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Single-Phase and Two-Phase Pressure Drops Across Sudden Contraction in Horizontal Rectangular Minichannel

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***Abstract*—This paper presents experimental investigations on the effects of liquid properties on pressure drop for both single-phase and two-phase flows through sudden contraction in horizontal rectangular minichannel. In order to know the effects, water and viscoelastic liquid, namely 0.1 wt% polyacrylamide (PAM) aqueous solution are selected as the working liquid, while air as the working gas. Liquid single-phase and air-liquid two-phase flow experiments were conducted at room temperature using a horizontal rectangular mini-channel with a sudden contraction. The cross-sectional dimensions of the channel with the height (*H*), the width (*W*) and the hydraulic diameter (D_H) for the narrow channel are 2.79 mm, 3.09 mm and 2.94 mm, while those for the wide channel are 2.95 mm, 5.98 mm and 3.95 mm. The local pressure upstream and downstream from the contraction were measured with calibrated pressure transducer to determine the pressure drop due to the contraction. As an analysis, the resulting data on the pressure drop at the contraction were compared with several correlations in literature. Results of such experiment and analysis are reported in the present paper.**

***Keywords*—two-phase flow, pressure drops, rectangular minichannel, sudden contraction**

I. Introduction

The flow of two-phase mixtures across sudden expansions and contractions is commonly seen among piping connections as well as relevant to many applications such as chemical reactors, power generation units, oil wells and petrochemical plants [1]. In particular, the small and narrow channels are widely adopted in compact heat exchangers [2]. Recently, such a flow through singularity in micro and minichannels ranged from 100 μm to 10 mm becomes popular because compact heat exchangers with phase change, such as cooling devices of electronic equipment and refrigerators, are miniaturized [3].

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In addition to the emergence of the micro chemical technology demands high efficient reactors with more compact structure, which have to consider gas/non-Newtonian fluid two-phase flow in micro- or mini-channels [4]. Therefore, the understanding of the characteristics on two phase flow through the singularities in minichannel is essential for designing such small scale devices. A number of researches have been reported on two-phase flows in small channel with singularities.

Sadatomi et al. [3] investigated flow regime, pressure drop, bubble velocity and void fraction for air-water two phase flow through U-bend, sudden expansion and sudden contraction in rectangular minichannel. Kusumaningsih et al. [5] conducted experimental investigations on nitrogen gas – liquid (distilled water, ethanol 49 wt% aqueous solution, pure ethanol and HFE 7200) two-phase flows in two kinds of rectangular microchannels with the widths of in the larger channels upstream of the contraction 0.53 or 0.78 mm (0.240 mm in height), while 0.240 mm (0.240 mm in height) the smaller ones.

Abdelall et al. [6] performed an experimental study of pressure drop cause by abrupt flow area changes in small circular channels. The larger and smaller tube diameters were 1.6 and 0.84 mm, respectively. Deionized water and air were used as two-phase flow mixture. Chen et al. [7] conducted experimental investigation of the two-phase flow characteristics across sudden contraction using air and water mixture. The contraction test section was from small rectangular channels (3x6 mm and 3x9 mm) into a small tube (3 mm). Padilla et al. [8] conducted experimental studies on two-phase flow of HFO-1234yf, R-134 and R-410A in a 10 mm glass tube with a cross-section area ratio of 0.49. The experimental pressure drop data are used to test six prediction methods from the literature.

In this connection, the aims of this study is to investigate experimentally the effects of liquid properties on pressure drops for both single-phase and two- phase flows in horizontal rectangular minichannel with sudden contraction. In this experiments, pressure distribution upstream and downstream from the contraction in the minichannel was measured for single-phase and two phase flows. From the pressure distribution data, the pressure drops due to the contraction was determined. As an analysis, the present data on the pressure drop at the contraction were used to test several correlations in literature. Results of such experiment and analysis were reported in the present paper.

II. Experiments

Figure 1 shows a schematic diagram of test channel with sudden contraction placed on a horizontal plane. The cross-section of the test channel is rectangular and the channel is made of transparent acrylic resin for visual observation. Table 1 shows the cross-sectional dimensions of test channel with the width (W), the height (H) and the hydraulic diameter (D_H) for the wide channel are 5.98 mm, 2.95 mm and 3.95 mm, while those for the narrow channel are 3.09 mm, 2.79 mm and 2.94 mm, thus the ratio of contraction σ_A is about 0.49.

