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Comparison of Predicted and Experimental External Heat Transfer Around a Film Cooled Cylinder in Crossflow

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COMPARISON OF PREDICTED AND EXPERIMENTAL EXTERNAL HEAT TRANSFER AROUND A FILM COOLED CYLINDER IN CROSSFLOW

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ABSTRACT

Calculations were made of the film cooling provided by rows of holes around the circumference of a cylinder in crossflow and the results were compared to experimental data obtained from a NASA grant to Purdue University. The calculations and experimental data were for conditions that simulate most of those that are typical of air cooled turbine vane leading edges. Injection was from single and multiple rows of holes located at different angular locations from the stagnation line. The holes in the rows were angled normal to the flow direction and at a 25 degree angle to the cylinder wall. The calculations and experimental data were for several constant values of blowing ratios for all rows and for different blowing ratios for each row, representing a simulation of a common coolant plenum supply to multiple rows of holes. The calculations were made using a finite difference boundary layer code, STAN5, developed under NASA contract with Stanford University and modified at the NASA Lewis Research Center. Contrary to initial expectations that injection would trip the boundary layer flow into the turbulent regime, the results indicated that the high free stream acceleration apparently kept the flow laminar for holes in the first 45 degrees past stagnation. The trend in Stanton number reduction due to coolant injection was predicted with generally good agreement at the lower blowing rates, but for multiple rows of holes, agreement was poor beyond the first row.

INTRODUCTION

The durability of gas turbine vanes and blades is to a large extent dependent on the ability to effectively cool the leading and trailing edges. In essentially all advanced large aircraft engines, the leading edges are cooled by a film of air ejected from rows of holes. This cooling air first picks up heat inside the airfoil and in its passage through the film injection holes. Externally it provides a cool layer of gas close to the metal surface. It is this external cooling effect that is addressed in this work.

The current film cooling hole geometries and arrays at the leading edges are based on iterations of empirically obtained heat transfer and cooling air flow data. Much of this information is proprietary to the engine manufacturers and is airfoil geometry and engine specific. Much published experimental data, however, is available on film cooled flat surfaces and to a lesser extent on film cooled curved surfaces or cylinders in crossflow. A good bibliography of information in this area is presented by Luckey and L'Ecuyer (1). Reference 1 also presents recent heat transfer data for a variety of single and multiple row arrays of film cooling holes in a cylinder in crossflow.

No analytical method is known to be currently used to predict the external heat transfer on film-cooled leading edges. It was, therefore, the purpose of the study reported herein to evaluate the use of a computational boundary layer code to predict the external heat transfer provided by the film ejected from rows of holes in a cylinder in crossflow simulating a turbine vane leading edge. Use was made of a version of the two dimensional, finite-difference boundary layer code STAN5 (ref. 2) which was modified to include the effect of coolant injection and surface curvature (refs. 3 to 5).

Predictions were compared to experimental data obtained from reference 1. The predicted and experimental data were for parameters that simulate most of those that are typical of air-cooled turbine vane leading edges. The leading edge Reynolds number (based on cylinder diameter) was 9.0×10^4, the gas-to-wall temperature ratio was 1.7, and the coolant exit temperature was equal to the wall temperature. Injection of the coolant was from single and multiple rows (2 to 5) of holes located at different angular locations (5 to 76.6 degrees) from the stagnation line. The axes of the holes were in a plane normal to the flow direction and angled 25 degrees with respect to the cylinder axis. The calculations and experimental data were for two different blowing schemes. In one, the blowing rate was the same for each row, and in the other, the coolant supply pressure was held fixed, simulating a common coolant plenum supply to multiple rows of holes. The predicted and experimental data are presented in terms of a reduction in Stanton number with cooled film injection compared to Stanton number without coolant injection.

CONDITIONS AND METHOD OF ANALYSIS

Conditions

The conditions of the analysis conducted herein were those of the experiment conducted on a film cooled cylinder in crossflow at Purdue University under contract to NASA (ref. 1). The parameters of the analysis and experiments were such as to simulate most of those that are typical of air-cooled turbine vane leading edges. The leading edge Reynolds number (based on cylinder diameter) was 9.0×10^4, the gas-to-wall temperature ratio was 1.7, and the coolant exit temperature from the cylinder was equal to the wall temperature. The Mach number of the gas stream was .03 which is low compared to about .1 to .2 for typical turbine vanes. However, studies (refs. 6 and 7) have shown no significant effect of Mach number on heat transfer at low Mach numbers. The turbulence intensity of the gas stream for the analysis and experiment was about 4 percent. This is, however, low compared to about 7 to 20 percent expected in engines. The analysis was applied to the 15 cm diameter cylinder in the experiment which had coolant

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ejection from single and multiple rows of holes located at different angular locations from the stagnation line. The axes of the holes were normal to the gas stream and at a 25 degree angle with the cylinder wall. Figure 1 (adapted from ref. 1) and the inset schematically illustrates the film cooling holes in the cylinder and other features such as cylinder construction and the locations of heat flux gages. The temperature of the copper outer wall of the test cylinder was kept constant at 294 K by water-cooled inner passages shown in the figure and described in detail in reference 1. The mainstream temperature for the analysis and experiment was constant at 500 K and the mainstream velocity was 14.3 m/sec. The rows of film cooling holes in the cylinder were located at angles of 5, 22.9, 40.8, 58.7, and 76.6 degrees from the stagnation line. The specific configurations of the film-cooled cylinder analyzed are summarized in Table I and include the following: single rows at either 5, 22.9 or 40.8 degrees at constant blowing ratios through the holes, and 2-, 3-, and 5-row configurations at either a condition of constant blowing ratio through all holes or for a condition of a constant coolant plenum supply to all the rows. The 2-row configurations had rows located at angles of 22.9 and 58.7 degrees from the stagnation line, the 3-row configuration had rows at 5, 40.8, and 76.6 degrees, and the 5-row configuration had rows at 5, 22.9, 40.8, 58.7, and 76.6 degrees. The spanwise hole spacing to hole diameter ratios, S/d, were either 5 or 10 for the single rows. The 2- and 3- row configurations had an S/d ratio of 10 and a circumferential spacing to hole diameter, P/d, of 10. The 5-row configuration had S/d = P/d = 5. Figure 2, taken from reference 1, shows schematically an unwrapped view of the cylinder and shows locations of the hole rows and some of the instrumentation that were used to obtain the local and spanwise averaged Stanton numbers downstream of a row of holes.

