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Discharge Coefficients of Cooling Holes with Radiused and Chamfered Inlets

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Abstract

The flow of cooling air within the internal passages of gas turbines is controlled and metered using orifices formed of holes in discs and casings. The effects of inlet radiusing and chamfering of these holes on the discharge coefficient forms the subject of this paper. Experimental results for a range of radiusing and chamfering ratios for holes of different length to diameter ratios are presented covering the range of pressure ratios of practical interest.

The results indicate that radiusing and chamfering are both beneficial in increasing the discharge coefficient. Increases of 10 - 30% are possible. Chamfered holes give the more desirable performance characteristics in addition to being easier to produce than radiused holes.

Nomenclature

- C_d - Ratio of actual to theoretical mass flow through hole based on p_1^+/p_2
- D - Diameter of hole*
- L - Lenth of hole*
- p^+_1 - Upstream stagnation pressure
- p_2 - Downstream static pressure
- R - Radius of inlet rounding*
- Re - Hole Reynolds number = $\frac{vD}{\nu}$
- v - Velocity through the hole
- W - Chamfer depth*
- θ - Chamfer half cone angle*
- * - See Figure 5

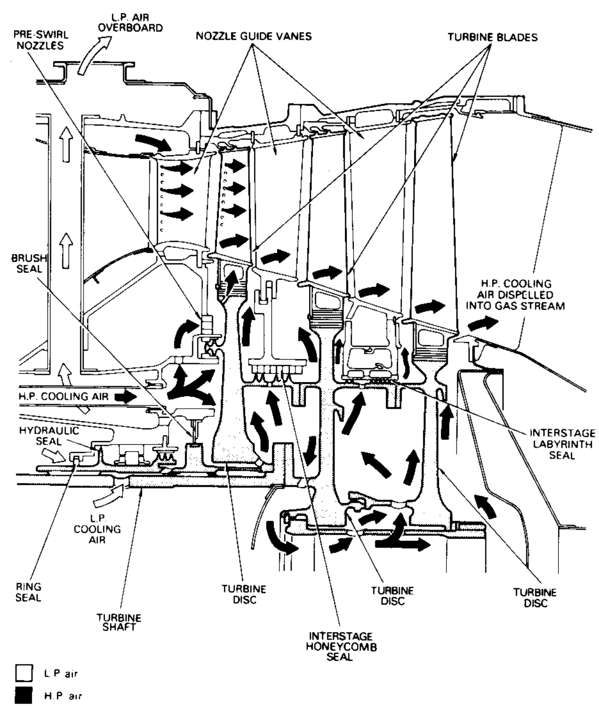

Fig. 1: Internal air cooling in an aero-engine (Ref. 8)

1. Introduction

Gas turbine engines incorporate a multiplicity of internal passages which serve to channel the cooling air tapped from the compressors to the various components to be cooled, Fig. 1. These internal flows need to be metered and the pressure drop associated with the metering needs to be as low as possible.

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Metering is effected by holes in casings, discs and blades which could have a wide range of length to diameter ratios and which will operate at an equally wide range of pressure ratios. In the design of the air distribution system knowledge of the value of the discharge coefficient C_d for these holes is required for the whole range of operating conditions envisaged.

The usual method of keeping the pressure drop associated with metering as low as possible is to use rounded instead of sharp edges at entry to the metering hole or orifice. For short orifices, rounding, or more precisely radiusing helps to reduce or suppress the vena contracta associated with the sharp edge as shown in Fig. 2. Thus the discharge coefficient rises above the value of 0.61 associated with sharp edged short orifices. For a given flow this means that metering can be effected with a smaller pressure drop penalty.

If a sharp edged orifice is long enough (L/D > 2.0) the flow reattaches downstream as shown in Fig. 3 and produces a measure of pressure recovery. Thus the coefficient of discharge will be higher than for the corresponding short orifice. Radiusing is still beneficial but not to the same extent as for short orifices. The improvement in the case of the short as well as the long orifice is a function of the extent of radiusing expressed as the ratio R/D. The discharge coefficient will also be a function of the Reynolds number although for the particular application in point the Reynolds number is high enough ($>2 \times 10^4$) for its effect to be negligible.

