The resolution of the pressure measurements is 0.1% of the test span. For validation of the present test setup, measurements of the single-phase pressure drops for air and water alone are in terms of friction factors to compare with the friction factor equations for laminar and turbulent flows in rectangular channels. The results are in line with the known correlations having a deviation within ±5%.

Leaving the test section, the air and water mixture flows are separated by an open water tank in which the air is vented and the water is re-circulated. The air and water temperatures are measured by resistance temperature device (Pt100 Ω) having a calibrated accuracy of 0.1 K (calibrated by Hewlett-Packard quartz thermometer probe with quartz thermometer, model 18111A and 2804A). Observations of flow patterns are obtained from images produced by a high-speed camera of Redlake Motionscope PCI 8000 s. The maximum camera shutter speed is 1/8000 s. The high-speed camera can be placed at any position along the rectangular channels or at the side view of the abrupt change of flow area.

The dimensions of the test sections are gap (G_a) × width (W) = 2 × 4, 2 × 6, 4 × 4 and 4 × 6 mm. All the test sections are connected with a 2 mm diameter glass tube such that the flow will meet the abrupt flow area change at the interconnection between the round tube and the rectangular channel. The area ratio for the abrupt flow area change (σ_A) is ranged from 0.131 to 0.393. The test sections are made of transparent acrylic resin, so that the flow pattern and flow structure at the vicinity of the abrupt cross-sectional area change could be visualized. These test sections are also be arranged in horizontal longitudinal (HL, the wide side is vertical) and the intersection between the rectangular and round tube is well fabricated to avoid any irregularity.

Fig. 2 is the variation of static pressure along the flow direction across singularity (contraction). When flow approaches the contraction, due to the acceleration of the flow in the transitional region, the static pressure initially decreases to the contraction area. After the pressure reaches the minimum, the pressure increases to a downstream point and then merges with the downstream fully developed pressure gradient line. The pressure change at the sudden contraction is defined as the pressure difference at the interception of singularity evaluated using the fully developed pressure gradients from upstream and downstream, respectively, i.e., ΔP_{con}, as shown in Fig. 2. For obtaining the exact pressure change across the sudden contraction, several pressure transducers are utilized for measuring the local pressures in the upstream and downstream parts of the test sections as shown in Fig. 1. The measured axial pressures versus the pressure tap positions are plotted in a figure to setup the fully developed pressure gradient lines in the upstream and downstream for further obtaining the corresponding pressure change from the extrapolation of those lines to the point of sudden contraction.

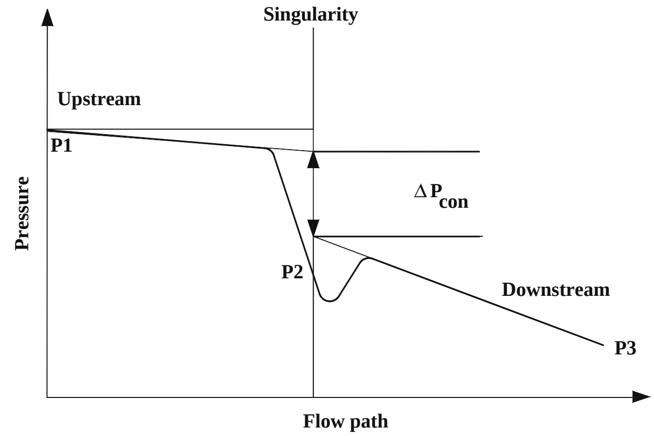

Fig. 2. Progress of flow pattern vs. quality across the sudden contractions.

4. Results and discussion

The observed flow patterns for the test sections at different flow conditions are shown in Fig. 3. The intermittent flow pattern prevails at low mass flux and low quality region before flow entering the singularity. The flow pattern may change into elongated bubble, twisted elongated bubble, or annular flow pattern pertaining to the effects of mass flux, gas quality, and aspect ratios. For a lower gas quality and mass flux, elongated bubble becomes the major flow pattern after contraction. With a rise of mass flux or gas quality, increasing gas shear twisted the elongated bubble and may even tear it into smaller bubbles. In the meantime, for the same gas quality and mass flux, it is interesting to note that the size of elongated bubbles is reduced when the aspect ratio is increased. This is applicable from 6 × 2 to 6 × 4 mm or from 4 × 2 to 4 × 4 mm channels. For elaborating this phenomenon, one should realize that the test section is rectangular. For the two-phase flow before entering the singularity, the presence of sharp corner retains liquid owing to the capillary effect. This phenomenon is further emphasized for a rectangular channel having a smaller aspect ratio (G_a/W) since the retained liquid in neighboring corners of upper portion conglomerates to form thin liquid film, resulting in comparably better flow entry condition of subsequent two-phase mixtures. As a consequence, the size of the elongated bubble is much longer. By contrast, for a wider channel gap or equivalently a larger aspect ratio, more rugged entry condition on the upper portion of the rectangular section may appear that provides tougher entry condition and additional twisting force. In this regard, the size of elongated bubble is reduced.