Method of Analysis

A modified version of the STAN5 boundary layer code was used to calculate Stanton number distributions for the experimental conditions. The modifications to STAN5 included the full-coverage film cooling model described by Crawford, et. al. (3) with some minor changes, and the modifications described by Gaugler (4). Luckey and L'Ecuyer (1) reported their data as the normalized Stanton number reduction as a function of location, SNR, defined as the difference between non-film cooled and film cooled Stanton numbers divided by the non-film cooled Stanton number. Thus, in order to directly compare the calculations with the data, STAN5 was run first for the case of no film cooling, then re-run with film cooling considered, and the normalized Stanton number reduction calculated.

The modification to the STAN5 film cooling model allowed the program to continue running in the event that some of the injected coolant penetrated through the boundary layer. The original model described in reference 3 terminated program execution in that case. For the cases studied here, the boundary layer was quite thin at the injection locations and significant portions of the coolant penetrated through to the free stream.

In reference 4 it was recommended that the boundary layer be forced to transition to turbulent flow at the first film cooling location. However, for the data in this study, with a highly accelerated free stream, transition might be suppressed. To check this, STAN5 was run both with and without the forced transition to turbulent flow.

The use of the full coverage film cooling model of reference 3 for the case of film cooling around the leading edge of a cylinder represents a significant departure from the conditions for which the model was originally developed; i.e., flat plate, zero pressure gradient, many rows of holes. However, it is the only model available, and this data provides a test of the assumed physics of the injection and entrainment process. It is expected that the largest error in the results will occur in the vicinity of the injection holes, since the model is strictly two-dimensional. However, downstream of the injection location, the two dimensional model might be sufficient to model the spanwise averaged results.

RESULTS AND DISCUSSION

Single Rows of Holes

The initial calculations for injection from single rows of holes at 5 and 22.9 degrees from the stagnation line showed that in the experiment the injected flow apparently did not trigger the boundary layer into the turbulent regime downstream of the rows. This is concluded because the assumption of laminar flow in the calculations gave the best agreement with the experimental heat transfer data. The calculated spanwise averaged normalized Stanton number reductions, SNR, around the cylinder for injection at 5 and 22.9 degrees compared with that experimentally obtained (in reference 1) are shown in figures 3 and 4 respectively. Figure 3 shows that generally good agreement is obtained over the range of blowing ratios, M, from 0.51 to 1.02 for the hole spacing to diameter ratio, S/d, of 5 and similarly good agreement for a row of holes with S/d = 10 and M = 1.0. The agreement at M=.51 was better than for the higher values of M where the predicted values of SNR were generally lower than the experimental data.

Comparison between prediction and experimental data for injection from a row at 22.9 degrees, in figure 4, also shows generally good agreement using the assumption of laminar flow in the calculation. Figure 4(c) shows the large discrepancy that would occur if the calculation assumed turbulent flow after injection. It should be noted that at the higher blowing ratios, M, of 0.77 and 1.00 for both the hole spacing to diameter ratios of 5 and 10 respectively, the predicted SNR is initially lower than measured for only the first data point, then becomes higher further downstream.

Comparison of predicted and experimental data for injection at 40.8 degrees in figure 5 shows that except for the data nearest the holes the measured SNR is significantly lower than predicted using the assumption of laminar flow. The slope of the majority of the data however is better represented by the laminar rather than the turbulent curves. The figure shows that as the blowing ratio M increases from .25 to .77 the experimental SNR becomes progressively lower than that predicted. It might also be noted that for injection from a single row of holes at this angular location, experimental SNR, except near injection, is negative and becomes more negative with increase in blowing ratio, indicating a detrimental effect of coolant injection on external heat transfer.

It might be interesting at this point to examine the effects of the injection entrainment-diffusion models used and their contribution to the data trends, looking for insights into potential changes that might be made to improve agreement with experimental data. Because of the thin boundary layer at the 5 degrees injection location, the calculated output from the STAN5 code showed that even at a blowing ratio, M, of .51 the majority of the coolant penetrates through the boundary layer. Only 16.2 percent of the coolant remained in the boundary layer. As the blowing ratio increased to 1.02 the percent of coolant in the boundary layer decreased to 5.2 percent. Reviewing the discrepancy between predicted and experimental data in figure 3(b) indicates that a model which retained more coolant in the boundary layer would improve the agreement.

At the 22.9 degrees injection location a larger percentage of coolant is retained in the boundary layer. At M=.5 the percentage of coolant retained was 23.3 percent for hole spacing to diameter ratio S/d=5 (figure 4(a)) and 45.5 percent for an S/d=10 (figure 4(c)). As M increased to .77 and 1.0 for the respective S/d values the percentage of coolant left in the boundary layer decreased to 18.1 percent and 13.2 percent respectively (figures 4(b) and 4(d)). At this location, a model which retained less coolant in the boundary layer with increasing M would make experimental and predicted SNR show greater agreement. This is opposite from the conclusion drawn from figure 3. This would indicate that a more complex model is required to improve the agreement.

Multiple Rows of Holes, Constant Blowing Rate

Figures 6, 7, and 8 show the comparison between data and calculation for the 2-, 3-, and 5-row cases, with each row having the same blowing rate. Agreement is generally good for the first row in each case, as would be expected based on the single row results already presented. However, the agreement deteriorates rapidly when additional rows of holes are considered. Still, the basic trends in the data are preserved in the calculations, i.e. a sharp rise just downstream of a hole row, followed by a rapid drop off which shows a tendency to level off.

Multiple Rows of Holes, Plenum Supply

Figure 9 shows the comparison of data and calculations for three cases where the coolant supply to each row had the same pressure, such as would occur if the holes were fed from a common plenum. This results in the blowing ratio, M, increasing with distance from the stagnation line due to the drop in freestream static pressure around the cylinder. The same pattern of behavior is observed in the comparison, with the first row comparing fairly well and subsequent rows showing poor agreement.

Discussion of Analysis

There were a number of concerns in applying the modified STAN5 boundary layer program (which included effects of coolant injection and surface curvature) to the film cooled cylinder data. Perhaps the greatest concern was applicability of the models in the subroutine COOL of the STAN5 program which accounted for the injection and coolant entrainment process and for the effects of injection on the turbulent transport terms. The reason for this was that the respective empirically derived parameters that accounted for these effects, DELMR, to control the jet entrainment, and ALAM, to control the turbulent mixing length augmentation, were obtained for different ejection geometry than on the cylinder and they were obtained from experiments on a flat plate. The hole geometries for which the parameters were obtained were rows of holes with their axes normal to the mainstream and the wall, rows of holes with their axes slanted 30 degrees to the wall, in a plane normal to the wall and parallel to the mainstream, and rows of holes with their axes angled 45 degrees with the mainstream and 30 degrees with the wall. This latter injection is generally referred to as compound angled injection. The empirically obtained trend of the parameters DELMR and ALAM with blowing ratio for the 3 injection geometries showed different slopes and levels for the DELMR parameter and same slope but different levels for the ALAM parameter. For the purpose of this analysis the compound angled injection configuration was assumed to be the closest to the injection configuration on the cylinder analyzed herein and all the calculations were made based on DELMR and ALAM parameters derived for the compound angled injection.

