THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

83-GT-30

Film Cooling With Steam Injection Through Three Staggered Rows of Inclined Holes Over a Straight Airfoil

G. E. Conklin
J. C. Han
P. E. Jenkins
Turbomachinery Laboratories
Department of Mechanical Engineering
Texas A&M University
College Station, TX 77843

ABSTRACT

Experiments have been performed to investigate the film cooling characteristics of steam injection through three staggered rows of 60 degree inclined holes over a straight aluminum airfoil with a circular leading edge. The axial distance between cooling hole rows is five hole diameters. The lateral distance is four hole diameters. Data have been taken for the local film cooling effectiveness of steam and air with blowing rates varying from 0.3 to 1.8. It shows that at small blowing rates, steam has an effectiveness up to 2.5 times greater than air; but, as the blowing rates are increased, the difference between the steam and air effectiveness is gradually decreased. It also shows that the steam effectiveness is less dependent upon the blowing rates than is the air effectiveness. The results generally support the previous analytical prediction.

NOMENCLATURE

Symbols

- D hole diameter
- M blowing rate, $\rho_2 U_2/\rho_\infty U_\infty$, equation (2)
- T_w wall temperature
- T_∞ mainstream temperature at the upstream of airfoil
- T_2 injectant temperature at the inlet of injection plenums
- U_∞ mainstream velocity at the upstream of airfoil in flow direction
- U_2 injectant velocity at the inlet of injection hole
- X coordinate in mainstream flow direction
- Z lateral coordinate
- ρ_∞ mainstream density
- ρ_2 injectant density at the inlet of injection hole
- η film cooling effectiveness, equation (1)

1 Numbers in bracket designate references at end of paper.

INTRODUCTION

It is well known that one of the methods for improving the turbine efficiency is to increase the turbine inlet temperature. However, higher gas temperatures will require more sophisticated cooling schemes for achieving acceptable component life with the same material. One technique currently in production is to bleed air from the air compressor into the turbine blade and vane to provide the blade internal convection and impingement cooling and to create the local blade external surface film cooling. In two-dimensional film cooling, the cooling air is injected locally through the continuous slot into the mainstream, isolating the turbine blade from the hot gas stream. In three-dimensional film cooling, the cooling air is injected locally through a row (or rows) of discrete inclined holes into the mainstream in order to protect the turbine blades from the hot gas stream heating. A detailed literature survey on film cooling has been done by Goldstein [1][1]. The effects of blowing rates [2-5], injection geometry [6-7] and pressure gradient [8-9] on two-dimensional air-to-air film cooling effectiveness are well understood. In three-dimensional film cooling, the majority of studies have been centered on the effects of blowing rates and injection geometry (single hole or rows of holes; normal or inclined injection) on the air-to-air cooling effectiveness [10-16].

Recently, Rice [17] proposed to use superheated steam from a conventional steam cycle for the gas trubine blade and vane cooling in a combined cycle for power generation. Han and Jenkins [18] predicted that the film cooling effectiveness of steam, due to its favorable thermal properties (such as specific heat and Prandtl number), was about twice that of air under the same operating conditions. However, the prediction has not been verified experimentally. There have been some studies which have evaluated the effects of foreign gas injection (such as helium, hydrogen, argon, or freon-12 vapor) on two-dimensional film cooling [1, 19-20]. But the thermal-fluid properties of helium, et al., are very different from those of steam, and two-dimensional film cooling effectiveness is always different from that of three-dimensional film cooling. Thus, although film cooling has been investigated extensively, data of the steam cooling are still not available in the open literature.

An experimental study to investigate the film cooling characteristics of steam injection through three staggered rows of 60 degree inclined holes over a straight airfoil with a circular leading edge for varied blowing rates was recently completed. This paper will first describe the experiments, then the results of steam-to-air cooling and air-to-air cooling will be presented and compared.