Figs. 4–7 are the measured two-phase pressure changes subject to the sudden contraction for the 6 × 2, 6 × 4, 4 × 2 and 4 × 4 mm channels, respectively. In general, the contraction pressure changes increase with the quality and mass flux. However, a detectable drop of the pressure change is observed at a very low mass quality ($x = 0.005$, $G = 300$ kg/m^2 s and $G = 700$ kg/m^2 s) for the 6 × 4 mm channel as shown in Fig. 5. This phenomenon was also reported from the test results of Schmidt and Friedel (1997) for their air–water data at $G = 1000$ kg/m^2 s and $x = 0.18$ where a local minimum of pressure drop vs. gas quality is seen. This phenomenon was characterized as a change of flow pattern in the inlet pipe or outlet pipe. This deflection of the pressure change was occurred with the observed gas stream surrounded by liquid with the smallest diameter of gas core, and this phenomenon was described as "liquid like vena contracta". This phenomenon, based on the observed flow patterns from collected photos (see Fig. 3), is associated with the tube size. As can be seen from the observed flow pattern, the liquid like vena contracta moves toward upsteam

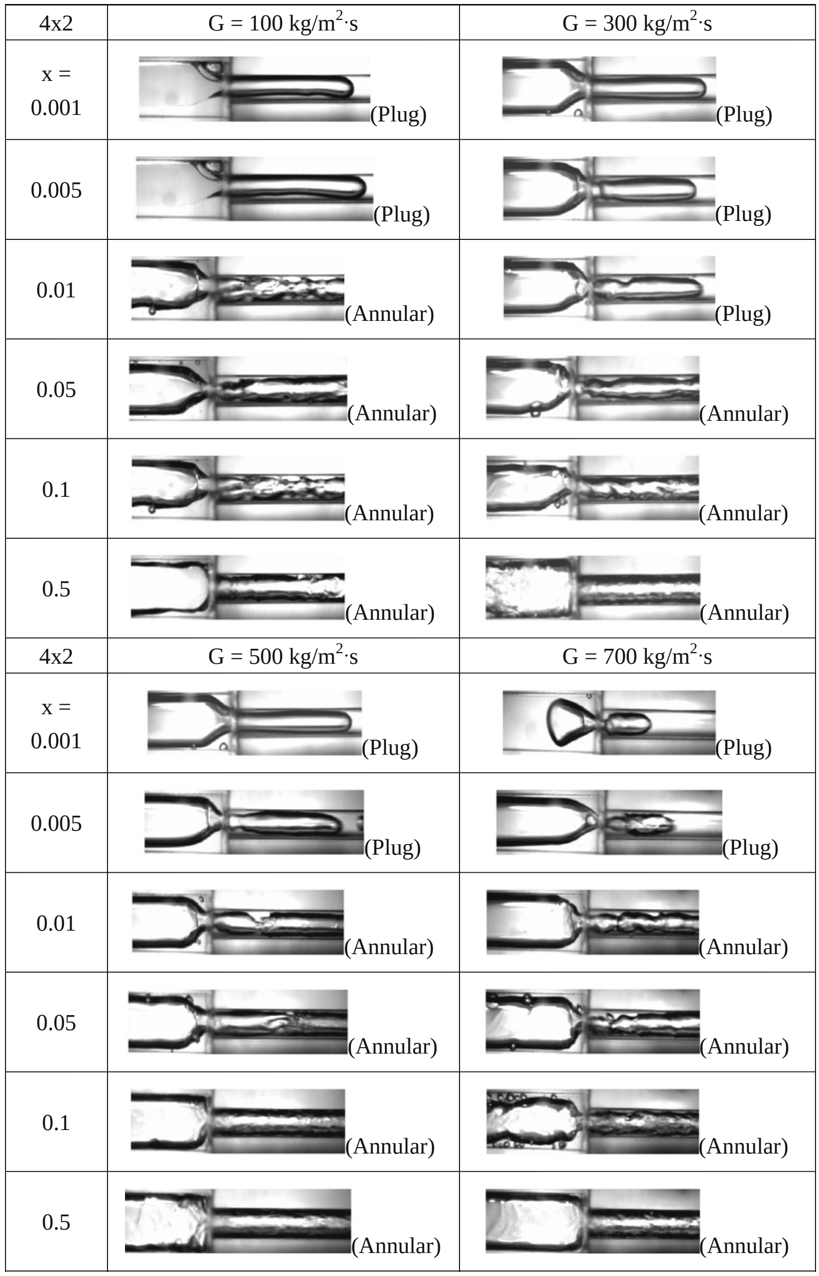

Fig. 3. Idealized pressure variations due to sudden contraction.

and even appears in front of the singularity. This of course lessens the influence of vena contracta, thereby leading to a less conspicuous pressure change.