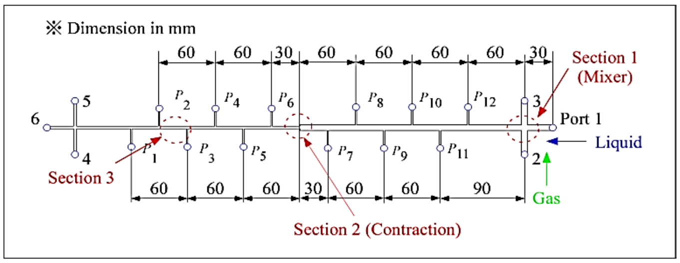


Figure 1. Test channel with sudden contraction.

TABLE I. DIMENSIONS OF TEST CHANNEL CROSS SECTION

	W [mm]	**H [mm]**	**D_H [mm]**
Wide, W	5.98	2.95	3.95
Narrow N	3.09	2.79	2.94

The port #1 and #2 in Fig. 1 were the liquid and the gas inlet ports. Therefore, two phases were supplied through a T-junction type gas-liquid mixer. The port #6 was the gas-liquid mixture outlet to atmosphere. The port #3, #4 and #5 were closed in the present experiment. It is noted that if port #5 and #6 were used as the inlet ports of gas and liquid, and port #4, #2 and#3 were closed, the sudden expansion test can be conducted with the same test channel.

P_1 to P_{12} are the pressure taps, and the pressure at P_4 was measured with a gauge type pressure transducer (Yokogawa, FP101-L31-L20). The pressures at other pressure taps were determined from the difference in pressure between the respective taps and P_4 tap measured with a differential pressure transducer (Validyne, DP15-32 and DP15-26 depending on the pressure range). The accuracy of the pressure measurement was within 3.5 Pa from a calibration test.

Volume flow rate of air was measured with a flow meter (KEYENCE, FD-A10 and FD-A1 depending on the flow rate range) within 2 %, while that of liquids with a flow meter (KEYENCE, FD-S) within 1 %. In order to obtain accurate time averaged values of air and water flow rates and pressures, the output signals from the respective sensors were fed to a personal computer via A/D converter over 10 sec. at nominally 1 kHz.

In this study, water and aqueous solution of 0.1 wt% polyacrylamide (PAM) are selected as the working liquid, while air as the working gas at room temperature. Polyacrylamide aqueous solution is known as a kind of non-Newtonian fluid having viscoelasticity [9]. Also, PAM aqueous solution has shear thinning effect where the fluid's viscosity decreases with increasing of shear rate and is often expressed by the Ostwald-de Waele power law model as follows :

$$\tau = K(du/dy)^n = K\left(\frac{du}{dy}\right)^{n-1} \cdot \frac{du}{dy} = \mu_a \frac{du}{dy} \qquad (1)$$

where τ is the wall shear stress, du/dy is the shear rate, K is the consistency coefficient, n is the flow index and μ_a is the apparent viscosity. In this study, the values of K and n were determined with a capillary method [10]. The n and K determined as well as the density, the surface tension for each liquid are listed in table II. n is nearly equal to unity for PAM aqueous solution because concentration of PAM is quite low and shear rate tested is relatively high (= 500 – 7500 1/s). It can be noticed that the difference in the density and surface tension values between water and PAM aqueous solution are small. So, any changes in the results obtained are related to the changes in the viscosity values of the test liquids.

TABLE II. PHYSICAL PROPERTIES OF TEST LIQUIDS

Working liquids	**K [Pa.s^n]**	**n**	**ρ_L [kg/m^3]**	**σ [N/m]**
Water	0.00100	1.00	998.2	0.0728
PAM	0.00151	1.00	998.2	0.0717

For single-phase flow experiments, the ranges of Reynolds number ($=\frac{\rho u D_H}{\mu}$, where u is the mean velocity, μ is the viscosity) in the narrow channel Re_N are from 320 to 9600 for water, and from 290 to 5900 for PAM aqueous solution. For two-phase flow experiments, the ranges of volumetric fluxes of liquid and gas are 0,2 < j_L < 2 m/s and 0.1 < j_G < 10 m/s.

III. Result and discussion

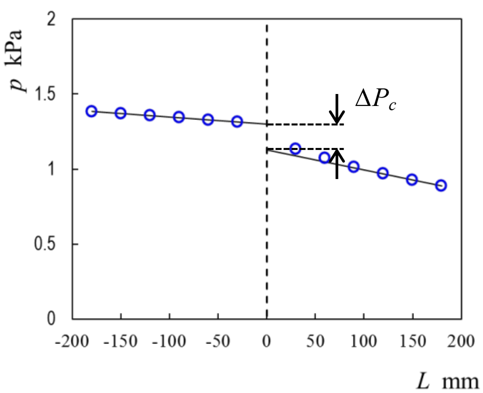
Fig. 2 (a) and (b) show examples of pressure distribution data obtained for single-phase water and PAM aqueous solution flows in the test channel with the contraction of