EXPERIMENTS

Apparatus

Figure 1 shows a schematic drawing of the experimental apparatus. A blower forced air at room temperature and pressure through heaters and mixing sections into a plenum. A contraction nozzle was used between the plenum and the test section to ensure that the air entering the test section had a uniform velocity and temperature distribution. At the end of the test section, the air was exhausted into the atmosphere. The cooling medium was injected through the side of the test section into the blade. The 7 1/2 HP blower provided a 120 fps (37.5 m/s) air velocity at the inlet of the test section. The 90 kw heaters were capable of providing a 285°F (140°C) air temperature at the inlet of the test section. Great care was taken in the design of the wind tunnel which consisted of a three-dimensional elliptical inlet, filter, straightening vanes and screens. The area ratio of the contraction nozzle, as shown in Figure 2 was 52:1 which was sufficiently large to ensure a reduction in turbulence and to obtain a uniform flow field. The overall contraction length was 36 inches (91.4 cm).

The test section was a 5 in. x 5 in. (12.7 cm x 12.7 cm) rectangular section with a 48 inch (122 cm) overall length. The blade was positioned 24 inches (61 cm) from the leading edge of the test section. The aluminum blade, as photoed in Figure 3, was a straight airfoil with a circular leading edge and three staggered rows of injection holes. Figure 4 showed the plane view and cross-section of the blade. The blade was 6.0 inches (15.2 cm) long, 4.85 inches (12.3 cm) wide with a 1.25 inch (3.17 cm) diameter circular nose. There were two 0.5 inch (1.27 cm) plenums which provided a means by which the coolant was introduced into the blade. The injection holes were 0.0625 inches (0.159 cm) in diameter and were drilled at a 60 degree injection angle relative to the blade surface. The axial distance between the cooling hole rows was five hole diameters. The lateral distance was four hole diameters. The thickness of the blade walls in the central hollow region of the blade, was 0.0625 inches (0.159 cm). Ten copper constantan thermocouples (five along Z/D=0, five along Z/D=2) were placed in the injection side. Three copper constantan thermocouples (along Z/D=0) were placed in the non-injection side of the blade as shown in Figure 4.

The secondary flow systems consisted of a compressor for the air tests and a boiler for the steam tests, as shown in Figure 5. The air first passed through a pressure regulator to eliminate pressure fluctuations. Following the regulator was a needle valve which controlled the air flow rate. A flowdyne venturi meter was used to measure the flow rate. The pressure drop was determined by a Validyne transducer demodulator. The cooling air temperature (about 95°F or 35°C) was measured at the inlet of the injection plenums by two copper constantan thermocouples. The saturated steam followed the similar path of the air except for a bleed valve located up-stream of the orifice plate to bleed off the condensate. Then steam was passed through a throttling valve (regulator) to lower the steam pressure and temperature. The steam temperature (about 218°F or 103°C) was measured at the inlet of the injection plenums by thermocouples which located at the same position as the case of air injection. The entire test rig was well-insulated to minimize the heat losses to the environment.

Test Procedure

To establish the symmetry of the blade, tests were conducted with no cooling air. Figure 6 showed the temperature difference between X/D of 10 and X/D of 60 was about 10°F (5.5°C). This might be due to the heat loss through metal spacers, which located between blade nose and side walls when the blade was positioned, to environment. However, the difference of the thermocouple readings from each side of the blade was within 3°F (1.7°C) as shown in Figure 6, thus showing the symmetry of the temperature profiles. Tests were then run for combinations of mainstream temperatures and coolant flow rates. Each test was conducted after the blade reached thermal equilibrium with its environment. Upon reaching equilibrium, coolant was injected into the blade and after a sufficient amount of time had elapsed to ensure that any transient effects had subsided and the blade was at equilibrium, the temperature readings were recorded. The next step was to increase the coolant rates and again record the temperatures. The blowing parameters were varied between M = 0.3 and M = 1.8 by controlling the coolant flow rate. The mainstream velocity at the upstream of airfoil was held constant at 120 f/s (37.5 m/s), and the mainstream temperature was maintained in a range between 275°F (135°C) and 300°F (149°C). The controlling parameter in setting the mainstream temperature was to ensure that the steam did not condense in the test section and on the blade. Also, to minimize uncertainty in effectiveness calculations, a temperature difference of at least 50°F (28°C) was needed between the coolant and mainstream temperatures. Both of these criteria were met since the steam entered the injection plenums at 218°F (130°C). Tables 1 and 2 show the typical data for air and steam cooling tested.