To test the validity of the foregoing described models/correlations from the existing literatures, the present data (156 points) and the literature data (357 points) listed in Table 1 are compared with the previously described homogeneous model, and correlations of Chisholm (1983), Schmidt and Friedel (1997), and Abdelall et al. (2005), but none of them can accurately predict the entire database. The comparison results for each correlation are summarized in Table 2. The data sets of Geiger (1964) are well predicted by the homogeneous model (mean deviation about 20%) than the other correlations (mean deviation from 58% to 447%). The McGee (1966) data are fairly predicted by the homogeneous model and the correlation of Schmidt and Friedel (1997). The Schmidt and Friedel (1997) data are well predicted by the Abdelall et al. (2005) correlation with a mean deviation of 24%, but their correlation gives the best prediction with a mean deviation of 21%. The Abdelall et al.'s (2005) data are best described by their correlation (15% mean deviation), but are significantly over predicted by the others. The homogeneous model gives the worst predictions to the Abdelall et al. data with a mean deviation of 223% which was also reported by themselves. The present mini tube data along with the micro tube data by Abdelall et al. (2005) show profound departure to the predictions of the existing correlations. The predictions against present data have deviations ranged from 823% to 1407%. As a result, a sharp rise of the mean deviation for all the correlations to all the data is encountered. The average mean deviations of the relevant predictions to all the data are 295%, 285%, 737%, 335% by Homogeneous model, Chisholm (1983) correlation, Schmidt and Friedel (1997) correlation, and Abdelall et al. (2005) correlation, respectively.

