Pressure losses in sudden transitions between square and rectangular ducts of the same cross-sectional area

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Experimental results are presented for the pressure loss in an abrupt sharp-edged transition (zero length) between square and rectangular ducts of the same cross-sectional area. The aspect ratios of the rectangular ducts were 0.3 and 0.625. A square screen ring with a square duct of length $9D$ (D=square side) was used to provide a fully developed flow at the entry. Rectangular ducts of the same length were used to allow flow redevelopment downstream of the transition section. All tests were run at Reynolds number 5×10^4 based on the flow in the square duct. Side and top wall static pressure variations along the flow duct are obtained. These variations are somewhat complicated and depend on the aspect ratio. The pressure loss coefficient is higher at low aspect ratio. The results are compared with previous test results published by the authors and with theoretical results obtained by the use of standard methods for abrupt contractions and expansions.

Keywords: ducts; transitions; pressure loss

Introduction

Energy losses occur in duct flows generated by changes of cross section. It is sometimes necessary to join different-shaped ducts by using transitional passages. Flow through these transitions is of considerable importance, since transitional systems are used in a wide range of applications. We previously published[1,2] experimental results for the pressure loss in transitions between square and rectangular ducts, and vice versa, where the two ends have the same cross-sectional area. It was found that an optimum length to hydraulic diameter ratio, for which the pressure loss is a minimum, exists. Though this ratio has not been found exactly, it is less than 2. Thus further tests are essential so that transitions may be designed with minimum energy losses. In this report, we are concerned with pressure losses in sharp-edged (sudden) transitions between square and rectangular ducts.

We present wall static pressure distributions along the ducts upstream and downstream of the transition plane. Horizontal and vertical velocity profiles are measured at several duct stations. The pressure drop is measured and compared to that of flows in divergent-convergent transitions reported previously. Standard methods[3,4] for sudden contractions and expansions were used to calculate the pressure drop in the sudden transitions for comparison with the experimental results.

Previous work

Many papers have been published on the performance of sudden enlargements and contractions in duct area. Most of this work considers only sudden transitions that have symmetric abrupt and overall area changes. However, a survey of the published literature on sudden transitions indicates no work has yet been published on sudden transitions between ducts of the same area but varying cross-sectional shapes.

The accuracy of the Borda-Carnot equation for losses of head due to sudden enlargement of a flow cross section was discussed by Schutt[5] in 1929. In 1962, Lipstein[6] described a series of experiments that studied the expansion of air from a nozzle into a long, constant diameter pipe for incompressible, turbulent flow. He obtained data for the pressure rise that could be expected as a function of axial distance downstream of the expansion interface. Moreover, using a perforated plate at various distances downstream of the expansion, he simulated the condition where blockage elements, such as heat exchangers, grids, or branching ducts, may interrupt the expansion process. In the same year, Abbott and Kline presented results for the flow over backward-facing steps covering a wide range of geometric variables. They gave velocity profile measurements for both single and double steps. The separated region was shown to consist of a complex pattern involving three distinct regions.

Idel'Chik[8] reported that the loss coefficient of a sudden expansion, with uniform velocity distribution over the section before the expansion and turbulent flow, is a function of the area ratio only for Reynolds number above 3500 and is calculated by the known Borda-Carnot formula. Benedict and Carlucci[9] and Benedict, Carlucci, and Swetz[10] examined losses associated with compressible and incompressible fluids flowing across abrupt area changes in the flow passages. A total pressure loss parameter is shown to have greater utility and validity than the usual loss coefficient for both compressible and incompressible flows.

Tyler and Williamson[11] reported results of measurements in a straight pipe equipped with sudden area enlargement ratios of 1.33, 1.71, 2.04, and 3.52 and crossflow-generated entry velocity distributions. The results have practical application on the performance of settling pipes located at diffuser exits where, in general, velocity distributions are significantly nonuniform. In 1968 and 1970, Heskestad[12,13] described an experimental study of the incompressible flow through a step expansion in a circular pipe with suction through an annular gap at the convex corner of the step. A uniform inlet flow with a thin boundary layer and fully developed turbulent pipe inlet flow are considered. He reported that whenever overall diffuser length is restricted to values less than some upper limit for a given expansion ratio, the suction device will produce pressure recoveries higher than conical diffusers.

