Journal of the Korean Nuclear Society
Volume 21, Number 2, June, 1989

An Experimental Investigation of the Effect of the Entrance Shape of Sudden Contraction on Single and Two-Phase Pressure Drop in Horizontal Air-Water Flow

Moon-Hyun Chun, Joo-Seok Baek and Jong-Ryul Park
Korea Advanced Institute of Science and Technology

(Received April 17, 1989)

공기와 물의 수평유동에 있어 관의 급격한 입구축소 모양이 단상 및 이상유 압력강하에 미치는 영향에 관한 실험적 연구

전문헌 · 백주석 · 박종률
한국과학기술원

(1989. 4. 17 접수)

Abstract

The pressure drops through contractions in horizontal single and two-phase flow were investigated. A total of 167 measurements were made for four different entrance shapes to study the effects of the entrance shape on the pressure drop through a contraction in horizontal single and two-phase flow. From this data, pressure drops were calculated and compared with the pressure drops predicted by analytical models for single and two-phase flow. For single phase flow the agreement between the data and predictions is within ±25%, whereas for two-phase flow Hoopes model, which gives a better agreement than the homogeneous model, underpredicts the data as much as 45%. In addition, the effects of void fraction and liquid phase mass velocity on the pressure drop through the sudden flow channel contraction were investigated for two-phase flow.

요 약

관의 급격한 축소모양이 단상 및 이상유의 수평유동 압력강하에 미치는 영향을 실험적으로 연구하였다. 급격하게 축소되는 수평관속을 흐르는 단상 및 이상유동에서 그 축소되는 입구의 모양이 압력강하에 미치는 영향을 조사하기 위해서 4가지의 다른 입구모양에 대해 총 167회의 압력강하 측정을 수행하였다. 여기서 얻은 실험자료로 부터 급격한 입구축소에 의한 압력강하를 계산하여 단상 및 이상유동에 관한 해석적 모델의 예측값과 비교하였다. 단상유동에서의 실험값과 예측값과의 오차범위는 대체로 ±25% 이내인데 반하여, 이상유동의 경우는 균일모델보다 더 잘 맞는 후프스(Hoopes)모델도 실험값보다 45% 정도나 적게 예측하고 있다. 특히 이상유동에 대해서는 기포분율과 액상의 질량속도가 급격한 유로축소에 의한 압력강하에 미치는 영향도 함께 조사하였다.

1. Introduction

One of the least-studied aspects of two-phase flow is that of the change in static pressure and the energy loss associated with entrance shape of sudden flow channel contraction. The losses through sudden enlargements and contractions may constitute a significant portion of the total pressure drop in forced and natural convective flow through the flow path with complex geometry. In nuclear reactor systems, the primary coolant encounters sudden contractions of the flow channel when the coolant enters into the core flow channels from the lower plenum of a reactor vessel, and also when the coolant enters into U-tubes from the lower plenum of a steam generator. The typical heat transfer applications, such as heat exchangers, involve a flow contraction at the entrance and a flow expansion at the exit.

The purpose of the present study is to investigate the effects of the void fraction and the entrance shape of sudden contraction on the pressure drop in horizontal two-phase (air-water) flow. In the present work, the pressure drops through four different entrance shapes of sudden flow channel contraction are determined experimentally and the data are presented in graphical form along with the predictions of existing models for single and two-phase flow.

2. Experimental Apparatus and Procedures

A. Test Apparatus

Fig.1 is a schematic diagram of single and two-phase flow test loop. The water leaving the pump passed through flow-measuring orifice, rotameter, and air-water mixer ; the air supplied from an air compressor passed through air flow meters and mixed with the water at the air-water mixer before entering the upstream test section. The two-phase fluid then passed through the entrance and downstream test sections and discharged to water reservoir.

1) Test Section :

The test section consisted of three parts : (1) upstream, (2) entrance, and (3) downstream sections, respectively. These three sections were connected in series by flanges. To visually observe the two-phase flow pattern in the measuring test section, the whole test sections were made of acryl tube. Detailed dimensions of test sections are shown in Fig.2. The upstream section consists of a 4 cm I.D. 150 cm long horizontal acryl tube preceded by an air-water mixer ; this provided 37.5 diameter of upstream pipe before the sudden contraction to be sufficient to serve as calming length and to obtain a fully developed flow.