Radiusing and the control of the degree of radiusing present manufacturing difficulties and hence increased cost. Chamfering is much easier and cheaper to produce. Thus if chamfering can approach radiusing in the extent of the improvement of C_d it could prove to be a preferable alternative.

This paper presents results of experimental measurements of C_d for a range of the parameters L/D and pressure ratio, for sharp edged orifices, radiused orifices at various R/D ratios and for 45° chamfered holes and some 30° chamfered holes for a range of chamfering ratios W/D.

2. Previous Work

Deckker and Chang [1] investigated the compressible flow through thick orifices. They compiled data for sharp edged orifices with length to diameter ratios of 0.0, 0.5, 1.0 and 2.0. Their findings showed that there was little dependence of the discharge coefficient on the pressure ratio above a pressure ratio of 2 when the flow chokes. They draw the conclusion that the length to diameter ratio is important because of the possibility of jet re-attachment, and the behaviour of the orifice can be explained on this basis. They also draw attention to marginal attachment/separation which can exist in some cases and which form an unstable area of operation which should be avoided since C_d may vary significantly. This was also noted by Ward-Smith [2].

Lichtarowicz et al [3] investigated non-compressible flow through long orifices. They gave details of the dependence of the discharge coefficient on the hole Reynolds number, as did Deckker and Chang [1], showing this to be negligible for $Re > 2 \times 10^4$. They found that C_d can be somewhat unpredictable for length to diameter ratios between 0.5 and 2.0 due to the effects of jet re-attachment. Length to diameter ratios of up to 10 were tested.

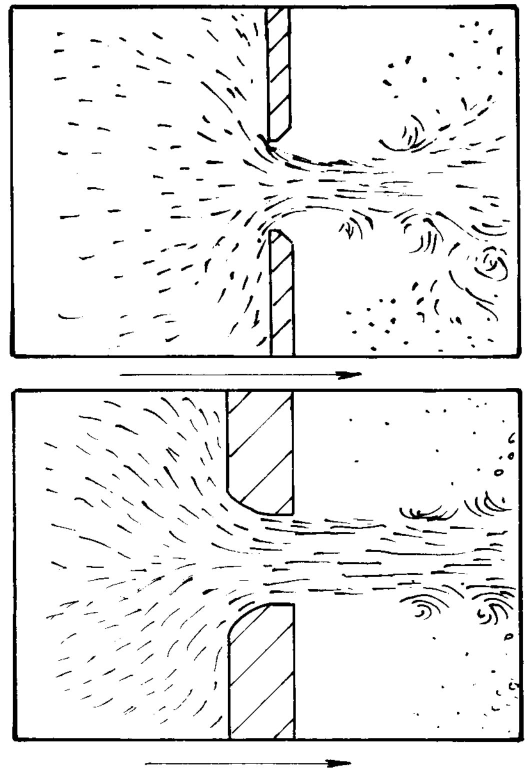

Fig. 2: Flows through sharp edged and radiused holes (based on flow visualisation, Ref. 9)

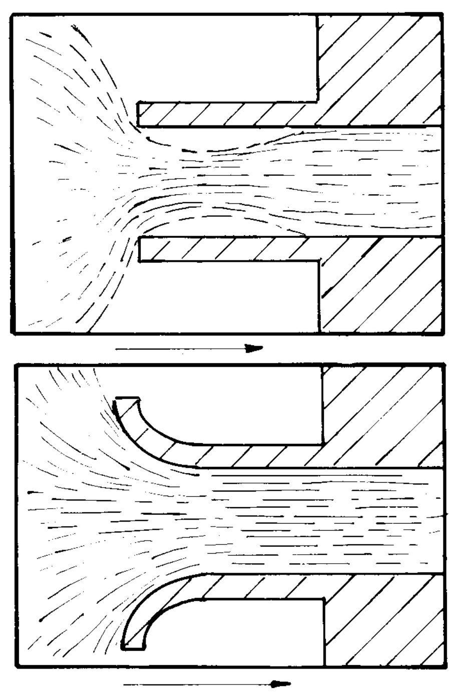

Fig. 3: Reattachment in a long orifice and the effect of inlet radiusing (based on flow visualisation, Ref. 9)

Hay et al [4] studied the combined effects of inlet radiusing and cross-flows on long orifices with length to diameter ratios of up to 6. They proceeded by producing a base line set of results with no cross flow, and then compared results with cross flow by

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relating the two by an additive loss coefficient. This base line set of results provides a further source for comparison.