Another concern was on the applicability of transition models. Initially it was thought that the injection might trip the boundary layer into turbulent flow. So two models were used, one in which flow was assumed to transition into turbulent flow after a row of holes and the other model which triggers the flow turbulent after the momentum thickness Reynolds number exceeds 200. Clearly more work is required in order to better understand the effect of film cooling on the transition of a boundary layer in a highly curved and accelerating region.

SUMMARY AND CONCLUSIONS

Contrary to initial expectations that coolant injection from the rows of holes would trip the average boundary layer flow into the turbulent range, comparisons of calculated versus experimental results indicated that the high flow acceleration aft of rows of holes at 22.9 degrees from stagnation and in some cases to 40.8 degrees from stagnation apparently kept the flow laminar.

For injection from single rows of holes, predicted and experimental spanwise averaged normalized Stanton number reductions (difference between non-film cooled and film cooled Stanton numbers divided by the non-film cooled Stanton number) generally showed good agreement downstream of injection from single rows of holes at 5 and 22.9 degrees from stagnation. Comparisons, except for trends, were poor for injection at 40.8 and 58.7 degrees from stagnation.

For injection from multiple rows of holes, generally good agreement was obtained between prediction and experiment for the first row of holes. Poor agreement was obtained at succeeding downstream rows. The predictions generally followed the trend of the experimental data, particularly agreeing with often large negative values of Stanton number reductions (indicating increased rather than decreased heat transfer by coolant injection).

For cases where the agreement is poor, the predicted curves of Stanton number reduction generally showed lower reductions than the experimental data.

Both the predicted and experimental data showed that for simulated conditions of a plenum supply to a 'showerhead' film cooled turbine vane leading edge, the Stanton number reductions were small or negative downstream of the film injection. This indicated little benefit or a detrimental effect due to film injection. Of course, there would still be the cooling provided by the flow of coolant internal to the vane, but this study only addressed the outer surface heat transfer due to the coolant film.

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TABLE I--CONDITIONS ANALYZED

Single Row Injection, Uniform Blowing

Row location, angle from stagnation, degrees	Hole spacing-to-diameter ratio, S/d	Blowing Ratio, M
5	5	.51
	5	1.02
	10	1.00
22.9	5	.51
	5	.77
	10	.50
	10	1.00
40.8	5	.25
	5	.51
	5	.77

Multiple Row Injection, Uniform Blowing
Hole spacing-to-diameter ratio, S/d = 10

	Row locations, angle from stagnation, degrees	Blowing Ratio, M
2 rows	22.9 & 58.7	.50
		.75
		1.00
3 rows	5, 40.8, & 76.6	.50
		.75
		1.25
5 rows	5, 22.9, 40.8,58.7&76.6	.50
		.75
		1.26

Multiple Row Injection, Blowing Distribution
Simulating Plenum-to-Mainstream Pressure Ratio of 1.01; S/d = 5

	Row locations, angle from stagnation, degrees	Blowing Ratios, M, Through Respective Rows
2 rows	22.9 & 58.7	1.08, .92
3 rows	5, 40.8 & 76.6	2.96, .95, .92
5 rows	5, 22.9, 40.8, 58.7 & 76.6	2.96, 1.08, .95, .92, .92

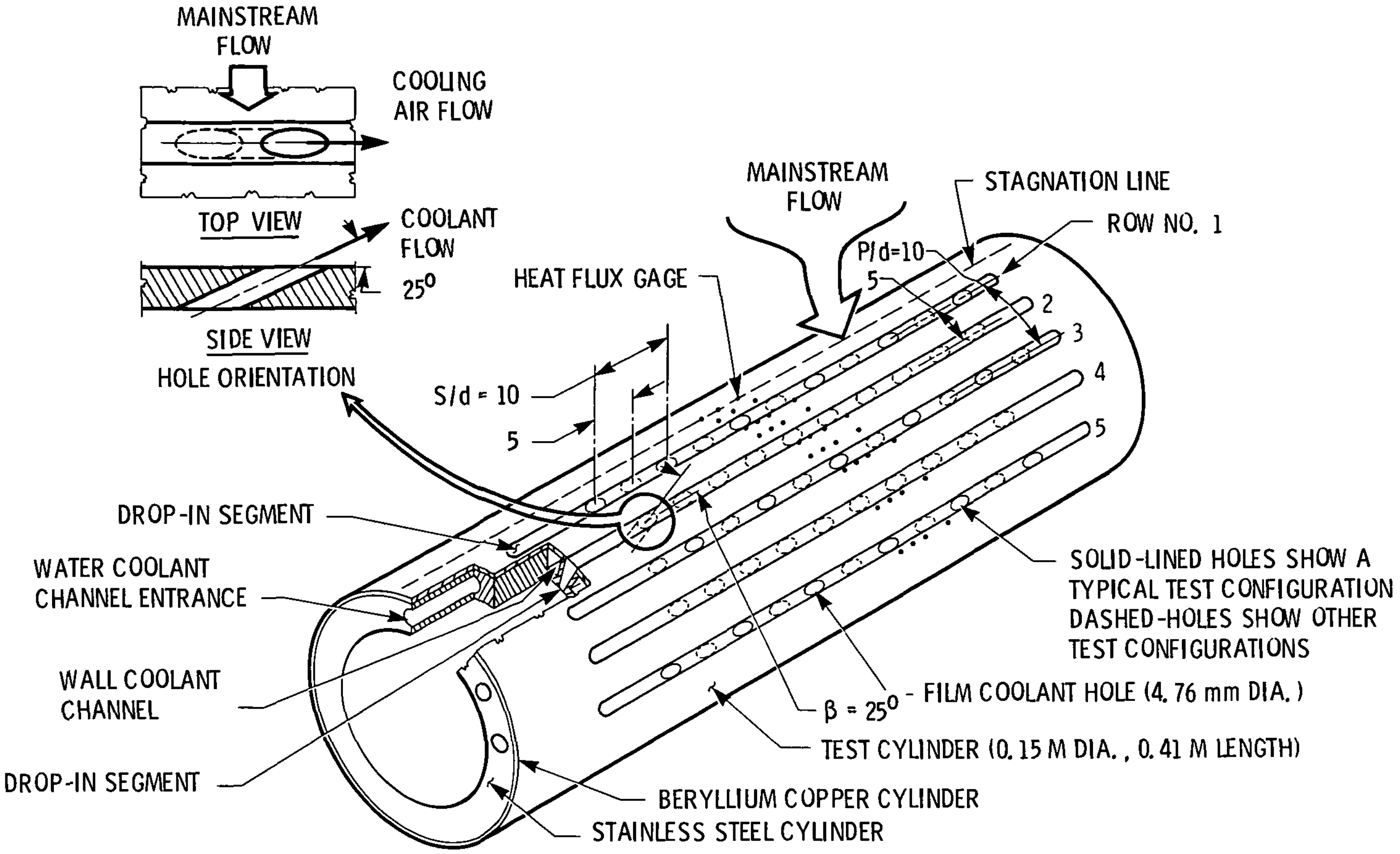


Figure 1. - Schematic of the test cylinder.