For the entrance test section, on the other hand, four different shapes of entrance were made of acryl as shown in Fig.2. These shapes were selected to observe the effect of typical entrance geometries of sudden contraction on single and two-phase pressure drop. For convenience in presentation, the four different entrance test sections shown in Fig.2 are designated as Type–1 (Flush entrance), Type–2 (Re-entrant shape), Type-3 (Conical shape), and Type–4 (Slightly rounded shape), respectively.

The length and inside diameter of the downstream test section were 110 cm and 1.9 cm, respectively.

2) Instrumentation :

Water flow rate was measured by rotameters and orifice ; two rotameters (max. capacity of 9.65 liters/min each) were used in parallel to increase the range of measurement. When the flow rate exceeds the capacity of the rotameters, the precalibrated orifice meter was employed. For air flow rate measurement, on the other hand, two air flow-meters (max. capacity of 110 liters/min each) were used.

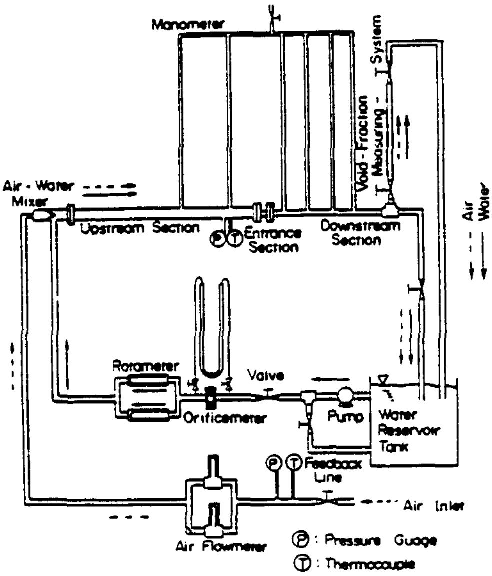
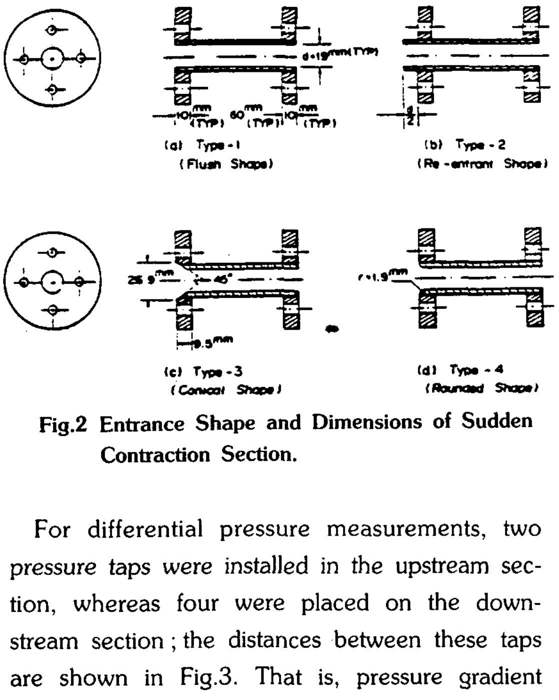


Fig.1 A Schematic Diagram of Experimental Apparatus.



(a) Type-1 (Flush Shape)

(b) Type-2 (Re-entrant Shape)

(c) Type-3 (Conical Shape)

(d) Type-4 (Rounded Shape)

Fig.2 Entrance Shape and Dimensions of Sudden Contraction Section.

For differential pressure measurements, two pressure taps were installed in the upstream section, whereas four were placed on the downstream section ; the distances between these taps are shown in Fig.3. That is, pressure gradient along the test sections including the sudden con*traction (i.e., the entrance section) were measured* with six manometers (water was used as manometric fluid) connected to the pressure taps. The manometers were 170 cm in height, 0.6 cm I.D., and provided with a scale graduated in 0.1 cm increments. Bypass lines are provided to remove the air bubbles from inside the connecting lines of manometers which otherwise will affect the pressure readings.

In addition, the average void fraction was measured by an acryl tube of 100 cm long and 2.5 cm in inside diameter mounted vertically at the end of the test section as shown in Fig.1. For each test run, void fraction was measured by simultaneously closing the two quick-closing valves installed at both ends of the tube, thus permitting the storage of the liquid columns of vertical tube. The void fraction can be determined by reading the water column contained in the acryl tube.