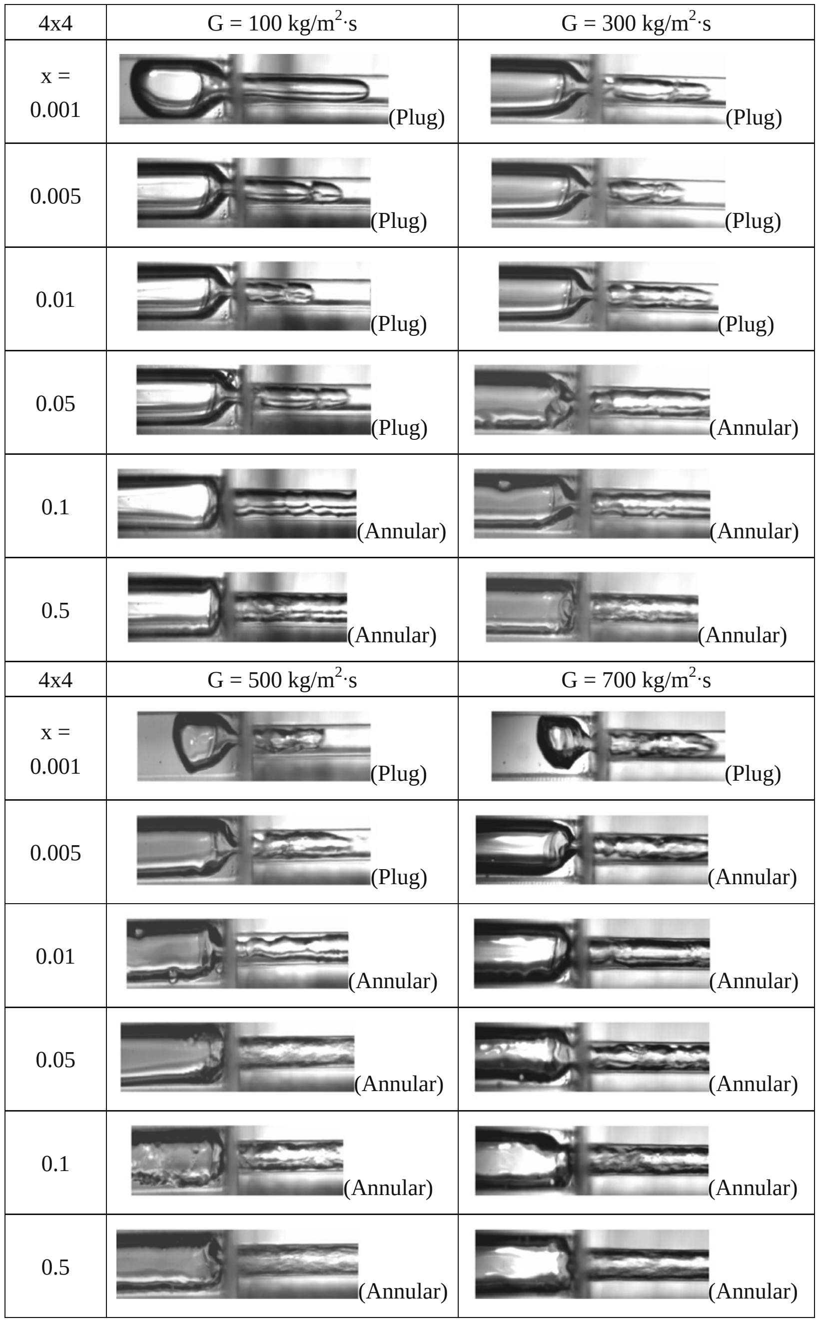

Fig. 3 (*continued*)

The significant departure of the existing correlations with the present data and Abdelall et al. (2005) data could be attributed to the very small outlet section, 2 and 0.84 mm, respectively. For these mini tubes, influence caused by surface tension takes control. For obtaining a better predictive ability, one should also take into account the influence of surface tension force (Tripplet et al., 1999). The balance of buoyancy force and surface tension can be represented by Bond number (*Bo*) as:

$$Bo = \frac{g(\rho_L - \rho_G)(D/2)^2}{\sigma} \tag{8}$$

where g is the gravity, σ is the surface tension and D is the internal diameter of outlet tube.

When the value of *Bo* is near or less than 1.0, the stratified flow pattern is not able to exist in most of the two-phase flow conditions (Chen et al., 2002). Table 1 also tabulated the change of Bond numbers being varied from 0.095 of Abdelall et al. (2005), 0.53 of present study to 71.6 of Geiger (1964) for the related database. Also, considering the effects of total mass flux and gas quality to the surface tension, Schmidt and Friedel (1996, 1997) had proposed a Weber number (*We*) to correlate the two-phase pressure change across sudden expansions and contractions.

$$We = G^2x^2\frac{D}{\rho_G\sigma}\frac{(\rho_L - \rho_G)}{\rho_G} \tag{9}$$

From the foregoing comparisons, it is found that the homogenous model gives good predictive ability but fails to predict Abdelall et al.'s (2005)'s and the present data. By examining the tabulated Bond number in Table 1, it is found that the departure of the predictive ability of homogeneous model is strongly related to the Bond