Miller[14,15] presented loss coefficients for sharp-edged sudden contractions. He reported that a radius at inlet to the smaller pipe of 0.1 diameter reduces the loss coefficient to approximately 0.06 at a Reynolds number greater than 10^5. Most of this loss is due to flow redevelopment in the first several diameters of pipe after the contraction. He also presented loss coefficients for sudden expansions in area. He plotted curves that give the number of downstream pipe diameters needed for mixing to produce the maximum static pressure recovery.

The Engineering Sciences Data Unit[3,4] gives information on the pressure changes that occur in the flow along a circular duct with a sudden enlargement of area. The data for incompressible flow is presented as total and static pressure-loss coefficients for uniform and nonuniform flow. The values given represent the overall changes between the plane of the enlargement and the recovery plane (four exit diameters downstream) and are strictly applicable only to sudden enlargements with that length of duct downstream. Data is also given for sudden contractions where the approaching flow is fully developed and where there is a long duct downstream to allow redevelopment of the flow. Since most contractions are fairly insensitive to conditions near their inlets, a length of about four upstream diameters is usually sufficient.

Theory

The static pressure loss coefficient is defined by

$$C=\frac{P_1-P_3}{\frac{1}{2}\rho u_{\text{av}}^2} \tag{1}$$

where $u_{\text{av}}=Q/A$ and is the average velocity at the reference section.

For comparison with theoretical results, flow in transition sections of zero length between square and rectangular ducts may be treated as a sudden contraction from area A_1 to area A_0, followed at once by a sudden enlargement to area A_2 $(=A_1)$. In the contracting part, the pressure will fall due to the contraction and losses. However, in the diffusing part, the pressure will rise due to the expansion and fall due to losses. Thus the overall static pressure drop is

$$\begin{aligned} P_1-P_3 &= \text{the pressure drop in the contraction process} \\ &\quad -\text{the pressure recovery in the diffusing process} \qquad (2) \\ &=(P_1-P_0)-(P_3-P_0) \end{aligned}$$

or

$$C=C_{\text{c}}-C_{\text{d}}$$

where C_{c} is the pressure loss coefficient for the contracting part, and C_{d} is the pressure recovery coefficient for the diverging part.

This expression ignores any of the effects of interference arising from lack of downstream duct for the contraction and upstream duct for the expansion.

To obtain C theoretically, C_{c} and C_{d} may be calculated by using, respectively, data from the Engineering Sciences Data Unit[3] for the contracting part and the Borda-Carnot relation[4] for the expanding part.

Apparatus and experiments

The experimental test sections were square to rectangular sudden transitions made from perspex (see Figure 1). The square duct was of side 158 mm. Two different aspect ratios were used for the rectangular ducts: 0.3 and 0.625. All the square and rectangular duct areas were 250 cm^2 cross-sectional area. The areas at the transition plane are 135.88 cm^2 and 197.50 cm^2, respectively, at the aspect ratios 0.3 and 0.625, corresponding to area ratios (Ar) of 0.544 and 0.790. A square duct (upstream) of length 1264 mm ($L_{\text{u}}/D=8$) and a rectangular duct (downstream) of length 1422 mm ($L_{\text{d}}/D=9$) were used. Perspex flanges 5 mm thick (Figure 2a) were used to join the square and rectangular ducts. The upstream and downstream ends were attached to curved plywood sections (Figure 2b). Figure 2(c) shows a hand-cut square screen ring (inside dimensions 50 mm × 50 mm) made from 12 mesh woven wire cloth (25 s.w.g.). It was mounted between the flanges between the upstream contraction and the straight section. The assemblies were fitted into a 310 mm square by 300 cm long glass-sided water channel.