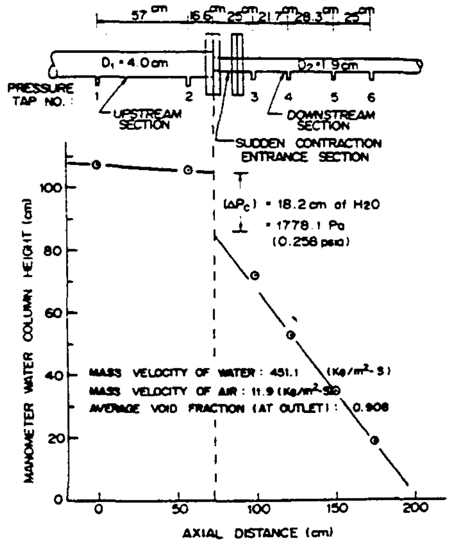


Fig.3 Pressure Variation Along a Test Section with Sudden Contraction.

B. Test Parameters

There are basically three controllable variables that must be considered in approaching a given test condition : (1) Number of phases (i.e., single or two-phase flow), (2) the sudden contraction entrance geometry, and (3) flow rates of each fluid. In this experiment, the best method for approaching a given condition was to keep flows of water and air to desired values.

The whole test program was divided into two parts : (1) single-phase and (2) two-phase tests. The total number of runs made for single and two-phase tests were 92 and 75, respectively. The breakdown of the tests for the four different shapes of sudden contraction is shown in Table 1, whereas the summary of test parameters is given in Table 2.

Table 1. Number of Runs Made for Single and Two-Phase Test

Sudden-Contraction Entrance Geometry	No. of Runs Made	
	Single-Phase Test	Two-Phase Test
(1) Flush Entrance(Type 1)	23	19
(2) Re-entrant Shape(Type 2)	23	18
(3) Conical Shape(Type 3)	21	19
(4) Slightly Rounded Shape(Type 4)	25	19
Total No. of Runs Made	92	75

Table 2. Summary of Test Parameters

Parameters	Single-Phase Test	Two-Phase Test
(1) System Pressure (at Inlet) (Pa) :	101300–140500 (14.7–20.4 psia)	101300–140500 (14.7–20.4 psia)
(2) Fluid Temperature (°K) :	285.2–289.9	285.2–289.9
(3) Test Section Position :	Horizontal	Horizontal
(4) No. of Sudden Contraction Geometry :	4 shapes	4 shapes
(5) Mass Inlet Velocity of Water(Kg/m^2-s)	366.8–2,303.1	233.3–1,099.9
Reynolds Number of Water	7,223–45,354	3,532–18,024
(6) Mass Inlet Velocity of Air(Kg/m^2-s) :	N/A	3.9–13.3
Reynolds Number of Air		3,717–12,436
(7) Outlet Void Fraction(α)	N/A	0.69–0.93
(8) Outlet Mass Flow Quality(x) :	N/A	0.004–0.043
(9) Flow Regimes	Turbulent	Turbulent and stratified flow

C. Test Procedure

To determine pressure drops due to a sudden contraction in single and two-phase flow in horizontal round pipes as a function of contraction shape, flowing mixture void fraction, and mass velocity, the follwing procedures were used ;

1. One of the four entrance test sections (i.e., types 1–4) was first installed between the upstream and downstream sections with two flanges.

2. After actuating the pump (for two-phase flow test, compressed air was allowed to flow into the air inlet), flow rate of water (and air for two-phase test) was adjusted according to the flow meters.

3. Flow patterns, pressure, and temperature at the inlet of the test section were checked.

4. When the flow became steady, the differential pressure measurements were made with U-tube manometers along with flow rates of water (and air for two-phase test.)

5. Void fraction was also measured using the quick-closing valves.

6. The above procedures were repeated at

different flow rates and with different entrance test sections.

3. Models Used for Predicting Single and Two-Phase Pressure Drop Through Contraction

A brief description of the methods used to predict the single and two-phase pressure drop through a sudden contraction is first given here for convenience in discussion.

A. Single-Phase

In single-phase flow, the static pressure change in sudden contraction between stations (1) and (2) (i.e., upstream and downstream) may be expressed as[1]

$$(\Delta P_c)_{SP}=(P_1-P_2)=\frac{G_2^2}{2g_c\rho_f}(1-\sigma^2)+K_c\frac{G_2^2}{2g_c\rho_f} \quad (1)$$

Since the losses are from the vena contracta to the reduced area the loss term is customarily given in terms of the downstream mass velocity (G_2). The first term in Eq.(1) is the pressure drop which would occur due to flow area change alone, without friction. The second term in Eq.(1) is the loss due to irreversible free expansion that follows the abrupt contraction ; the irreversible component of the pressure drop is contained in the abrupt contraction, or entrance coefficient K_c.