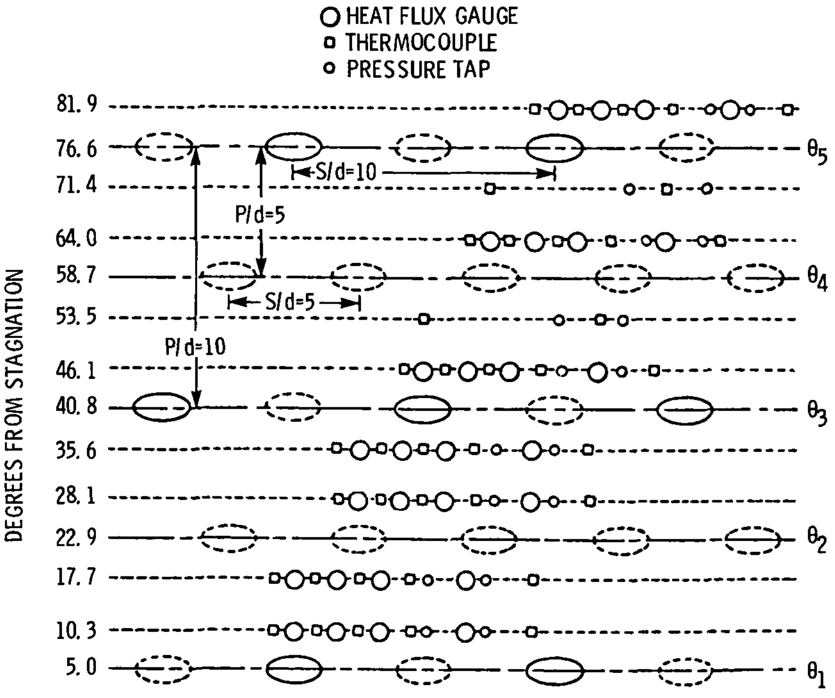
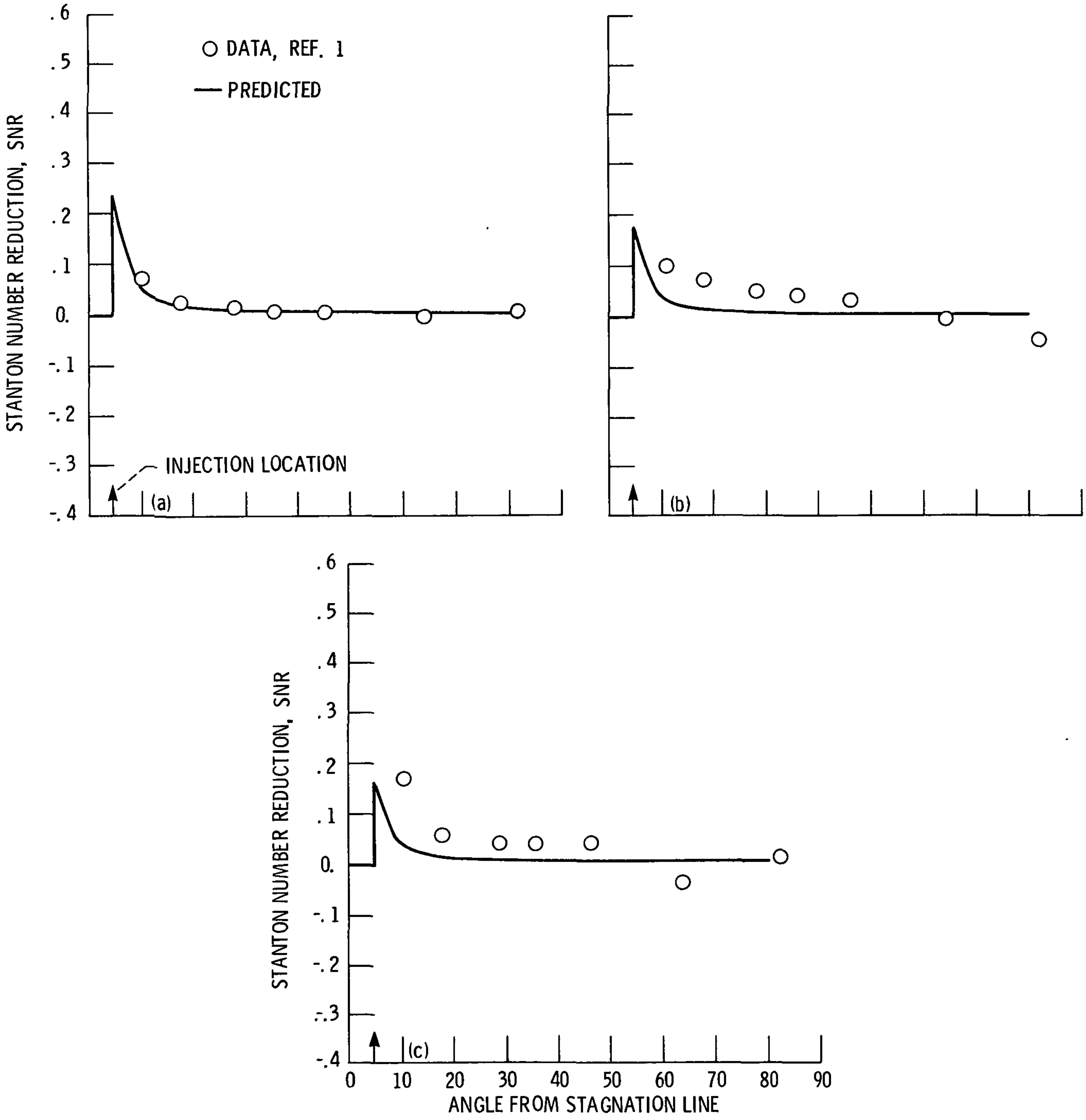


Figure 2. - Schematic of the instrumentation in the film cooling region.