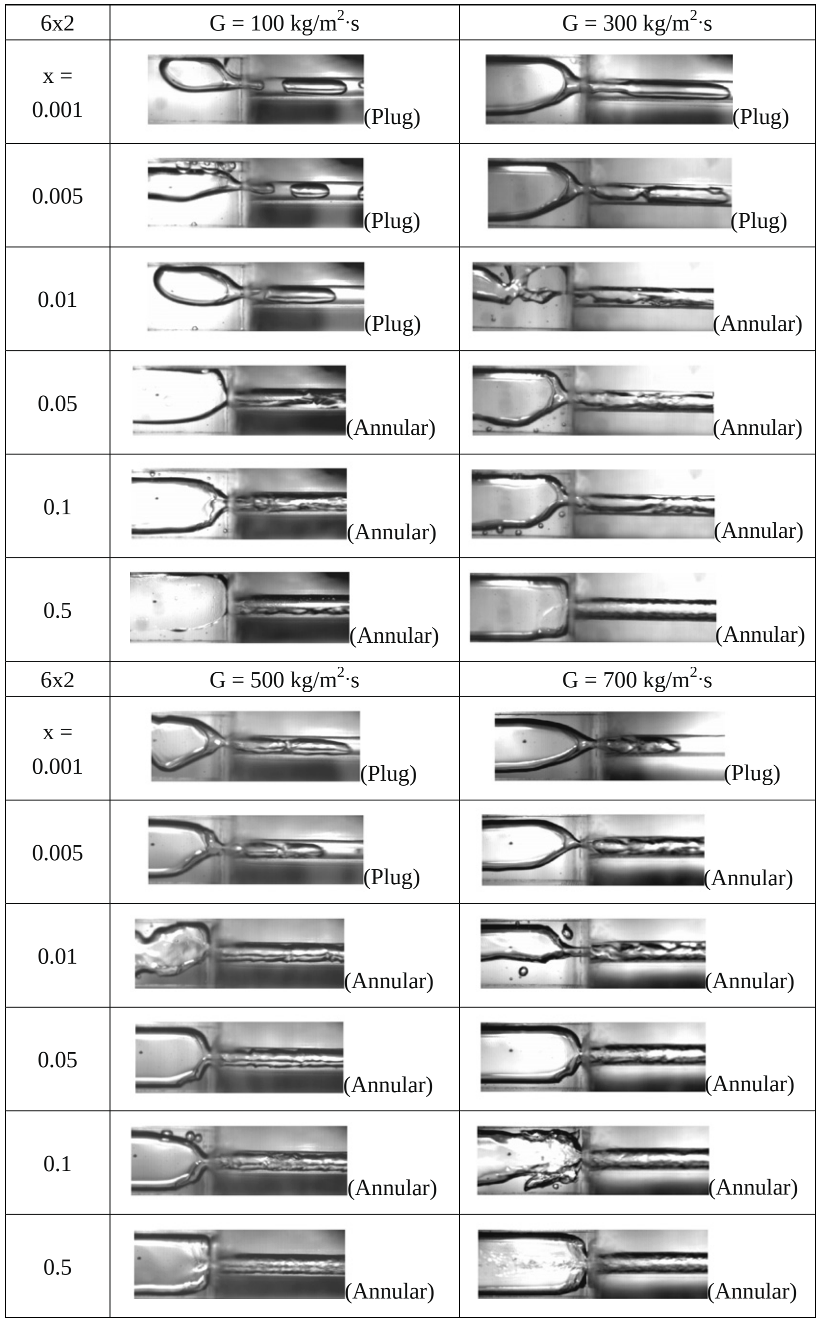

Fig. 3 (*continued*)

number. The database of Geiger (1964) and McGee (1966) contains a relatively larger Bond number (>13), indicating a rather small influence of surface tension and thus showing a good predictive ability of homogeneous model. The data of Schmidt and Friedel (1997) also shows fair predictive ability of homogeneous model with its Bond number around 39.03. Its very small contraction ratio (0.057) may reinforce the influence of contraction (similar to the forgoing liquid vena contracta). In that regard, an effort is made in this study to include the effects of Bond number, Weber number, gas quality and flow cross-sectional area contraction ratio (σ_A) to extend the applicable range of homogeneous model. Though the Chisholm (1983) correlation has a very close average mean deviation to all the data with the homogeneous model, the homogeneous model is much easier to use and to modify. The proposed modification is applicable to the present data (156 points) and those data available from the literatures shown in Table 1 (357 points). By introducing correction factors to the original homogeneous model, Eq. (3), the proposed modification takes the following form:

$$\Delta P_c = \Delta P_{cHom} \times (1+\Omega_1) \times (1+\Omega_2) \times (1+\Omega_3)^{-0.08} \quad (10)$$

$$\begin{aligned}
\Omega_1 &= -0.99 e^{\frac{-13.1 \times C_1}{C_2}} \\
\Omega_2 &= -39.4 e^{C_1^{-0.25}} \left(16.1 C_3^{-1.5} - 13.2 C_3^{-1.8} - 4.2 C_3^{-1}\right) \\
\Omega_3 &= 0.1 C_3^{-13} C_4^{-3} \\
C_1 &= Bo^{1.1} (1-x)^{0.9} \\
C_2 &= 470 e^{-\sigma_A^{-0.2}} \\
C_3 &= We \times Bo \times \sigma_A \times (1-x)^{-3} \\
C_4 &= \sigma_A^{2.5} (1-x)^{-1}
\end{aligned} \quad (11)$$