McGreehan and Schotsch [5] presented a method for calculating the discharge coefficient of long orifices with rotation and corner radiusing in terms of the discharge coefficients produced by each of these effects individually. They conclude that this method produces quite accurate results. Though the method is tedious to calculate by hand it is well suited to computer coding. Here length to diameter ratios of up to 10 are considered.

Briggs [6] investigated the effect of inlet radiusing on the discharge coefficient for length to diameter ratios of 0.25, 0.5, 1 and 2 on the same rig as used for the present chamfered holes investigation. These results which are also presented here provide the basis on which the comparisons between inlet radiusing and inlet chamfering are made.

3. The Test Rig

The rig, shown in Fig. 4, consisted of a 100 mm diameter plenum which was designed to sit on existing ducting fed with air from a screw compressor through a control valve. The lid of the plenum housed the test orifices which were secured by four smoothed countersunk screws. The air from the test orifice was then ducted to an orifice meter designed to BS 1042 and then vented to atmosphere. The pressure ratio across the test orifice was varied using the control valve to give the range of 1 to 2.2. Pressures were measured using appropriate manometers. The data from the rig were fed to a computer for immediate analysis.

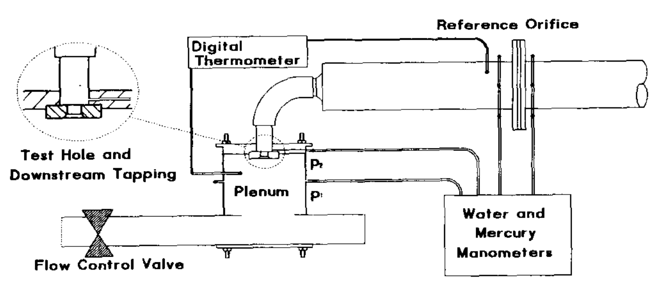

Fig. 4: General arrangement of the test rig

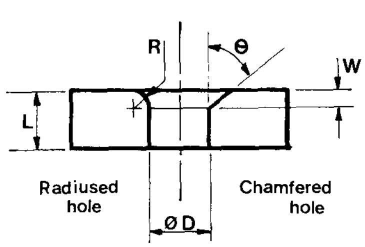

Fig. 5: Hole geometries

The test orifices were made to the same diameter of 10 mm as previously used by Briggs [6]. This diameter was sufficiently small to achieve the minimum specified Reynolds number of 2 x 10^4 with the available flow, ensuring that the discharge coefficient is independent of the Reynolds number. Fig. 5 shows a drawing of a test orifice on which the radiused and chamfered geometries are shown. A range of values of R and L, and W and L were specified on the basic diameter of 10 mm to give the ranges of R/D, W/D and L/D of 0 - 0.2, 0 - 0.2 and 0 - 2 respectively. After manufacture each orifice was checked to ensure that there were no burrs and that the dimensions were correct.

4. Results

Measurements of C_d were made at six or seven pressure ratios between 0 and 2.2 for the range of geometries listed above. Representative results can be seen in Table 1. This table shows the discharge coefficient for only three pressure ratios, chosen to straddle the whole range, and for each combination of length to diameter ratio and chamfering (and radiusing) to diameter ratio. Also shown in the table is the extent of variation of C_d in the range of pressure ratios between 1.2 and 2.2.

We will look at representative results in more detail first and then comment on the general trends as exhibited by the whole set of data.

4.1 Comparison with other results in the literature

The results for the sharp edged holes (R/D = 0, W/D = 0) were compared with those of Deckker and Chang [1]. A typical comparison is shown in Fig. 6 for L/D = 0.25. It can be seen that all the data fall within a band of ± 5%. The same spread was