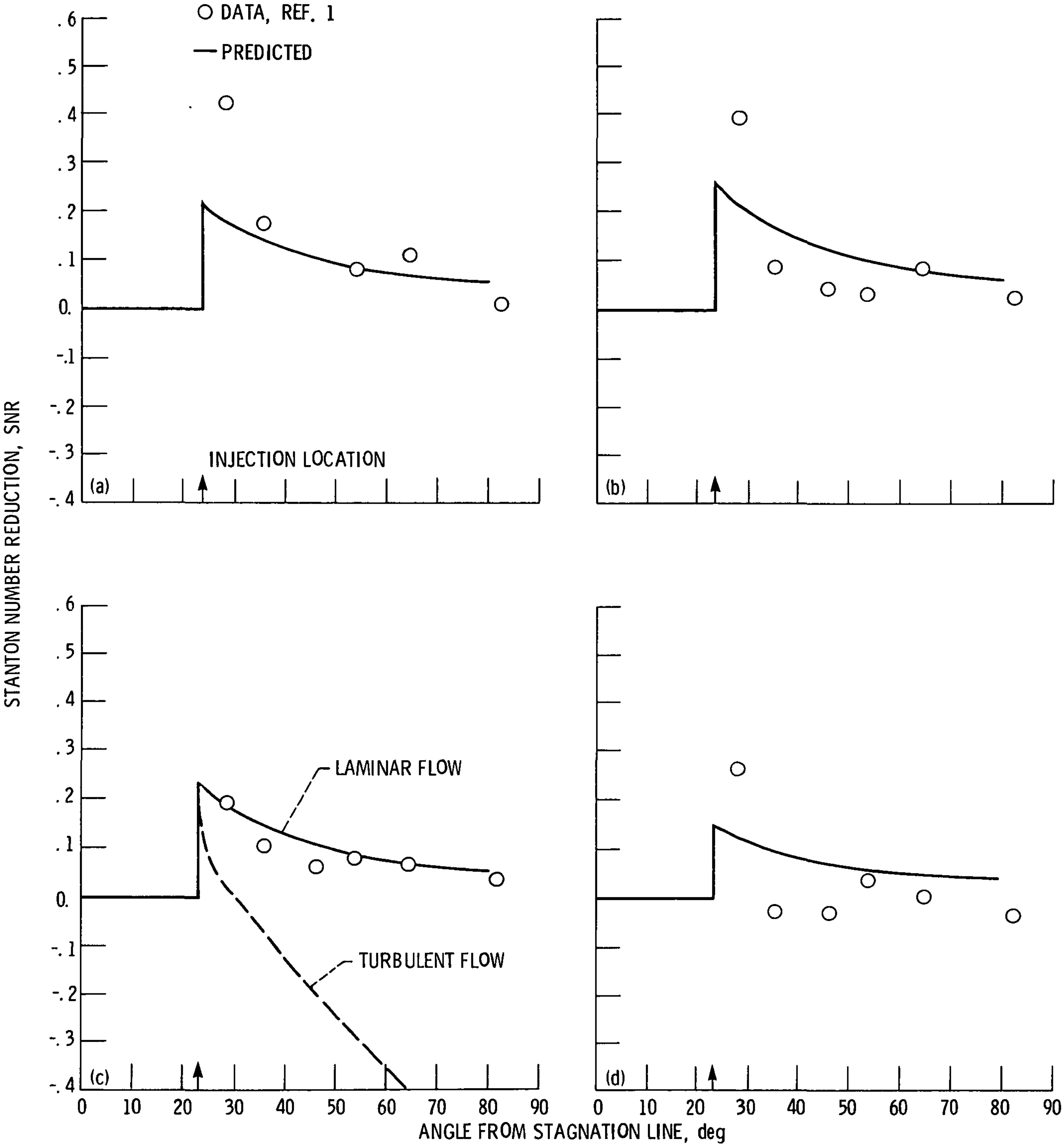


(a) Blowing ratio, M, =. 51, hole spacing/diameter, S/d = 5.

(b) Blowing ratio, M = 1. 02, S/d = 5.

(c) Blowing ratio, M = 1. 00, S/d = 10.

Figure 3. - Stanton number reduction for injection from a single row of holes at 5 degrees from stagnation.



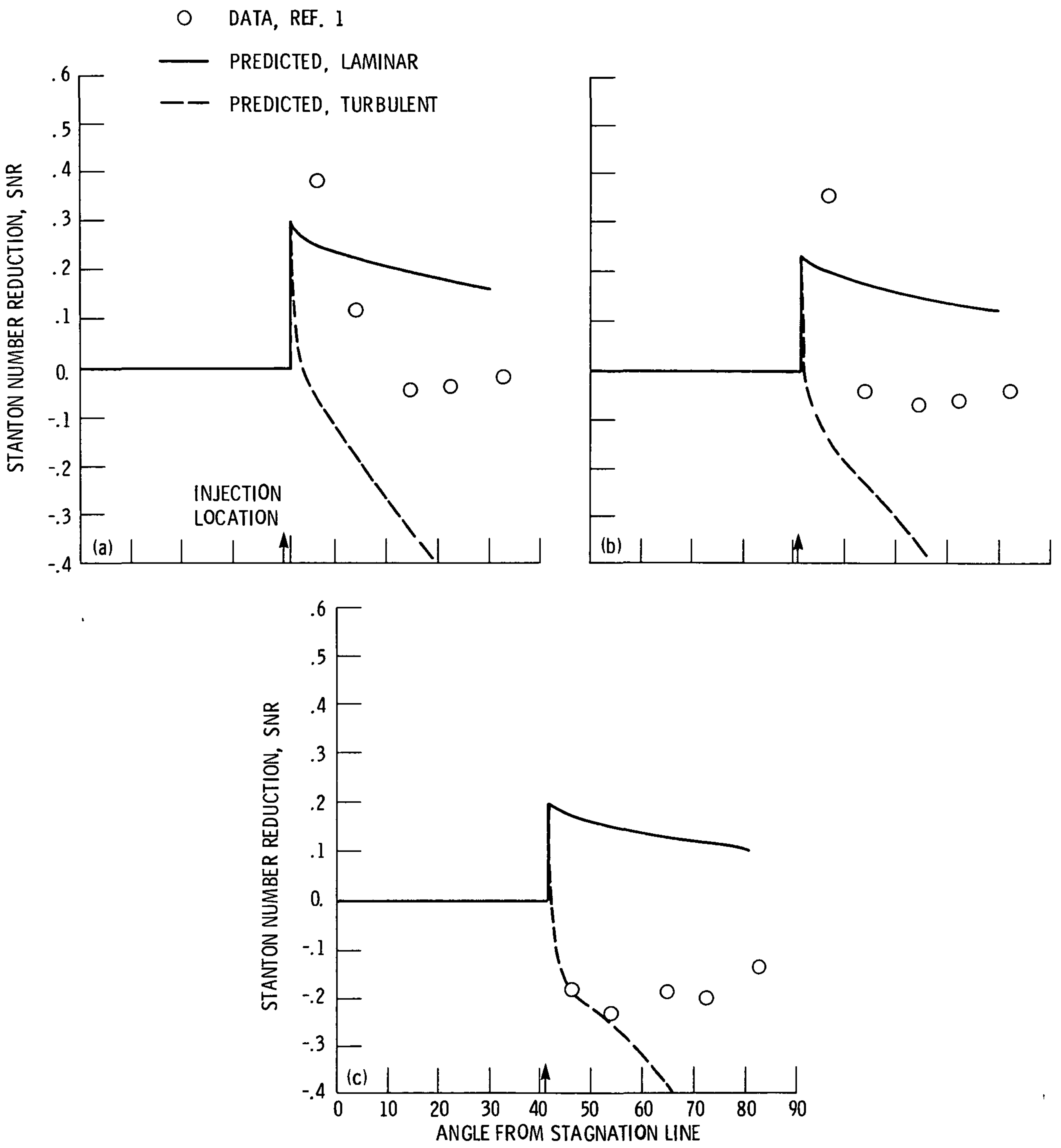
(a) M = .51, S/d = 5.