The contraction form loss is caused primarily by the turbulence and vortex motion created by the enlargement of the stream after it passes vena contracta. Therefore, K_c depends strongly upon the formation of vena contracta, which is affected primarily by following three factors : (1) Area contraction ratio (σ), (2) geometrical shape of the contraction entrace, and (3) Reynolds number. Figure 4.11 (Entrance loss coefficients) and Fig.4.9 (Values of K_c for a tube bundle) in Ref. [2] show the effects of these factors on the value of K_c.

The analytical expression for contraction loss coefficient is given by[3]

$$K_c=\left(\frac{q}{C_v^2C_c^2}-\frac{2}{C_c}+1\right) \quad (2)$$

Magnitudes of the velocity and contraction coefficients at the tube entrance, C_v and C_c, can be obtained from Tables 1 and 2 in Ref. [3]. In any case, values of the entrance loss coefficients have been determined experimentally.

K_c may be considerably reduced by rounding or tapering the inlet. A re-entrant tube, such as shown in Fig.2 (b) produces a maximum contraction of the entering stream because the streamlines come from around the outside wall of the pipe, as well as more directly from the fluid in front of the entrance. The degree of the contraction depends upon how far the pipe may project within the upstream and also upon how thick the pipe walls are, compared with its diameter. Figure 4.11 in Ref. [2] shows the ratios of K_c for a particular inlet shape to that for a sharp-edged entry.

B. Two-Phase

The two-phase pressure drop due to sudden contraction of flow channel area is usually expressed by multiplying the single-phase pressure drop by a two-phase multiplier. The two-phase multiplier depends on several parameters, such as the void fraction (α) and the relative velocity between the phases.

The expression for the static pressure drop across the contraction for two-phase flow is :[4]

$$(\Delta P_c)_{TP}=(\Delta P_c)_{SP}\Phi=[(1-\alpha^2)+K_c]\frac{G_2}{2g_c\rho_f}\Phi \quad (3)$$

It should be noted that $(\Delta P_c)_{TP}$ is static pressure drop across the contraction and not the pressure loss across the contraction which is

$$(\Delta P_{loss})_{TP}=K_c\frac{G_2}{2g_c\rho_f}\Phi \quad (4)$$

The functional form of Φ can sometimes be derived from the two-phase conservation equations, but it is normally synthesized empirically. Over the last three decades, a number of correlations have been proposed to calculate pressure drop across restrictions under two-phase bulk boiling conditions. A brief study was made to determine which model predicts the data best and to examine what significant difference exists between the various correlations. The correlations of particular interest in the present work are those of Geiger and Rohrer's homogeneous model[4,5] and Hoopes model.[6] There are several existing models to obtain a proper functional form of Φ.

1. Homogeneous Model : For homogeneous flow, the change in static pressure at a sudden contraction is given by the sum of the frictional dissipation and the theoretical kinetic energy change.[5]

$$(\Delta P_c)_{TP}=\frac{G_2^2}{2g_c\rho_f}[(\frac{1}{C_c}-1)^2+$$

$$(1-\sigma^2)]\,[1+(\frac{V_{fg}}{V_f})x]$$

$$=(\Delta P_c)_{SP}\,[1+(\frac{V_{fg}}{V_f})x] \tag{5}$$

For the homogeneous model, therefore, Φ can be expressed as

$$\Phi_{HOMO.}=[1+(\frac{V_{fg}}{V_f})x] \tag{6}$$

2. Hoopes Model : The model used by Hoopes[6] to predict orifice pressure losses can be expressed as

$$\Phi_{HOOPES}=\frac{x^2}{\alpha}(\frac{V_g}{V_f})+\frac{(1-x)^2}{(1-\alpha)} \tag{7}$$

Equation (7) can also be obtained from Romie's equation[7] when $\alpha_1=\alpha_2$ (i.e., when α is nearly the same upstream and downstream). Practically, for area ratios of 0.5 or larger and high void fractions, the change of void fraction across a flow restriction may be ignored, i.e., $\alpha_1=\alpha_2=\alpha$. In case of sudden enlargement, Eq.(7) can be derived analytically on the basis of separated flow model.