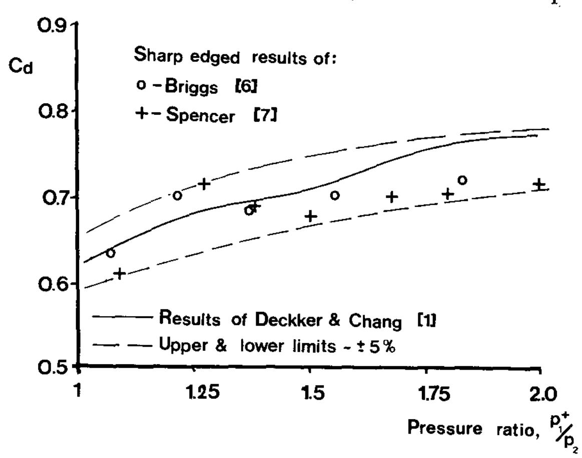

Fig. 6: Comparison of sharp edged results L/D = 0.25.

found to apply for the other L/D ratios. Thus the results can be taken to have an uncertainty of ±5%. For the length to diameter ratio of 0.25 there is good agreement between all three sets of data. For length to diameter ratios of 0.5 and 1.0 the results of this experimental investigation and those of Briggs [6] are consistently 5% less than those of Deckker and Chang [1]. However, Lichtarowicz [3] in his investigation of long orifices concludes that below L/D = 1.5, the discharge coefficient varies rapidly with L/D. This could account for the difference in this unstable region where marginal re-attachment occurs. Finally for the length to diameter ratio of 2 the three sets of data again correlate well except for Briggs' [6] results at low pressure ratios. From this comparison it is concluded that the results obtained in this investigation are sufficiently reliable and show the trends well.

4.2 The effect of pressure ratio

The variation of the discharge coefficient with the pressure ratio can be seen in Fig. 7. This is typical of all geometries tested.

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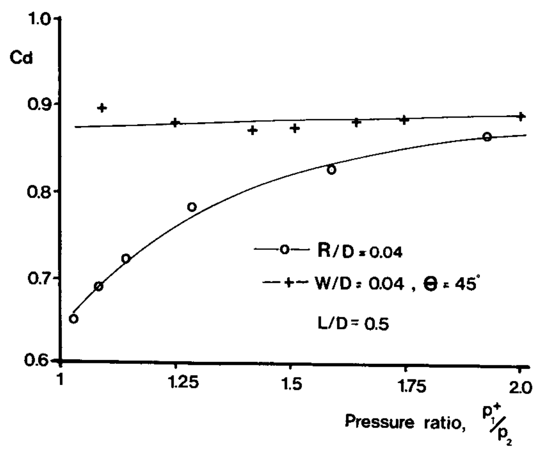

Fig. 7: Dependence of C_d on pressure ratio for inlet radiused and chamfered holes

It can be seen from Fig. 7 and from Table 1 that by increasing the pressure ratio the discharge coefficient is increased, the amount of increase depending on the hole geometry. This increase levels off at a pressure ratio of around 2 when the flow chokes. This is in line with the results of Deckker and Chang [1]. The general trends of the effect of pressure ratio on C_d can be gleaned from the "range of C_d" section of Table 1. The thin holes, L/D = 0.25, can be seen to have the strongest dependence on the pressure ratio for all W/D and R/D ratios with variations in C_d of about 10 to 15%. For chamfered holes this dependence almost disappears as L/D and W/D are increased. Hence if a hole is required where the discharge coefficient is to vary little with the pressure ratio then the hole should have a L/D > 1.0, and incorporate some inlet chamfering. For inlet radiusing the results show a dependence on the pressure ratio for every radiusing ratio with variations of about 15%. For this reason inlet chamfering would be more desirable.

4.3 The effect of length to diameter ratio

The effect of the parameter L/D has been the subject of past publications and formulae have been derived to model the effect with good accuracy. McGreehan and Schotsch [5] were able to derive an empirical expression for sharp edged holes which fitted the C_d results of Lichtarowicz et al [3] to within 0.02. The shape of this curve is shown in Fig. 8. The effect of chamfering or radiusing is to cause the plateau of maximum discharge coefficient to start at a lower value of L/D. Therefore using a chamfered or radiused inlet reduces the length of a hole required to avoid a strong dependence of the discharge coefficient on L/D. With a sharp edged hole Lichtarowicz [3] suggested L/D should be greater than 1.5 to avoid this strong dependence. Now this can be reduced to between 0.5 and 1.0 if required by using a small chamfer. This is because the flow will re-attach to the wall closer to the inlet of the hole when the hole is chamfered. Lichtarowicz [3] found that for the sharp edged hole C_d dropped linearly from the maximum to 0.74 at L/D=10. The peak in C_d is not obvious in Fig. 7 because the hole is short and the frictional effects which lead to the subsequent drop in C_d are not manifested.