Each duct was fitted with a line of wall static pressure tappings of diameter 2 mm (50 mm apart) lying in a common vertical plane through the duct centerline. The square duct and rectangular duct with aspect ratio 0.625 were also fitted with a

Notation

A	Duct cross-sectional area, $A=D^2=(ab)$
A_0	Minimum cross-sectional area, $A_0=(aD)$
Ar	Area ratio, A_0/A
a, b	Sides of rectangular section
C	Overall pressure loss coefficient
C_{c}	Pressure loss coefficient for contracting part
C_{d}	Pressure recovery coefficient for diverging part
D	Side of square section
g	Aspect ratio, a/b
L	Duct length
L_{d}	Downstream duct length
L_{u}	Upstream duct length
P	Static pressure
P_0	Total pressure
Q	Volumetric flow rate
Re	Reynolds number
U	Maximum velocity
u_{av}	Average velocity
x_{d}	Axial position (downstream)
x_{u}	Axial position (upstream)
y	Perpendicular distance from wall surface
ρ	Fluid density

Subscripts

0	At transition plane
1	At station 1
2	At station 2
3	At station 3

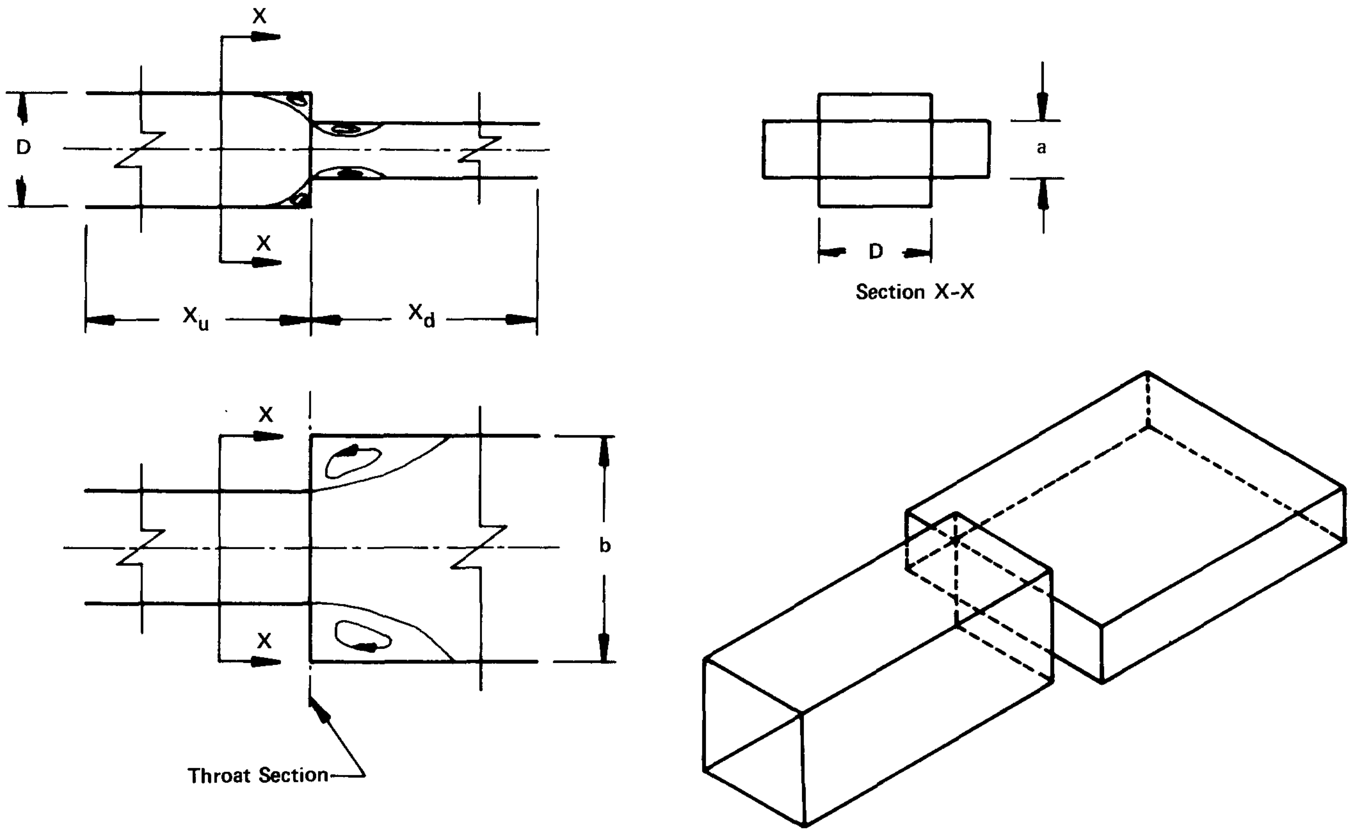

Figure 1 An abrupt transition between square and rectangular ducts

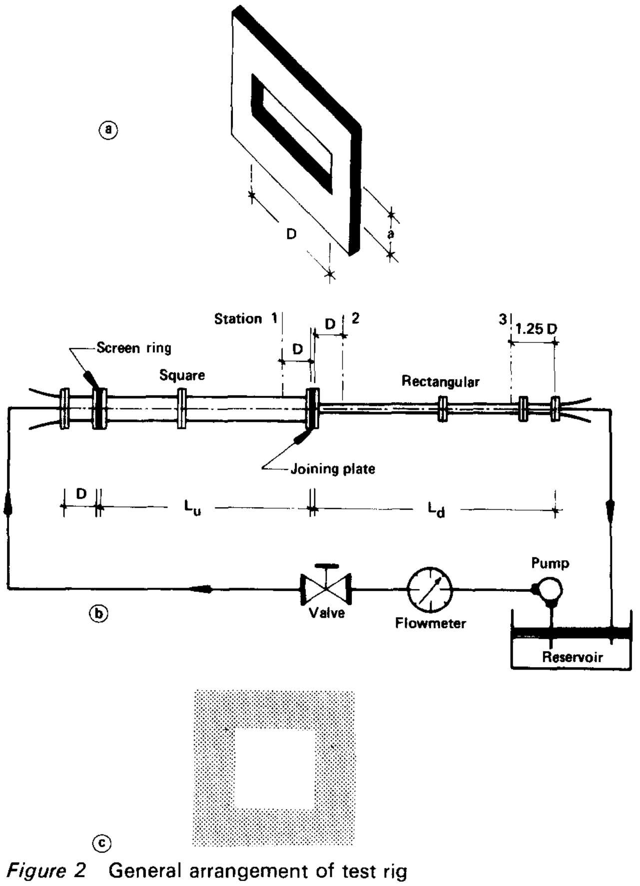

Figure 2 General arrangement of test rig

corresponding line of wall static pressure taps lying in a common horizontal plane through the duct centerline; (the channel width is not adequate for such tappings on the 0.3 aspect ratio duct).

All tests were run at Reynolds number of approximately 5×10^4 based on the hydraulic diameter of the square duct. Wall static pressures were measured at the wall tappings by means of water manometers. Traverse stations in vertical and horizontal planes through the centerline were available 158 mm ($x_u/D = 1$) upstream and 158 mm and 1224 mm ($x_d/D = 7.75$) downstream of the transition plane. Total and static pressures across the flow were measured with pressure probes mounted on a traverse gear. Pressure differences were measured by means of inclined water manometers accurate to within ± 0.125 mm. Figure 2(b) shows a general arrangement of the apparatus.

The estimated maximum errors in the various measured quantities are all $\pm 1\%$ or less, except the measurements of low velocities, which are subject to larger errors. Specifically, where reverse flow was observed, the magnitude was not ascertained. The cumulative maximum errors in the derived quantities are estimated to be $\pm 5\%$ or less.

Results and discussions

Comprehensive data collected during the test program included observations of the flow patterns and measurements of wall static pressure distributions and velocity profiles. The flow direction and size of separated regions were observed by injecting a fine stream of dye onto the wall and into the flow field through a capillary tube that could be passed through a wall pressure tapping.