$\sigma_A = 0.49$, while those for two-phase flows were shown in Fig. 3. The total pressure drop across sudden contraction, Δp_c, was determined by extrapolation of the axial pressure profiles in the channels upstream and downstream from the contraction. Δp_c consists of the irreversible and reversible pressure drop, and could be expressed by the following Kays's [11] equation :

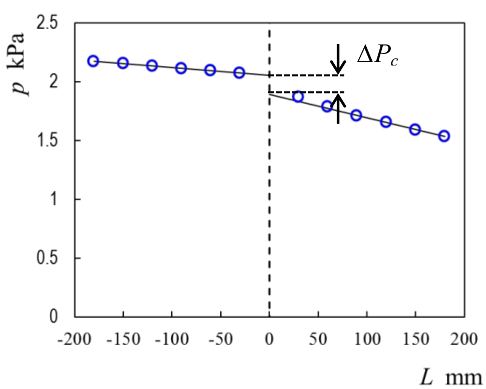
$$\Delta p_c = \frac{\rho_L {u_N}^2}{2}(K_c + 1 - {\sigma_A}^2) \qquad (2)$$

$$K_c = \left(1 - \frac{1}{C_c}\right)^2 \qquad (3)$$

where ρ is the density of working fluid, u_N the mean velocity in the narrow channel from the contraction, K_c the contraction loss coefficient and C_C the contraction coefficient.

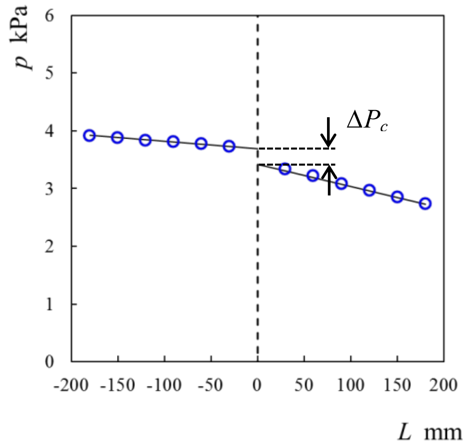


(a) Water ($Re_N \fallingdotseq 1500$)

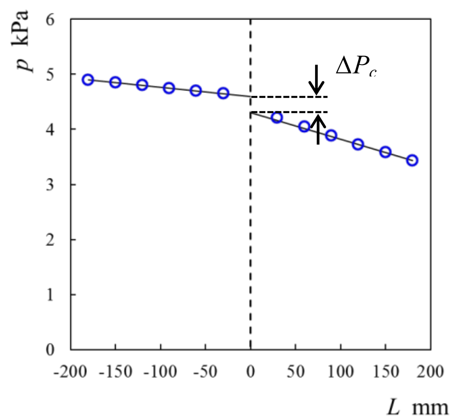


(b) PAM ($Re_N \fallingdotseq 900$)

Figure 2. Pressure distribution along contraction channel for typical single-phase flows.



(a) Water (j_G = 0.1 m/s, j_L = 0.5 m/s)



(b) PAM (j_G = 0.1 m/s, j_L = 0.5 m/s)

Figure 3. Pressure distribution along contraction channel for typical two-phase flows.

Figure 4 shows the present contraction coefficient data for single-phase liquid flows, C_C, against Reynolds number in the narrow channel. Solid line show the calculation by Geiger's [12] correlation which is applicable to a conventional size circular channel.

$$C_C = 1 - \frac{(1-\sigma_A)}{2.08(1-\sigma_A)+0.5371} \qquad (4)$$

This correlation was developed based on the data obtained for contraction ratio from ranges from 0.144 to 0.398 under turbulent flow conditions in 9.70 mm, 12.87 mm and 16.10 mm diameter circular channels. From Fig. 4, it can be seen that the C_C data increase with the Reynolds number. In turbulent flow region, C_C data seem to approach to the calculated value by Geiger's equation.

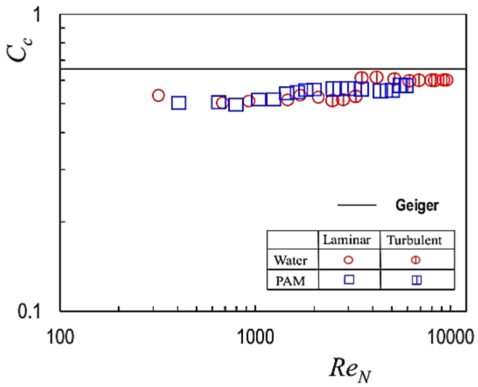


Figure 4. Contraction coefficient data against Reynold number in the narrow channel for single-phase liquid flow.