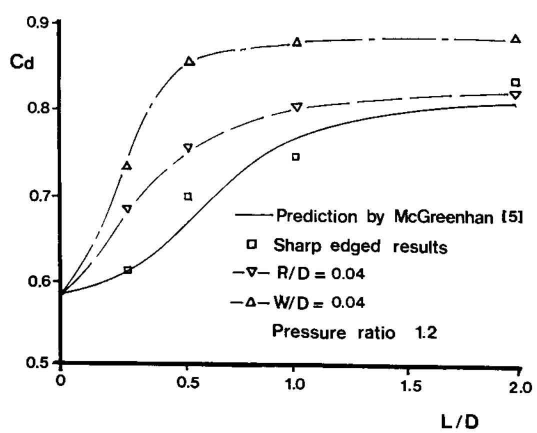

Fig. 8: Dependence of C_d on length to diameter ratio

4.4 The effect of inlet radiusing

Inlet radiusing increases the discharge coefficient, Fig. 9. At a pressure ratio of 1.6 (Table 1) maximum increases of 27%, 19%, 17% and 14% were found for length to diameter ratios of 0.25, 0.5, 1.0 and 2.0 respectively. The effects of inlet radiusing have been the subject of past investigations and again McGreehan and Schotsch [5] have produced a correlation to model this effect. A comparison between this correlation and Briggs' [6] results can be seen in Fig. 10. It can be seen that there is a good correlation between the experimental and the predicted results.

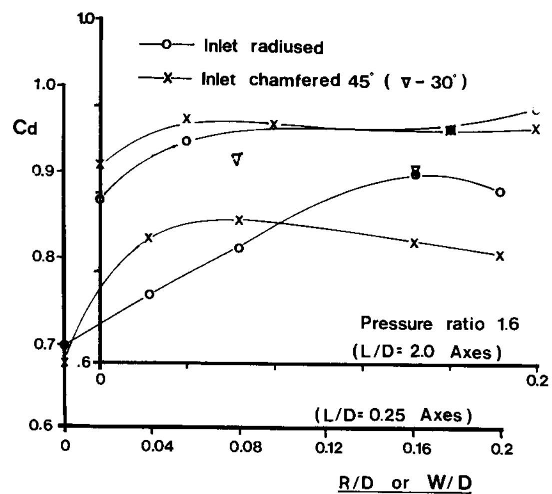

Fig. 9: Effect of inlet radiusing and chamfering on C_d at two length to diameter ratios

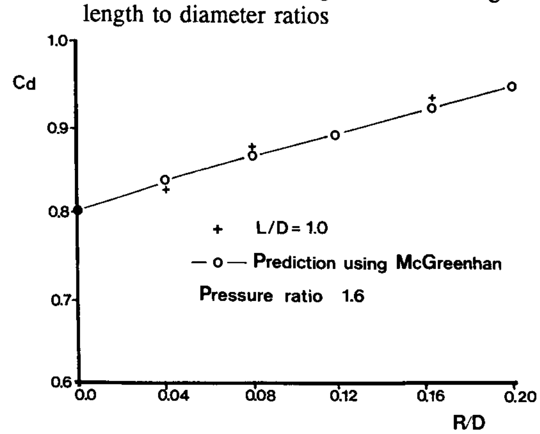

Fig. 10: Comparison of experimental results and prediction for radiused inlet holes

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Table 1: Representative Results for Three Pressure Ratios