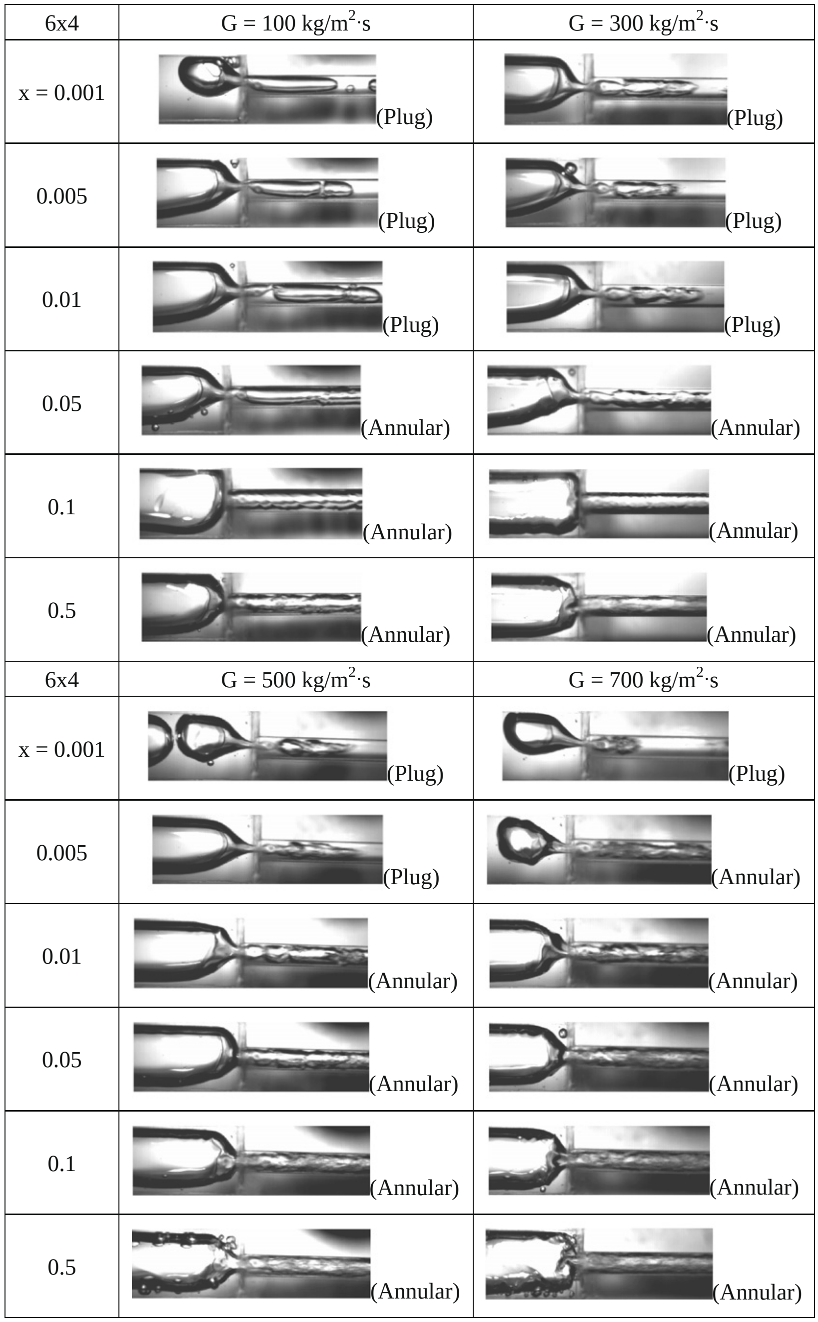

Fig. 3 (*continued*)

The correction factors $\Omega_{i=1,2,3}$ asymptotically approach zero when the Bond number is large enough in which influence of surface tension is negligible. For assessing this proposed correlation, the comparison results with all available data are shown in Fig. 8. The total mean deviation of this modified homogeneous model is 30% which has been greatly improved from 295% of the original homogeneous model. The mean deviation to the data of Schmidt and Friedel (1997) predicted by this proposed correlation is 17%. Though Schmidt and Friedel (1997) indicated that 80% of their own data and available literature data were predicted within ±30%, their correlation is rather complicated to use. Furthermore, the mean deviation for the data of Abdelall et al. (2005) is tremendously reduced from 223% by homogeneous model to 31% by this proposed modification. Although the correlation of Abdelall et al. (2005) gives a mean deviation of 15% to their data, their correlation is only valid for their data in a very small test section. In summary, the proposed correlation shows a very good accuracy against the existing data and is capable of handling the effect of surface tension and buoyancy force and is valid for much wider ranges of: $100 < G < 6538$ kg/m^2 s, $0.0008 < x < 0.9$, $0.057 < \sigma_A < 0.608$, $0.84 < D_h < 72$ mm.