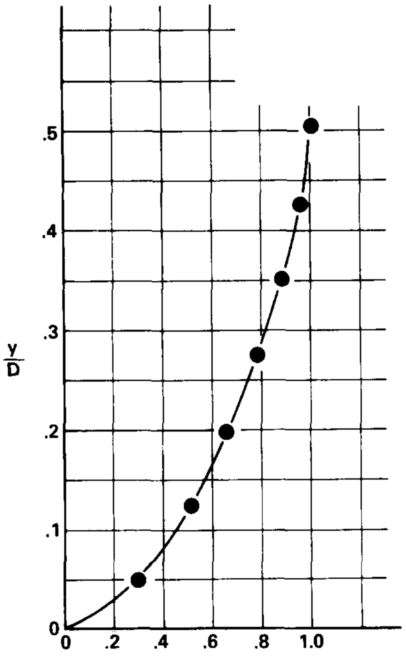

Figure 3 Inlet velocity profile

Velocity profiles

Inlet velocity profiles were measured at station 1, and exit velocity profiles were measured at stations 2 and 3 (Figure 2b) in vertical and horizontal planes through the duct centerline.

Inlet velocity profile

Use of the long inlet section (considered a settling length that prevents the screen ring from influencing the pressure measurements at the reference station because of the change of the turbulence pattern of the flow) and screen ring forced the flow to develop rapidly and provide approximately fully developed turbulent flow at station 1. Figure 3 shows the inlet velocity profile, which was approximately the same for all tests. Downstream of station 1 are two upstream stalled regions (Figure 1) along the top and bottom walls of the square duct due to the abrupt contraction. These regions extend to fill the top and bottom corners in the square duct. Because of the effect of the step height, these regions are larger in the transition with $g=0.3$ than in that with $g=0.625$. The separation points are roughly at $x_u/D=0.32$ and 0.15, respectively, in transitions with $g=0.3$ and 0.625.

Outlet velocity profiles

It is important to compare outlet velocity traverses in different aspect ratio sudden transitions for approximately the same fully developed flow at the entrance. Figures 4(a) and 4(b) show horizontal and vertical outlet traverses for sudden transitions of two different outlet aspect ratios.

Just upstream of the transition plane, the flow behavior is very complicated because of separated regions along the top, bottom, and sides of the rectangular duct (Figure 1). From velocity measurements and observations of flow direction, reverse flow is indicated in both transitions. The separated regions are larger at the lower aspect ratio.

Top and bottom wall separation regions exist only upstream of station 2. Use of a paint streak technique indicates the reattachment points are roughly at $x_d/D=0.44$ and 0.2, respectively, in transitions with $g=0.3$ and 0.625. Side wall separation regions exist upstream and downstream of station 2. The reattachment points are roughly at $x_d/D=2.2$ and 1.2, respectively, at $g=0.3$ and 0.625.

By station 3 at $x_d/D=7.75$ downstream, the flow has redeveloped (bearing in mind the small pressure loss along the duct compared to that which occurs in the transition). Figures 4(a) and 4(b) show the horizontal and vertical traverses at this station are quite similar.

Wall static pressure distributions

Figures 5(a) and 5(b) show the side and top wall static pressure variations along the flow ducts. The side wall static pressure distribution indicates an initial depression in pressure just before the transition plane and then gradually decreases toward a fully developed pipe flow value. The top wall static pressure distribution shows an initial rise just before the transition, followed by a deep depression and a rapid rise to attain a maximum value, and then gradually decreasing toward the fully developed flow value where the side and top wall static pressures are approximately equalized.

Downstream of the transition, the side and top wall static pressure distributions are very similar to those found after abrupt expansions and contractions, respectively, in duct area. The average of the side and top wall pressure distributions in the transition with $g=0.625$ is evaluated and also plotted in Figure 5(a). Roughly, this curve may be considered the average static pressure distribution along the flow duct.

Figure 5 also indicates the flow redevelopment process in the downstream duct takes place faster in transition with $g=0.625$ than in transition with $g=0.3$. The fully developed values are approximately at $x_d/D=1.6$ and 4.8 in transitions of aspect ratios $g=0.625$ and 0.3, respectively.