4. Experimental Results and Discussion

A. Experimental Determination of Single- and Two-Phase Contraction Pressure Drop

The pressure drop due to a sudden contraction of flow channel is not a directly measurable quantity but can be determined from static pressure measurements taken along the sections upstream and downstream of the area change :[4] The pressure gradients are first established on both sides of the sudden flow channel contraction by plotting these static pressures. The pressure gradients are then extrapolated to the point of the sudden flow channel contraction from both sides as illustrated in Fig.3. The pressure drop at the sudden contraction is defined here as $(\Delta P_c)_{SP}$ and $(\Delta P_c)_{TP}$ for single- and two-phase flow respectively. These are the increase in pressure drop due to the presence of a flow channel contraction.

Measurements of (ΔP_c) were made in single- and two-phase flow. For single-phase (i.e., water) flow, the inlet mass velocity varied between 366.8 and 2,303.1 Kg/m^2-s. For two-phase (water and air) flow, inlet mass velocity of water varied from 233.3 to 1,099.9 Kg/m^2-s, whereas that of air was between 3.9 and 13.3 kg/m^2-s ; this combination resulted in a stratified flow whose void fraction ranged from 0.69 to 0.93.

B. Analysis of Single-Phase Experimental Data

1) $(K_c)_{REF}$ versus $(K_c)_{SP\text{-}EXP}$:

The entrance-loss coefficients for four different entrance shapes shown in Fig.2 were first determined from the information given in Ref. [2,3] and they are designated here as $(K_c)_{REF}$. The $(K_c)_{REF}$ values are listed in the third column of Table 3.

Experimentally determined single-phase contraction loss coefficients, on the other hand, are defined as $(K_c)_{SP\text{-}EXP}$ and they are obtained from the following expression :

$$(K_c)_{SP\text{-}EXP}=\frac{(\Delta P_c)_{SP\text{-}EXP}(2g_c\rho_f)}{G_2^2}-(1-\sigma^2) \tag{8}$$

Equation (8) can be derived from Eq.(1) replacing $(\Delta P_c)_{SP}$ and K_c by $(\Delta P_c)_{SP\text{-}EXP}$ and $(K_c)_{SP\text{-}EXP}$. The$(\bar{K}_c)_{SP\text{-}}$

$_{EXP}$ values shown in Table 3 are mean values and standard deviations of $(K_c)_{SP\text{-}EXP}$ calculated by Eq. (8). Notice that the $(\bar{K}_c)_{SP\text{-}EXP}$ values are generally larger than $(K_c)_{REF}$ values except for the re-entrant shape.

2) Comparison of Experimental $(\Delta P_c)_{SP\text{-}EXP}$ Data and Predicted Values :

Experimental and predicted pressure drops due to sudden contraction for four different entrance shapes are graphically shown as a function of Reynolds number in Fig.4. Predicted $(\Delta P_c)_{SP}$ values are obtained from Eq.(1) using the $(K_c)_{REF}$ values listed in Table 3. Figure 4 shows that the pressure drop due to sudden contraction increases as Reynolds number increases for all entrance shapes. The agreement between the experimental data and model predictions is within ±25%. It should be noted that the model predictions might be somewhat improved if the more appropriate K_c values for each entrance shapes vere known.

Table 3. Comparison of Contraction Loss Coefficients for Various Entrance Shapes

Entrance Type No.	Entrance Shape	$(K_c)_{REF}$	$(\bar{K}_c)_{SP\text{-}EXP}$
1	Flush	0.459	0.52±0.08
2	Re-entrant	0.918	0.59±0.09
3	Conical	0.077	0.22±0.07
4	Slightly rounded	0.153	0.32±0.09

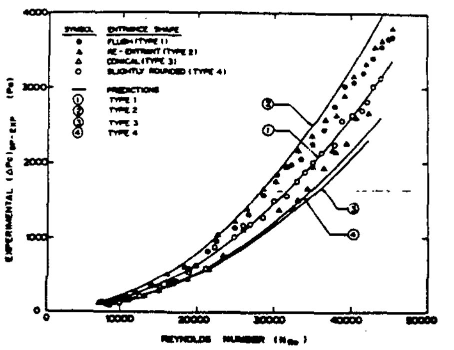


Fig.4 Comparison of Experimental Contraction Pressure Drops for Single-Phase Flow.