Figure 5 shows the present data for two-phase pressure drop due to sudden contraction, $\Delta p_{ct,TP}$, against the mass quality, x. A comparison is made between water and PAM aqueous solution. In general, results show that the pressure drops increase with the quality, especially at a fixed volumetric flux of liquid, j_L, of 0.5, 1.0 and 2.0 m/s, and the pressure drops increase with j_L at a fixed x.

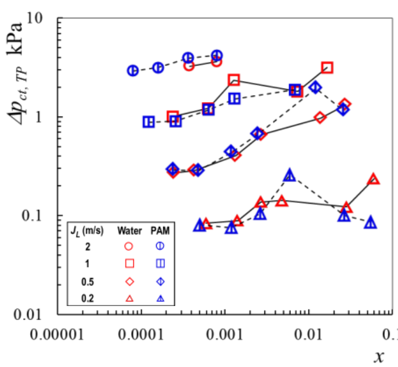


Figure 5. Contraction-loss for two-phase flow.

Contraction pressure drop correlations for two-phase flows in literatures are tested against the present data. For evaluating the accuracy in prediction, the following absolute mean and root mean square errors are used.

$$\varepsilon_M = \frac{1}{N}\Sigma(\Delta p_{c,cal} - \Delta p_{c,exp}) \quad (5)$$

$$\varepsilon_{RMS} = \sqrt{\frac{1}{N-1}\Sigma(\Delta p_{c,cal} - \Delta p_{c,exp})^2} \quad (6)$$

Table III lists the ε_M and the ε_{RMS} of six correlations against the present data. Of these, Schmidt & Friedel and Collier & Thom correlations give better prediction the other.

Figures 6 and 7 show examples of comparisons between the experiment and the calculations by Collier and Thom's and Schmidt & Friedel's correlations. Most of the data in $0.5 < j_L < 2$ m/s could be predicted by these correlations within 100 % in the relative error.

TABLE III. MEAN AND RMS ERRORS FOR SUDDEN CONTRACTION PRESSURE DROP PREDICTION

Correlation	ε_M kPa	ε_{RMS} kPa
Collier and Thome [13]	0.066	0.822
Chisholm [14]	3.872	6.066
Schmidt and Friedel [15]	-0.377	0.577
Slip flow model proposed by Abdelall et al. [6]	0.107	0.838
Abdelall et al. [6]	-0.315	0.787
Chen et al. [7]	7.892	32.677

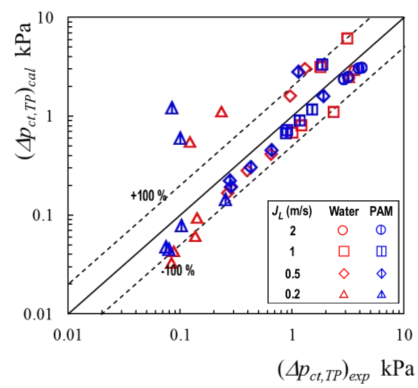


Figure 6. Comparison of $\Delta p_{ct,TP}$ between experiment and calculation by Collier and Thom's correlation..

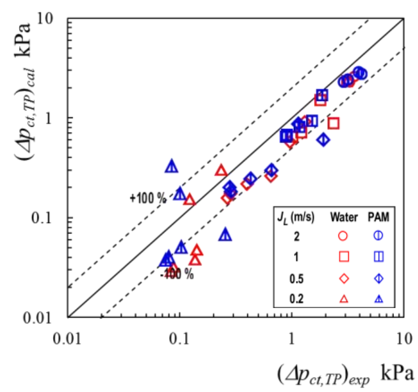


Figure 7. Comparison of $\Delta p_{ct,TP}$ between experiment and calculation by Schmidt and Friedel's correlation

IV. Conclusions

Liquid single-phase flow and air-liquid two phase flow experiments were conducted at room temperatue and at near atmospheric pressure using a horizontal rectangular minichannel with sudden contraction. The width and the height of the channel was from 6 mm by 3 mm to 3 mm by 3 mm. In order to study the effects of liquid viscosity, water and polyacrylamide (PAM) aqueous solution with mass concentration of 0.1 wt% were used as the test liquid. The main findings are as follows ;

1. Contraction coefficient data for the single-phase flows increases with Reynolds number and asymptotically approaches to a value calculated by Geiger's correlation.
2. Pressure drop due to contraction, $\Delta p_{ct,TP}$, for two-phase flows increases with the mass quality at a fixed volumetric flux of liquid, j_L. In addition, $\Delta p_{ct,TP}$ increases with j_L at a fixed quality.
3. The two-phase pressure drop data for both water and PAM aqueous solution were used to test six correlation in literature. Schmidth & Friedel's and Collier & Thom's correlations gave better prediction than others, except for the data at j_L = 0.2 m/s, whose accuracy in measurement was insufficient.

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