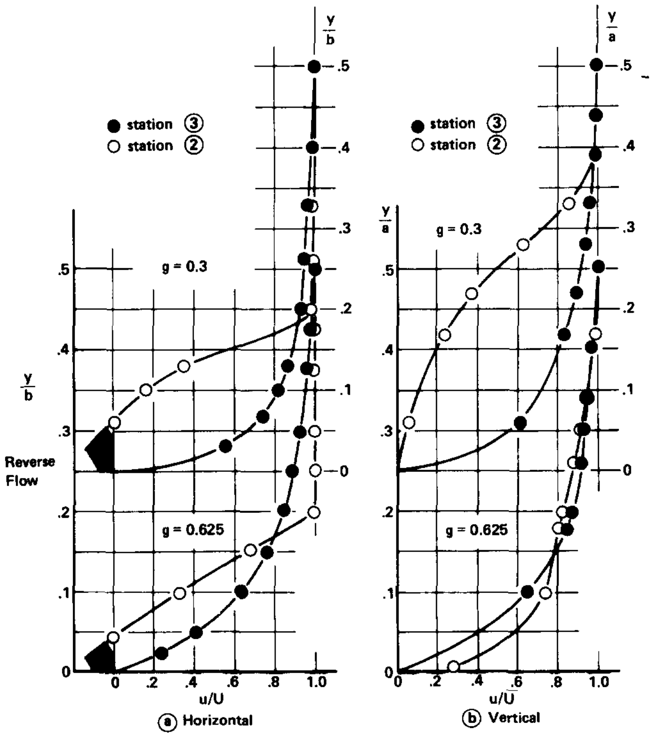

Figure 4 Outlet velocity profiles

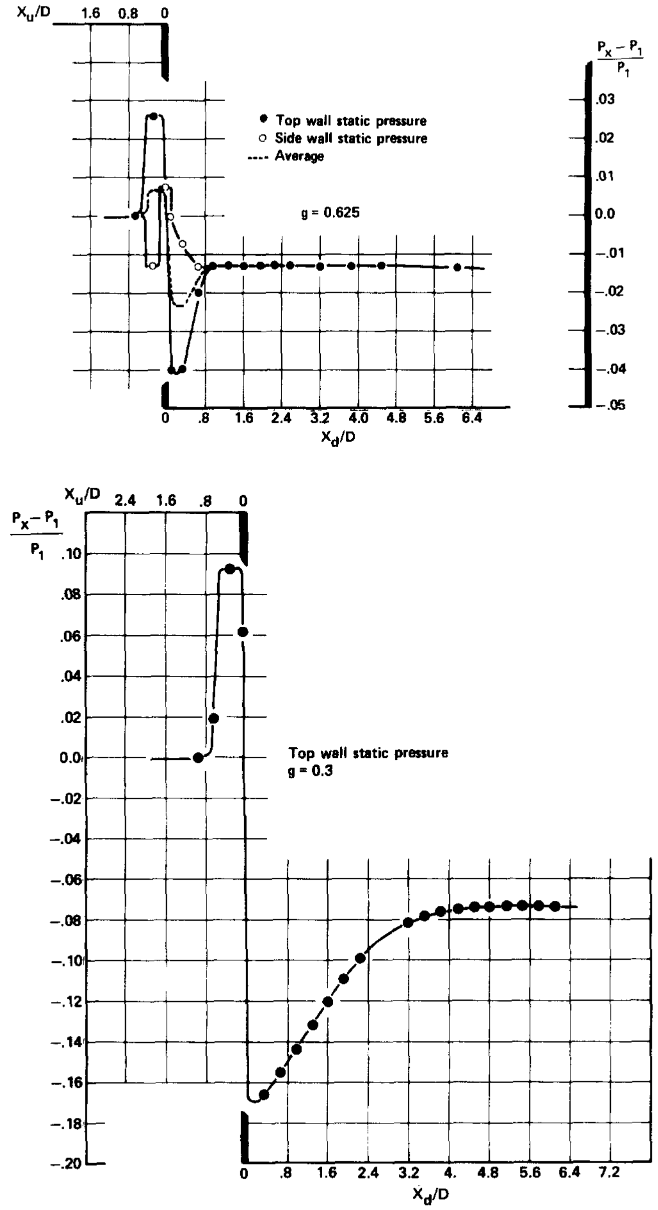

Figure 5 Wall static pressure distributions

Static pressure loss coefficient

Figure 6 plots the static pressure loss coefficient C. This figure shows the pressure drop increases as the aspect ratio of the rectangular duct falls. For transitions with $g = 0.3$ and 0.625, approximately $C = 1.92$ and 0.28, respectively. As the rectangular aspect ratio falls, the step heights rise in the flow path. Thus this increases the flow separation region and more fluid energy is dissipated. However, as g increases toward unity, the transition is between square and square sections, and the pressure drop tends to zero, as Figure 6 indicates.