C. Analysis of Two-Phase Experimental Data

1) Comparison of Experimental Data with Predictions of Models :

The predicted pressure drops for the two models were calculated and are tabulated in Ref. 8. For the homogeneous flow model, $(\Delta P_c)_{TP}$ was calculated using Eqs. (3), (6) and measured flow quality, while Eqs. (3), (7), measured flow quality and void fraction were used for the Hoopes model. For both models, $(K_c)_{REF}$ listed in Table 3 is substituted for K_c in Eq.(3). These predicted pressure drops are plotted against the experimentally determined pressure drops and are shown in Figs. 5 and 6. The 45-degree line indicates where perfect correlation is achieved. In general, the homogeneous model over-predicts the experimental data, whereas the Hoopes model under-predicts the data. The maximum deviation between the predictions of homogeneous model[5] and the experimental data is as much as 218%, whereas the maximum deviation between the predictions of Hoopes model[6] and the data is 45%. The Hoopes model[6] consistemly gives a better agreement than the homogeneous model for the range of variables covered in the present work. The main reason for this may be attributable to the following : The test conditions in the present work were such that a stratified flow occurred in all the two-phase flow tests. Also, calculation of the slip ratio for the present two-phase flow test showed that the slip ratio varied from 3.38 and 1.28. Therefore, the homogeneous model[5] is not directly applicable since it assumes the slip ratio of unity. The Hoopes model[6], on the other hand, is based on the separated flow, and consequenty this model is readily applicable to the present two-phase flow tests where a stratified flow occurred. These comparisons are made assuming that the K_c values in single-phase flow and in two-phase flow are equal. It should be noted that the agreement between the data and the model predictions could be somewhat improved if the more appropriate K_c

values were known. However, nothing is definitely known about K_c values for two-phase flow, and even the published K_c values (for various entrance shapes) for single-phase flow are open to question.

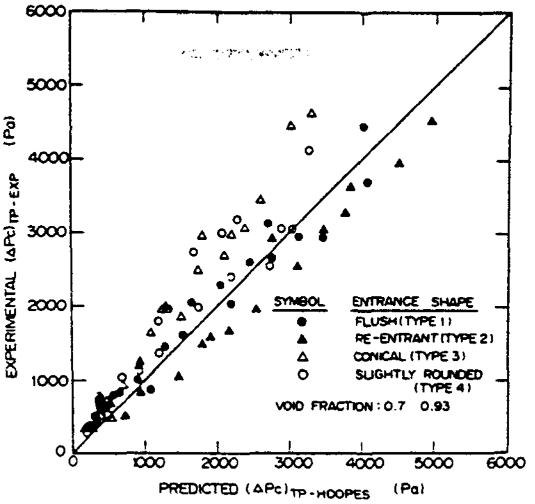


Fig.5 Comparison of Experimental Data with Predictions from Homogeneous Model for Two-Phase Contraction Pressure Drop.

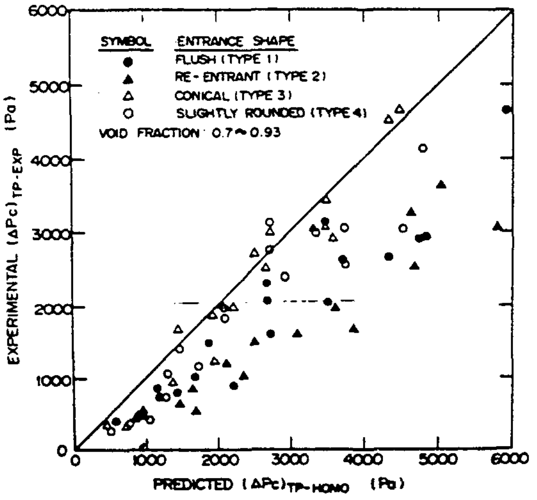


Fig.6 Comparison of Experimental Data with Predictions from Hoopes Model for Two-Phase Contraction Pressure Drop.

2) Effect of the Entrance Shapes of Sudden Contraction on $(\Delta P_c)_{TP\text{-}EXP}$:

Under approximately the same liquid mass velocity and void fraction, a few experimental two-phase pressure drops for four different entrance shapes are obtained and they are summarized in Table 4. This result shows that when the liquid-phase mass velocity and the void fraction are held constant the $(\Delta P_c)_{TP\text{-}EXP}$ increases in the following order :

Type 3<Type 4<Type 1<Type 2

This order is the same as that of the $(K_c)_{REF}$ for single-phase flow.

3) Effect of the Void Fraction on $(\Delta P_c)_{TP\text{-}EXP}$:

Experimentally determined two-phase pressure drops due to sudden contraction $(\Delta P_c)_{TP\text{-}EXP}$ are plotted against the void fraction α for all entrance shapes at similar liquid-phase mass velocity ranges as shown in Fig.7. This figure clearly shows that $(\Delta P_c)_{TP\text{-}EXP}$ increases as the void fraction α increases when G_l is held constant.