(b) M = .77, S/d = 5.

(c) M = .5, S/d = 10.

(d) M = 1.0, S/d = 10.

Figure 4. - Stanton number reduction for injection from a single row of holes at 22.9 degrees from stagnation, for different blowing rates, M, and hole spacing-to-diameter ratios, S/d.

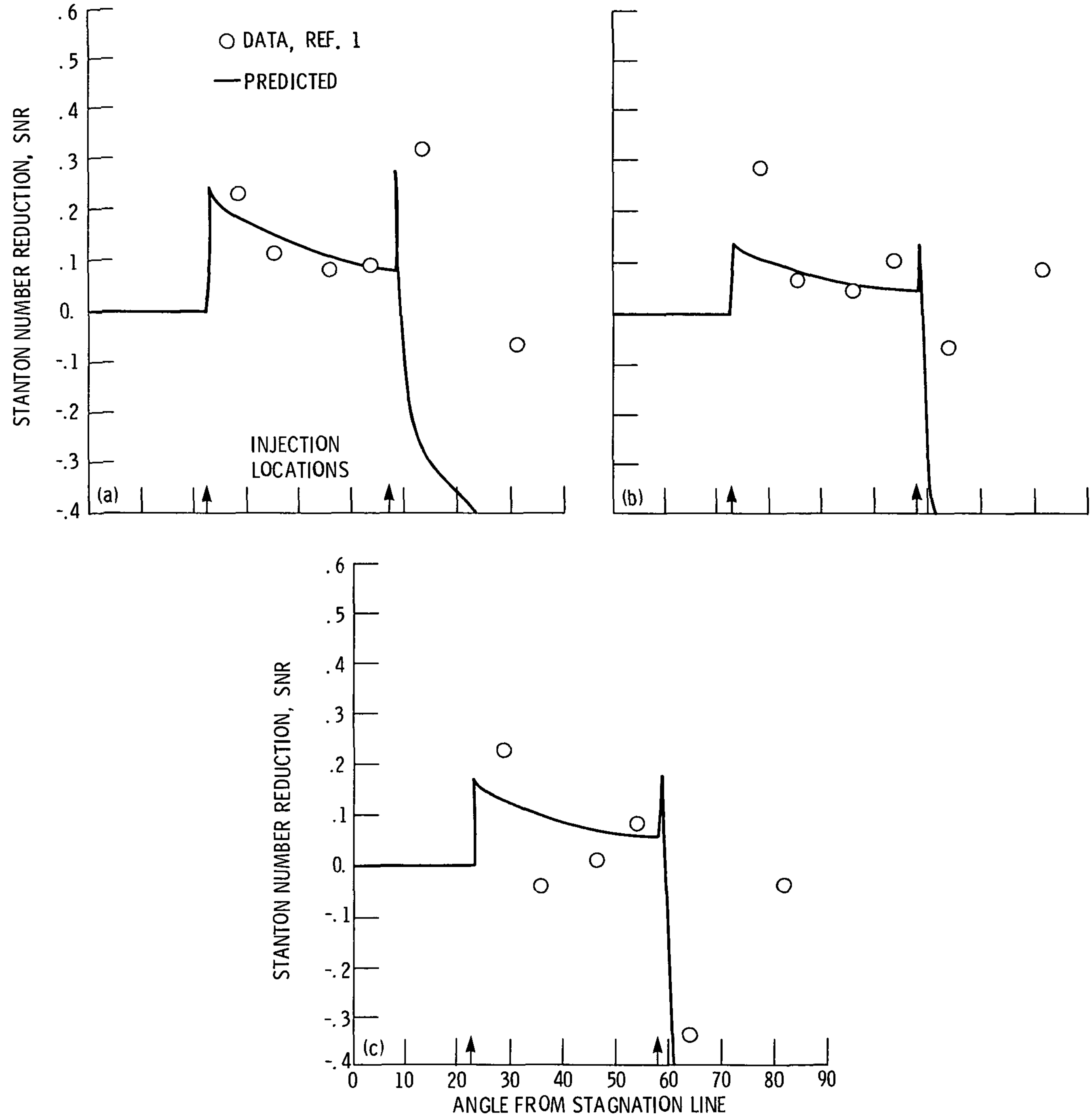


(a) Blowing ratio, M, =. 25, hole spacing/diameter, S/d = 5.

(b) Blowing ratio, M = .51, S/d = 5.

(c) Blowing ratio, M = .77, S/d = 5.

Figure 5. - Stanton number reduction for injection form a single row of holes at 40.8 degrees from stagnation.