In Figure 6, these results are compared with our previously obtained results from tests on divergent-convergent transitions[1]. For abrupt transitions with aspect ratio 0.3 and 0.625, the pressure drop increases by a factor of approximately 5.6 and 2, respectively, compared with transitions of length $L/D = 2$. These results confirm that there must be an optimum length between $L/D = 0$ and $L/D = 2$, which has not been found in this study.

Figure 6 also shows the calculated data obtained by considering the transition as a sudden contraction followed by a sudden enlargement. Good agreement exists between the experimental and theoretical results. The experimental results are approximately 4% and 27% higher at $g = 0.3$ and 0.625, respectively.

Effect of direction of flow

The direction of the flow in the sudden transition tested was reversed so that the pressure drop can be measured in rectangular to square sudden transitions. The same inlet duct length and a similar screen ring (inside dimensions 40 mm x 60 mm) were used to obtain fully developed flow at the reference station.

We found no significant difference in the pressure loss coefficient for the sudden transitions with reversed flow. This may be because of the equality of the area ratios (Ar) in both directions that govern the contraction and expansion processes. Neither pressure nor velocity distributions were measured with reversed flow.

Conclusions

We obtained the pressure loss in an abrupt sharp-edged transition between square and rectangular ducts of the same cross-sectional area from measurements of static pressure and total pressure at traverse stations in vertical and horizontal planes through the duct centerline. We also found the wall static pressure distribution along the ducts. These measurements were taken at Reynolds number of approximately 5×10^4 based on the flow in the square duct.

The pressure drop increases as the aspect ratio of the rectangular duct falls. This behavior may be explained in terms of increasing step heights in the flow path and, thus, larger separation regions and more fluid energy dissipation as the aspect ratio falls. Good agreement exists between these results and theoretical results obtained by considering the transition as a sudden contraction and an expansion separately. All the loss coefficients are much higher than our previously published test results on divergent-convergent transitions.

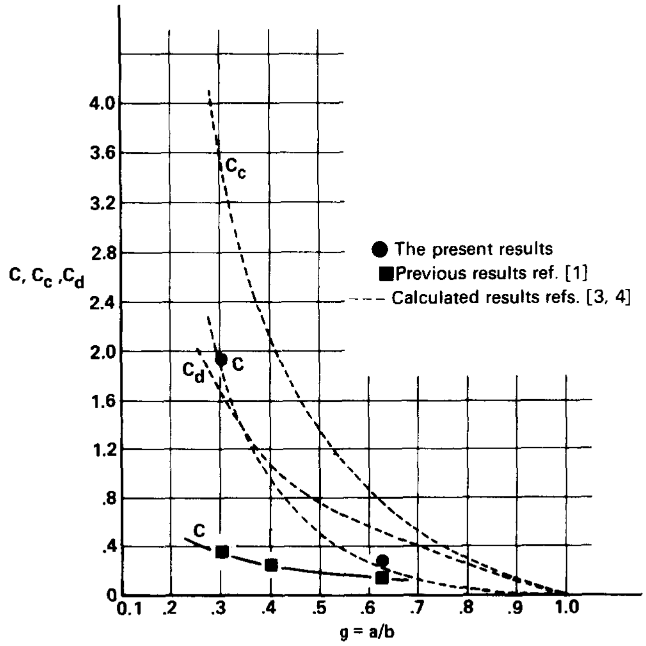

Figure 6 Effect of aspect ratio on pressure loss coefficient

Since the effect of edge blending is large on the performance of sudden contractions and expansions, conducting further experiments with different edge shapes would be of interest. This work could also be extended to study sudden transitions with offset centerlines, for example, where it is desirable to have a horizontal floor for access.

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