4) Effect of the Liquid-Phase Reynolds Number $(N_{Re})_l$ on $(\Delta P_c)_{TP\text{-}EXP}$:

As can be seen in Fig.8 $(\Delta P_c)_{TP}$ increases as the liquid-phase Reynolds number $(N_{Re})_l$ increases for all entrance shapes of sudden contraction.

5) Effect of the Liquid-Phase Reynolds Number on the Two-phase Multiplier Φ_{EXP} :

Figure 9 shows experimentally determined two-phase multiplier Φ_{EXP}. versus $(N_{Re})_l$ for all entrance shapes. The Φ_{EXP} values shown in Fig.9 are determined by using $(\Delta P_c)_{TP\text{-}EXP}$ and $(K_c)_{REF}$ in Eq.(3). This figure shows that, in general, Φ_{EXP} decreases as $(N_{Re})_l$ increases for all entrance shapes of sudden contraction. This indicates that as the liquid-phase mass velocity is increased the two-phase flow effect is decreased.

Table 4. Comparison of Experimental Two-Phase Pressure Drops Between Four Different Entrance Shapes of Sudden Contraction under Approximately the Same Liquid Mass Velocity and Void Fraction

Entrance Shape (Type No.)		Flush (1)	Re-entrant (2)	Conical (3)	Slightly Rounded (4)
	G_f	428.6			426.6
	α	0.85			0.85
	$(\Delta P_c)_{TP\text{-}EXP}$	977.0			898.8
	Run No.	#6			#62
2	G_f	882.1	891.0	884.4	
	α	0.73	0.73	0.74	
	$(\Delta P_c)_{TP\text{-}EXP}$	2335.0	2823.5	1817.2	
	Run No.	#13	#32	#50	
3	G_f	882.1			882.1
	α	0.86			0.86
	$(\Delta P_c)_{TP\text{-}EXP}$	4210.9			4057.4
	Run No.	#16			#72
4	G_f			1093.2	1093.2
	α			0.71	0.71
	$(\Delta P_c)_{TP\text{-}EXP}$			2628.1	3312.0
	Run No.			#54	#73

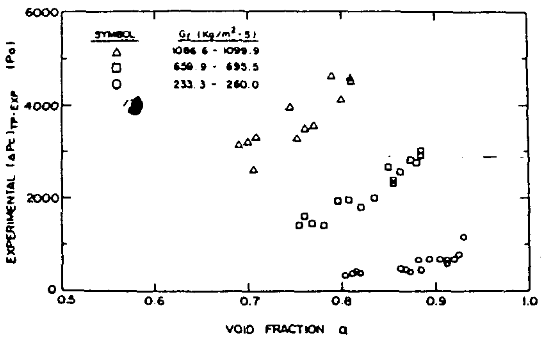


Fig.7 Two-Phase Contraction Pressure Drop Versus Void Fraction for All Entrance Shapes at Similar Liquid Mass Velocity Ranges.

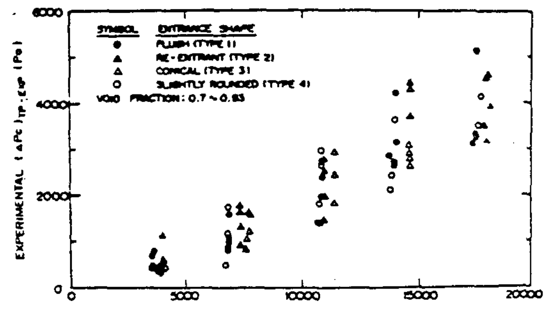


Fig.8 Two-Phase Contraction Pressure Drop Versus Liquid-Phase Reynolds Number for all Entrance Shapes.

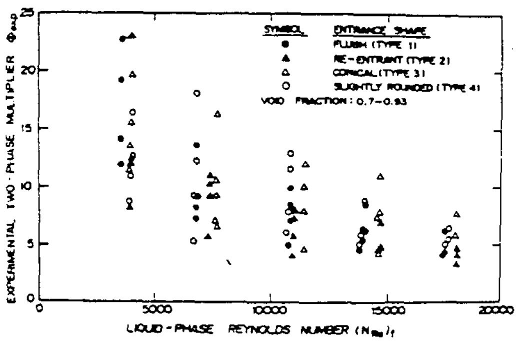


Fig.9 Experimental Two-Phase Multiplier Φ_{EXP} Versus Liquid-Phase Reynolds Number.