5. Conclusions

Experiments were performed to examine the two-phase pressure drops and flow pattern changes across sudden contractions in small rectangular channels. A total of 4-test sections (gap (G_a) × width (W) = 2 × 4, 2 × 6, 4 × 4 and 4 × 6 mm) into a round tube (2 mm) are made. Test results shows that the contraction pressure change generally increases with the gas quality, yet a special deflection of contraction pressure drop vs. gas quality is seen at a very low gas quality in the 4 × 6 mm test section. This

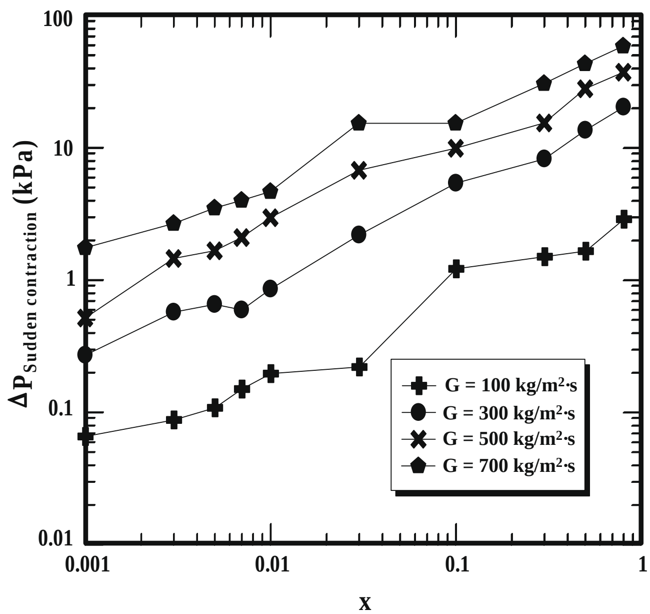

Fig. 4. Measured pressure change for the 6 × 2 mm channel.

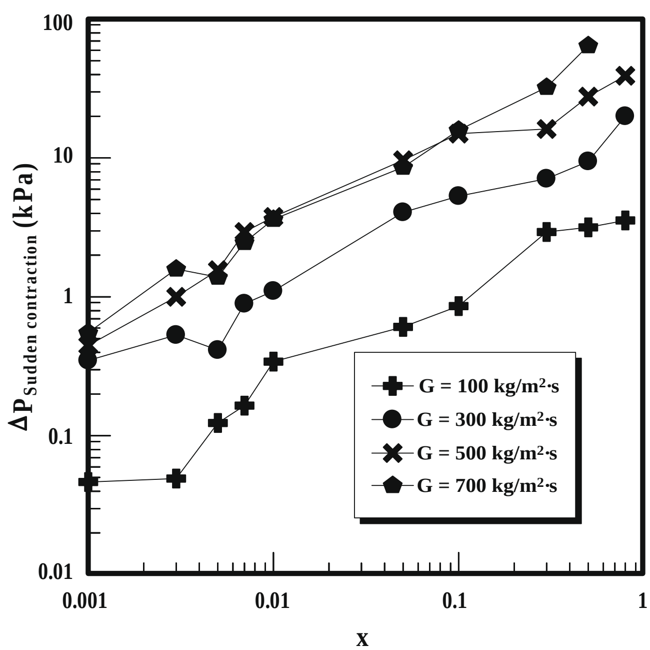

Fig. 5. Measured pressure change for the 6 × 4 mm channel.

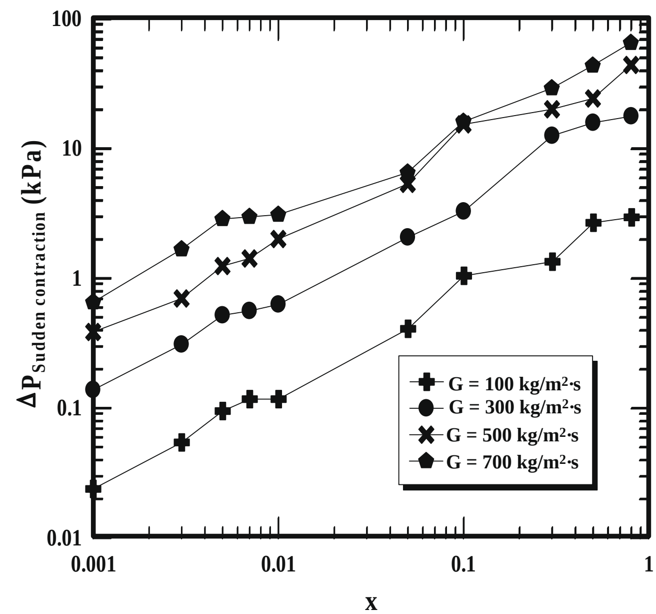

Fig. 6. Measured pressure change for the 4 × 2 mm channel.