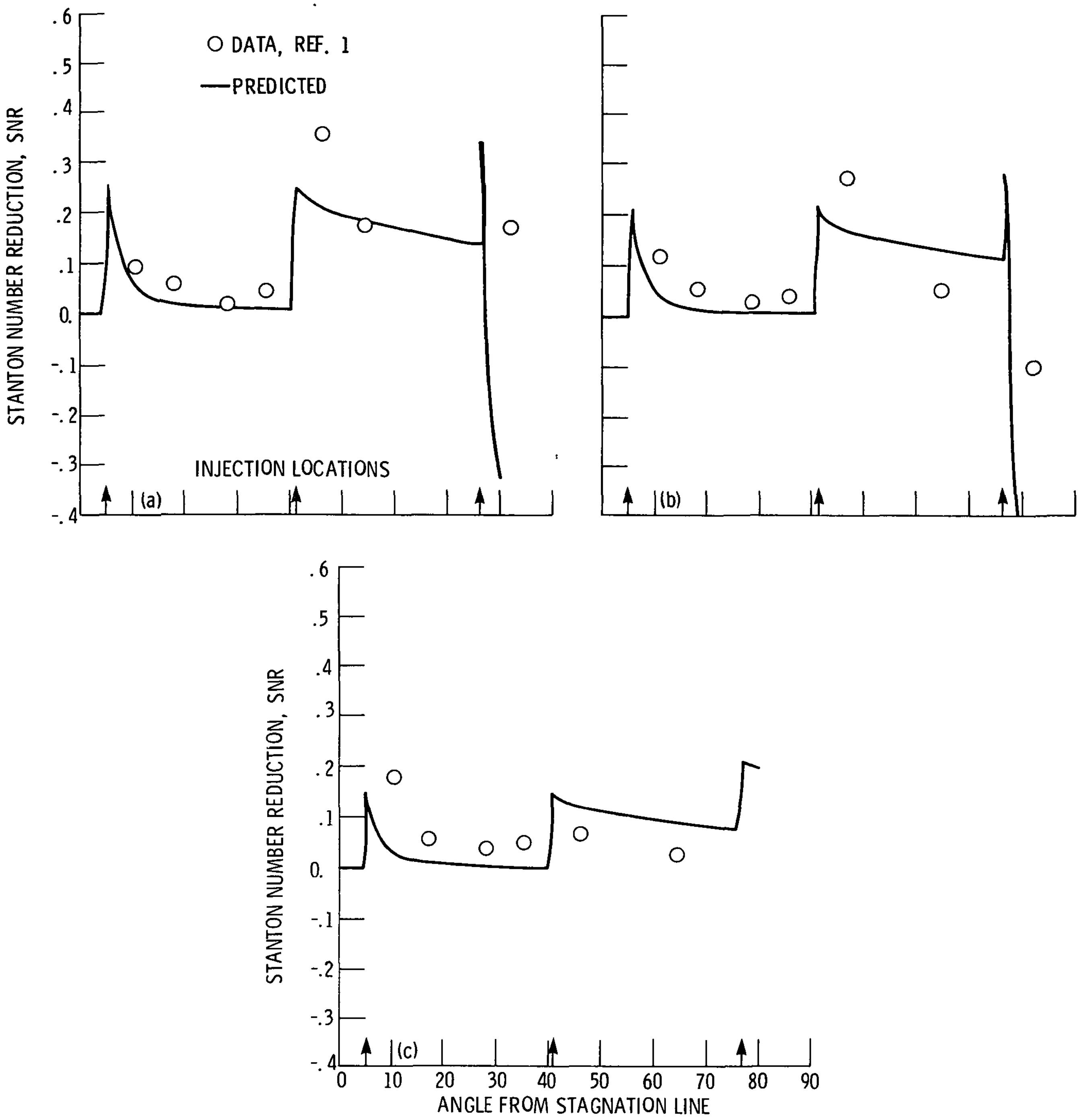


(a) Blowing ratio, M, =. 50, hole spacing/diameter, S/d = 10.

(b) Blowing ratio, M = .75, S/d = 10.

(c) Blowing ratio, M = 1. 00, S/d = 10.

Figure 6. - Stanton number reduction for injection from 2 rows of holes, at 22.9^0 and 58.7^0. Uniform blowing ratio, M, thru both rows.

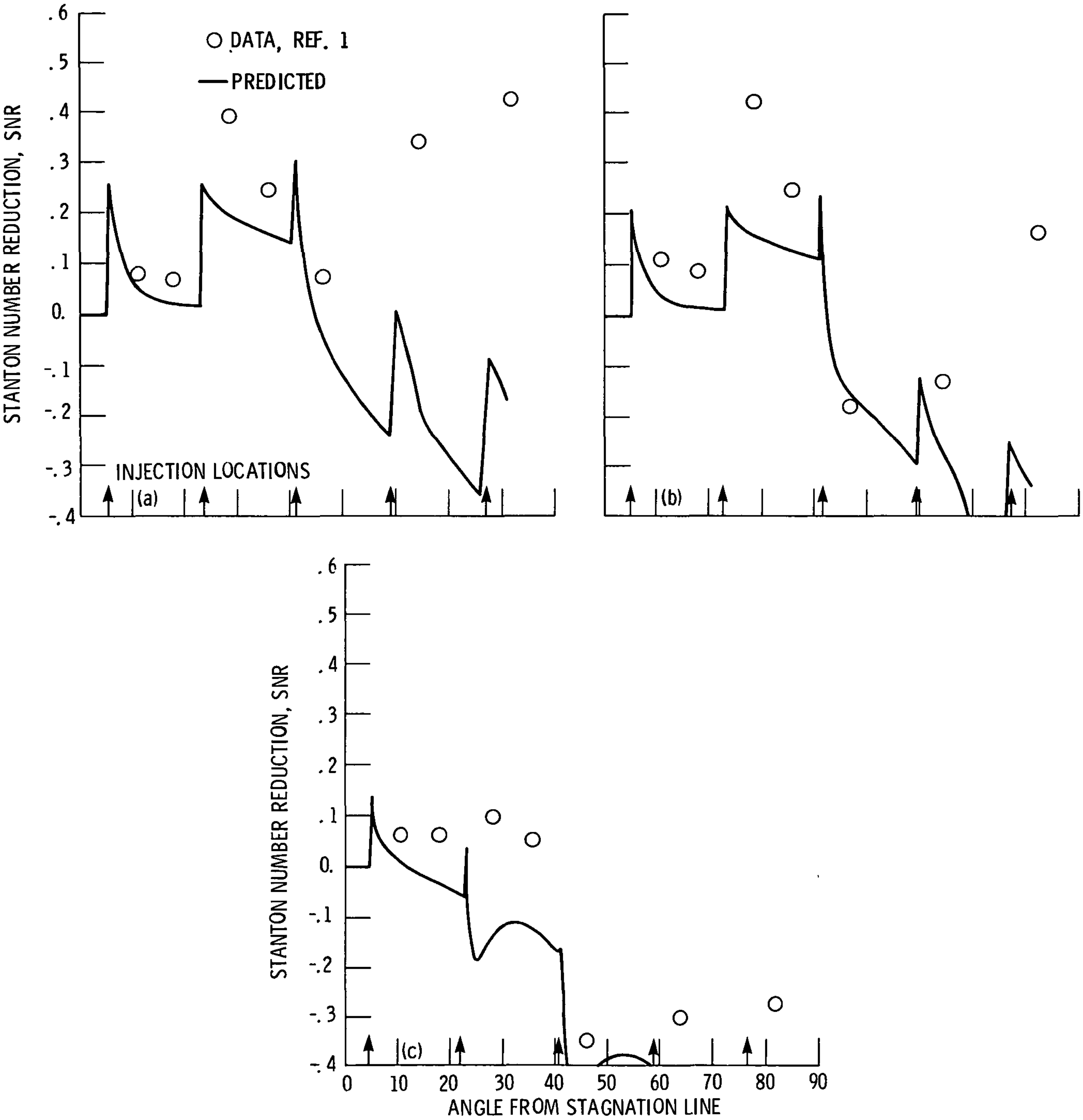


(a) Blowing ratio, M = .50, hole spacing/diameter, S/d = 10.