5. Conclusions

The pressure drops through contractions in horizontal single and two-phase flow were investigated. A total of 167 measurements were made for four different entrance shapes of sudden contraction at system pressures between 14.7 and 20.4 psia. From this data, pressure drops were calculated and compared with pressure drops predicted by analytical models. Plots of experimental pressure drop against predicted pressure drop for single-phase flow show that agreement is within ± 25%. For two-phase flow, even though Hoopes model underpredicts the data as much as 45% this model gives a better agreement than the homogeneous model for the range of variables studied in the present work. The measured pressure drops showed that the effect of entrance shape on the pressure drop in single and two-phase flow is very large. The magnitude of the pressure drop is closely related with the degree of flow distrubances caused by the flow-obstruction geometry and the pressure drop increases with the increase of the Reynolds number. For two-phase flow, in particular, the pressure drop increased as the void fraction is increased, whereas the two-phase flow effect is decreased as the liquid-phase mass velocity is increased. Finally, the pressure drop through the sudden flow channel contraction is much greater in two-phase flow than in single-phase flow.

Nomenclature

A	Flow area, m^2
A_c	Flow area at vena contracta, m^2
C_c	Contraction coefficient (A_c/A_2) of vena contracta
C_v	Velocity coefficient of entrance
g_c	Conversion factor
G_2	Mass velocity at the station downstream of the vena contracta, Kg/m^2-s
G_f	Mass velocity of liquid phase alone, Kg/m^2-s
K_c	Contraction loss coefficient, dimensionless
$(K_c)_{SP\text{-}EXP}$	Mean value of the contraction loss coefficient for single-phase flow determined by experimental data, dimensionless
N_{Re}	Reynolds number for single-phase flow, dimensionless
$(N_{Re})_f$	Reynolds number of liquid phase alone for two-phase flow, dimensionless
P_1, P_2	Static pressure, Pa
ΔP_c	Static pressure drop across the contraction, Pa
ΔP_{loss}	Static pressure loss due to sudden contraction, Pa
V_f	Specific volume of liquid, m^3/kg
V_{fg}	Difference in specific volumes of saturated liquid and vapor, m^3/kg
x	Mass flow quality, dimensionless
α	Void fraction, dimensionless
ρ_f	Density of liquid phase, Kg/m^3
σ	Area contraction ratio (A_2/A_1), dimensionless
Φ	Two-phase multiplier

Subscripts

1	At the station upstream of the area change
2	At the station downstream of the vena contracta
c	At the vena contracta station
EXP	Determined by experiment
f	Liquid phase
g	Gas phase
HOMO	Homogeneous model
HOOPES	Hoopes model
REF	Detemmined from Ref. [2,3]
SP	For single-phase flow
SP-EXP	For single-phase flow determined by experiment
TP	For two-phase flow
TP-EXP	For two-phase flow determined by experiment
TP-HOMO	For two-phase flow predicted by homogeneous model
TP-HOOPES	For two-phase flow predicted by Hoopes model

References

1. W.M. Rohsenow and J.P. Hartnett, Handbook of Heat Transfer, McGraw-Hill(1973), pp.7.12–7.13
2. W.M. Rohsenow and Harry Y. Choi, Heat, Mass, and Momentum Transfer, Prentice-Hall, Inc.(1961), pp.67–70
3. P.B. Robert et al., “Flow Losses in Abrupt Enlargements and Contractions,” Westinghouse Electric Corp., E-1435 (1964)
4. G.E. Geiger and W.M. Rohrer, “Sudden Contraction Losses in Two-Phase Flow,” J. Heat Transfer, pp.1–9(1966)

5. J.G. Collier, Convective Boiling and Condensation, McGraw-Hill, New York,(1981), pp.92–93
6. J.W. Hoopes, "Flow of Steam-Water Mixtures in a Heated Annulus and Through Orifices," AIChE Journal, pp.268–275 (1957)
7. J.O. Cermak, J.J. Jicha, an R.G. Lightner, "Two-Phase Pressure Drop Across Vertically Mounted Thick Plate Restrictions," J. Heat Transfer, 86, pp.227–239 (1964)
8. J.S. Baek, "Effects of the Void Fraction and the Entrance Geometry of Sudden Contraction on the Pressure Drops in Horizontal Air-water Flow," M. Sc. Thesis, Dept. of Nuclear Engineering, KAIST (1988)