		Radiused Inlet					Chamfer angle 45°					Chamfer angle 30°				
		R/D	L/D				W/D	L/D				W/D	L/D			
			0.25	0.5	1.0	2.0		0.25	0.5	1.0	2.0		0.25	0.5	1.0	2.0
Pressure ratio p^+_1/p_2	1.2	0.00	0.62	0.68	0.79	0.75	0.00	0.62	0.71	0.74	0.83	0.00				
		0.04	0.68	0.74	0.76	0.79	0.04	0.73	0.85	0.86	0.87	0.04				
		0.08	0.79	0.83	0.83		0.08	0.73	0.86	0.88	0.86	0.08	0.90	0.94	0.94	0.95
		0.16	0.80		0.86	0.86	0.16	0.74	0.86	0.88	0.88	0.16	0.90	0.94		
		0.20	0.78	0.83		0.84	0.20	0.75	0.86	0.88	0.88	0.20				
	1.6	0.00	0.70	0.73	0.80	0.79	0.00	0.68	0.74	0.77	0.83	0.00				
		0.04	0.76	0.81	0.83	0.86	0.04	0.82	0.87	0.88	0.88	0.04				
		0.08	0.81	0.88	0.88		0.08	0.83	0.88	0.88	0.88	0.08	0.90	0.95	0.94	0.95
		0.16	0.89		0.94	0.88	0.16	0.82	0.88	0.88	0.88	0.16	0.90	0.94		
		0.20	0.87	0.90		0.90	0.20	0.81	0.87	0.88	0.89	0.20				
	2.2	0.00	0.75	0.76	0.84	0.86	0.00	0.74	0.79	0.82	0.85	0.00				
		0.04	0.84	0.86	0.88	0.88	0.04	0.87	0.88	0.89	0.89	0.04				
		0.08	0.89	0.92	0.89		0.08	0.87	0.89	0.89	0.88	0.08	0.93	0.95	0.94	0.95
		0.16	0.91		0.96	0.96	0.16	0.87	0.92	0.89	0.88	0.16	0.92	0.94		
		0.20	0.94	0.95		0.94	0.20	0.86	0.88	0.88	0.89	0.20				
Range of Cd for $1.2 < p^+_1/p_2 < 2.2$		0.00	0.13	0.08	0.05	0.11	0.00	0.12	0.08	0.08	0.02	0.00				
		0.04	0.16	0.12	0.12	0.09	0.04	0.14	0.03	0.03	0.02	0.04				
		0.08	0.10	0.09	0.06		0.08	0.14	0.03	0.01	0.02	0.08	0.03	0.01	0.00	0.00
		0.16	0.11		0.10	0.10	0.16	0.13	0.08	0.01	0.00	0.16	0.02	0.00		
		0.20	0.16	0.12		0.10	0.20	0.11	0.02	0.00	0.01	0.20				

The increase in C_d with increasing R/D occurs in view of the fact that as the radius becomes larger the local acceleration of the fluid around the periphery drops and separation becomes less likely.

4.5 The effect of inlet chamfering

It is clear from the results (Table 1) that inlet chamfering significantly increases the discharge coefficient. At a pressure ratio of 1.6 the discharge coefficient could be improved by 22%, 19%, 14% and 6% for length to diameter ratios of 0.25, 0.5, 1.0 and 2.0 respectively. At least 95% of this increase had been achieved at a chamfer ratio of 0.04. These trends can be seen in Fig. 9. The reason for this increase is that the chamfer reduces the size of the vena contracta by encouraging the flow to enter the hole axially. some separation at the inlet is still expected but to a much lesser degree than for the sharp edged hole. It appears that the size of the vena contracta remains constant as the chamfer ratio is increased above 0.08, i.e. increasing W/D gives no further benefit. Figure 9 also shows that for L/D = 0.25, the discharge coefficient drops fractionally as the chamfer ratio is increased beyond 0.08. A similar behaviour was observed with L/D = 0.5 and 1.0. The reason for this drop is that in this range of L/D the flow is marginally re-attached and as the chamfer depth is increased there is less pressure recovery within the hole, which leads to a reduced C_d. This phenomenon does not occur when the hole L/D = 2.0. Here the flow always re-attaches within the hole and so no drop in C_d occurs with increase in W/D (Fig. 9). A much deeper chamfer would be required before the flow could become separated at exit. Therefore we see that there is a distinct limit to the improvement that can be made by increasing the chamfering ratio for thin holes. Also for holes with L/D > 2.0, C_d is virtually independent of the chamfering ratio. This allows designers to specify broader tolerances on the chamfering depth, thereby easing manufacturing difficulty and cost.

4.6 The effect of the chamfer angle

The holes tested were predominantly chamfered at 45°. However, it was thought important to test a different angle to see how much of an effect this had. From the results (Table 1) it is evident that chamfering at 30° gives a considerable increase in C_d over chamfering at 45°. More importantly there is an even smaller dependence on the pressure ratio. This is a desirable feature when designing the holes to control the flow as it means that the discharge coefficient is much more predictable.