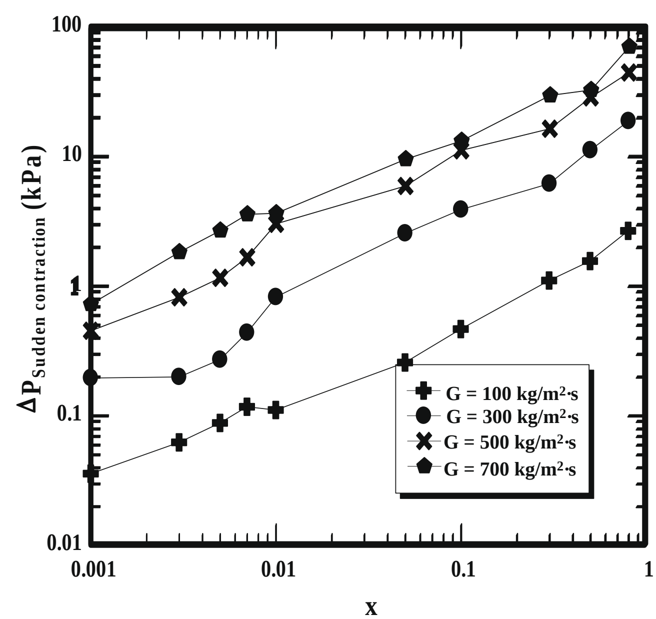

Fig. 7. Measured pressure change for the 4 × 4 mm channel.

phenomenon is in line with observed liquid vena contracta appeared in front of the singularity. Elongated bubble becomes the dominate flow pattern when gas quality or the mass flux is small. However, the size of the elongated bubbles is detectably reduced when the aspect ratio is increased.

For the measured contraction pressure change, comparisons are made between the present data (156 points) and available literature data (357 points) to the predictions of homogeneous model and correlations of Chisholm (1983), Schmidt and Friedel (1997), and Abdelall et al. (2005). Normally the proposed models/correlations are applicable only to their own database. Among these models/correlations, homogeneous model gives moderate predictive ability than the others, but none of them can accurately predict the entire database. In addition, the significant deviation of the existing correlations with the present data and Abdelall et al. (2005) data could be attributed to the very small outlet section. The possible cause of this significant departure is due to the influence of surface tension which takes control in small diameter tubes. The corresponding effect can be corrected by introducing the correction factors that includes the influences of gas quality, Bond number (*Bo*), Weber number (*We*) and area contraction ratio (σ_A) to the original homogeneous model. Through this rational-based modification, the mean deviation of this proposed correlation is dramatically reduced to 30% to the entire database. In summary, the proposed correlation shows a very good accuracy against the existing data in a wider range of application, and is capable of handling the effects of surface tension and buoyancy force.

Table 2
Comparison of available data with 4 published correlations.

Data	Methods			
	Schmidt (1997) predictions (%)	Homogenous predictions (%)	Chisholm (1983) predictions (%)	Abdelall et al. (2005) predictions (%)
McGee (1966) 44 points	66	73	107	100
Geiger (1964) 211 points	35	21	20	58
Present data 156 points	705	861	823	982
Abdelall et al. (2005) 26 points	58	223	223	15
Schmidt and Friedel (1997) 77 points	21	51	41	24
Total mean deviation for 514 points	240	295	285	335

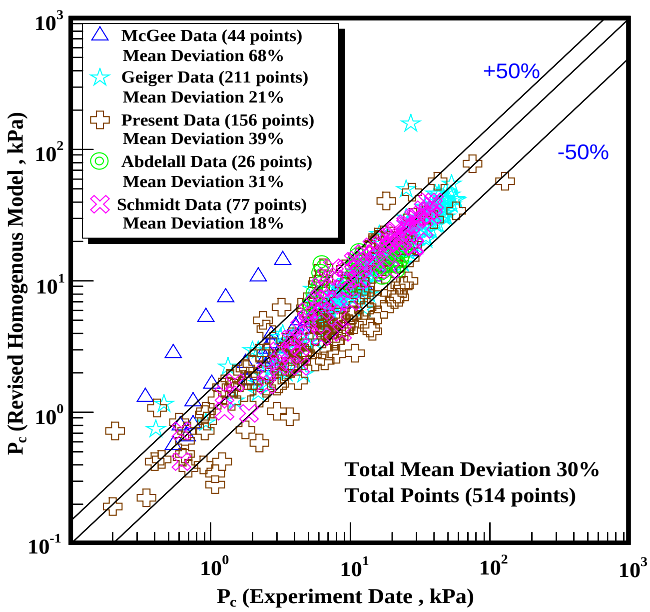

Fig. 8. Comparison of all available data with the revised homogeneous model.

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