(b) Blowing ratio, M = .75, S/d = 10.

(c) Blowing ratio, M = 1.25, S/d = 10.

Figure 7. - Stanton number reduction for injection from 3 rows of holes, uniform blowing ratio, M, thru holes.

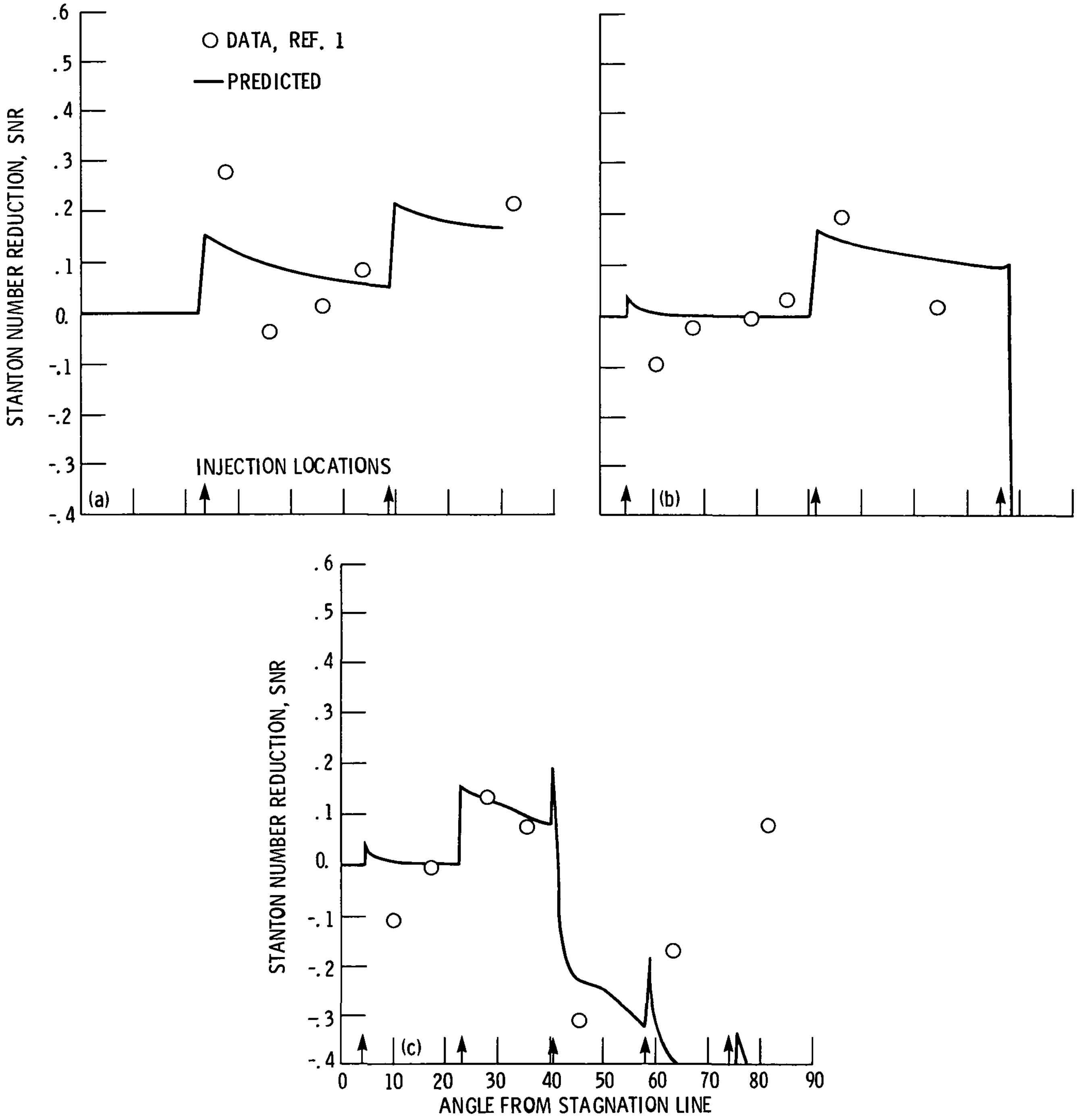


(a) Blowing ratio, M, =.50, hole spacing/diameter, S/d = 5.

(b) Blowing ratio, M = .75, S/d = 5.

(c) Blowing ratio, M = 1.26, S/d = 5.

Figure 8. - Stanton number reduction for injection from 5 rows of holes, uniform blowing. Transition to turbulent flow at third row.



(a) Two rows of holes, S/d = 10.

(b) Three rows of holes, S/d = 10.

(c) Five rows of holes, S/d = 5.

Figure 9. - Stanton number reduction for injection from multiple rows of holes. Coolant plenum supply-to-mainstream pressure ratio = 1.01.

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16 Abstract

Calculations were made of the film cooling provided by rows of holes around the circumference of a cylinder in crossflow and the results were compared to experimental data obtained from a NASA grant to Purdue University. The calculations and experimental data were for conditions that simulate most of those that are typical of air cooled turbine vane leading edges. Injection was from a single and multiple rows of holes located at different angular locations from the stagnation line. The holes in the rows were angled normal to the flow direction and at a 25 degree angle to the cylinder wall. The calculations and experimental data were for several constant values of blowing ratios for all rows and for different blowing ratios for each row, representing a simulation of a common coolant plenum supply to multiple rows of holes. The calculations were made using a finite difference boundary layer code, STAN5, developed under NASA contract with Stanford University and modified at the NASA Lewis Research Center. Contrary to initial expectations that injection would trip the boundary layer flow into the turbulent regime, the results indicated that the high free stream acceleration apparently kept the flow laminar for holes in the first 45 degrees past stagnation. The trend in Stanton number reduction due to coolant injection was predicted with generally good agreement at the lower blowing rates, but for multiple rows of holes, agreement was poor beyond the first row.

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