Fig. 11 shows a comparison between the two chamfering angles for W/D = 0.08. We see from Fig. 11 that altering the chamfer angle to 30° does not affect the way in which C_d varies with L/D but increases its value by about 0.07. Fig. 12 shows the expected dependence of C_d on the chamfer angle based on the three points known. The value at 90° is deduced from the fact that at 90° the hole will again be sharp edged but shorter by the depth of the chamfer and can then be predicted from Fig. 11. In order to locate the exact position of the maximum C_d further tests would be required on at least two more chamfering angles less than 30°.

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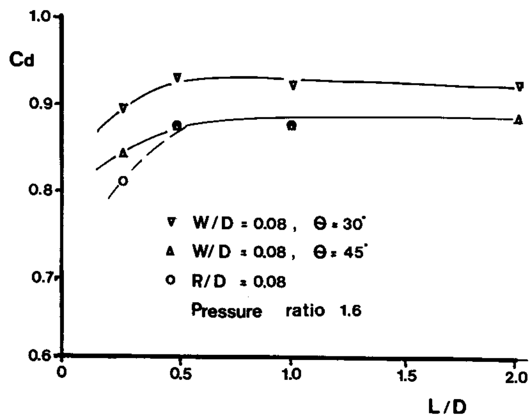

Fig. 11: Dependence of C_d on chamfering angle

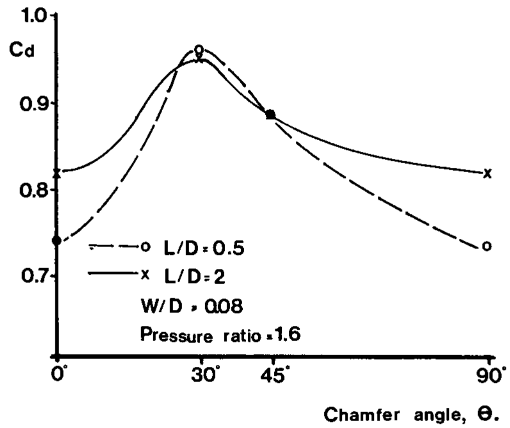

Fig. 12: Predicted variation of C_d with chamfering angle

4.7 Comparison between inlet radiusing and chamfering

Fig. 9 shows the effects of increasing W/D and R/D for L/D = 0.25 (similar trends are shown at other L/D ratios). It is evident that at small chamfering or radiusing ratios the chamfered hole has a higher C_d. At a ratio of about 0.08 the graphs cross over and above this ratio the radiused hole has the higher C_d. However, by using a 30° chamfer instead of a 45° chamfer C_d increases to the same level as the maximum achieved by radiusing (Fig. 9). It is seen from Fig. 7 that for chamfered holes the dependence of C_d on pressure ratio is small which is beneficial. Another advantage of chamfering is that for a given variation in W/D or R/D imposed by manufacturing tolerance bands, C_d for the chamfered holes would vary less than that for radiused holes (Fig. 9). The conclusion here must be that the advantages of inlet chamfering far outweigh those of inlet radiusing in the range tested.

To put the results into a more useful form for design purposes, contour plots of C_d have been generated for the ranges of L/D, W/D and R/D tested. The plots for the pressure ratio of 1.6 are shown in Fig. 13. In an attempt to complete the picture contour plots for the holes chamfered at 30° are also given, interpolated from the rather limited experimental data gathered for this chamfering angle. Similar plots were generated for a pressure ratio of 2.2 and may be found in Spencer [7].

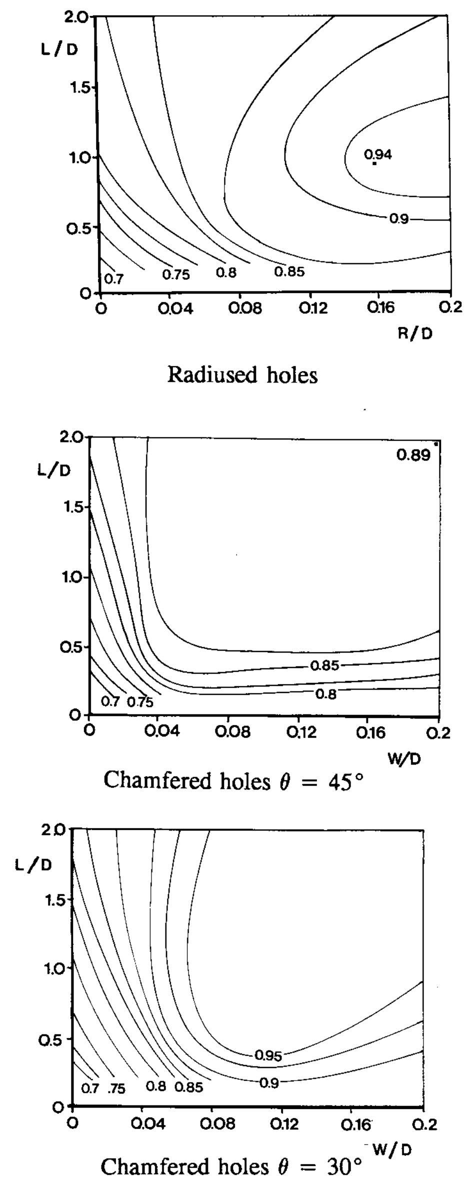

Fig. 13: Discharge coefficient contours at a pressure ratio of 1.6

5. Conclusions

1. It can be concluded that inlet radiusing and chamfering have a beneficial effect on the value of the discharge coefficient and on the way it varies with the length to diameter ratio and the pressure ratio across the hole.

2. Inlet radiusing gave a maximum increase in C_d of 27% at a pressure ratio of 1.6. The maximum increase produced by chamfering at the same pressure ratio was 22% for the 45° chamfer angle and 33% for the 30° chamfer (all of these at L/D = 0.25).

3. All of the benefit of inlet chamfering is achieved within W/D = 0.08. For thin holes, L/D < 2.0, further increase in the chamfering ratio will fractionally reduce the discharge coefficient.

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4. Increasing both L/D and W/D decreases the dependence of C_d on the pressure ratio across the hole.

5. In order to avoid a strong dependence of C_d on L/D it has been suggested [3] that L/D > 1.5. By using a chamfer ratio of 0.04 this limit can be reduced to L/D > 0.5.

6. The discharge coefficient is affected noticeably by the chamfer angle. A 30° angle gave an increase in C_d of 9% over the 45° chamfer. There was also a reduction in the dependence of C_d on the pressure ratio.

7. Chamfered holes give the more desirable performance characteristic in addition to being easier to produce than radiused holes.

8. Of the range of hole geometries tested the best geometry to give a high discharge coefficient and low dependence on pressure ratio was found to be the hole with a 30° chamfer.

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References

1. Deckker B E L and Chang U F, "An investigation of steady compressible flow through thick orifices" Proc Inst Mechanical Engineers. 1965/1966, Vol 180, part 3J.

2. Ward Smith A J, "Pressure losses in ducted flows", Butterworths, 1971.

3. Lichtarowicz A, Duggins R K and Markland E, "Discharge coefficients for incompressible, non cavitating flow through long orifices", Journal of Mechanical Engineering Science, Vol 7, No 2, pp210 - 219, 1965.

4. Hay N, Khaldi A and Lampard D, "Effect of crossflows on the discharge coefficients of film cooling holes with rounded entries or exits". 2nd ASME-JSME Thermal Engineering Joint Conference, Honolulu, Hawaii, Vol 3, pp 369 - 374, 1987.

5. McGreehan W F and Schotsch M J, "Flow characteristics of long orifices with rotation and corner radiusing". Gas Turbine Conference, Anaheim, California, 1987. ASME Paper 87-GT-162.

6. Briggs P A, "The effects of inlet rounding on orifice discharge coefficients", Third Year project report, Department of Mechanical Engineering, University of Nottingham, 1988-89.

7. Spencer A, "Discharge coefficient of cooling holes in gas turbine components", Third Year project report, Department of Mechanical Engineering, University of Nottingham, 1989-90.

8. "The jet engine", Rolls-Royce PLC publication, Fourth Edition, 1986.

9. "Visualised flow", The Japan Society of Mechanical Engineers, Pergamon Press, 1988.

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