Experimental Accuracy

The film cooling characteristics of the two media were compared on the basis of film cooling effectiveness at different blowing rates. The film cooling effectiveness can be determined by measuring the mainstream, coolant, and blade temperatures at a given blowing rate. With this data, the local film cooling effectiveness can be calculated from its definition:

$$\eta = \frac{T_w - T_\infty}{T_2 - T_\infty} \qquad (1)$$

The maximum uncertainty in the film cooling effectiveness was estimated to be 3.5%. The blowing rate can be determined by measuring the coolant mass flow rate and mainstream air velocity. With this data, the blowing rate can be calculated from its definition:

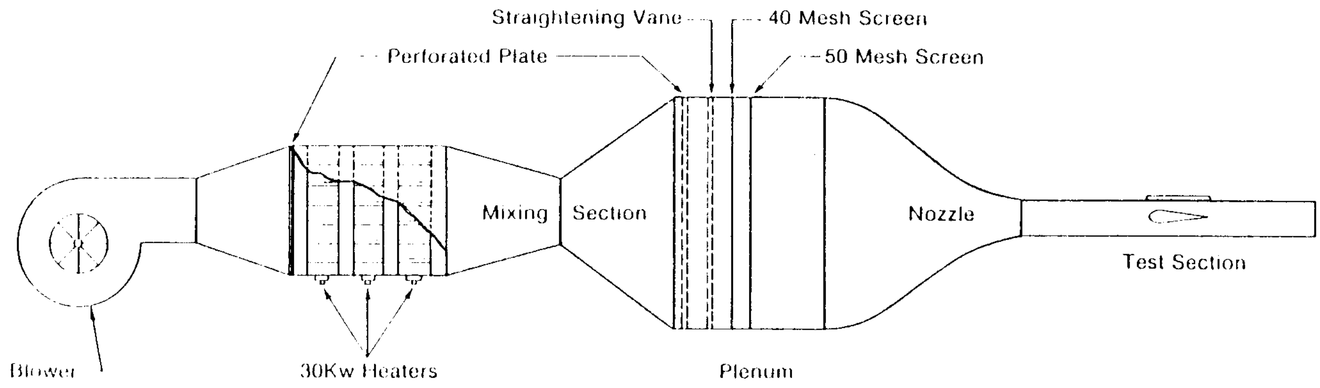

Figure 1 Schematic of the Test Apparatus

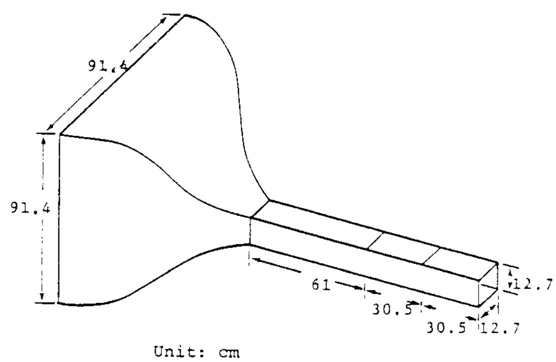

Figure 2 Schematic of Contraction Section

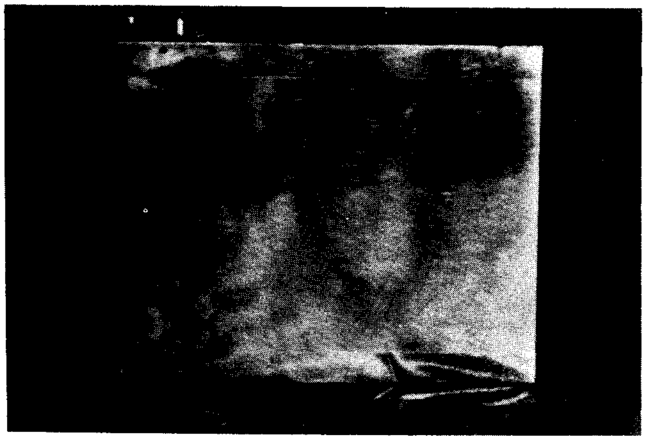

Figure 3 View of Blade with Injection Holes

$$M = \frac{\rho_2 U_2}{\rho_\infty U_\infty} \qquad (2)$$

The maximum uncertainty in the blowing rate was estimated to be 6.7% for air injection and 8.1% for steam injection.

RESULTS

Based on the thermocouples reading at Z/D=0 and Z/D=2, it has been found that the film cooling effectiveness at locations beyond about 10 hole diameters downstream of injection is about laterally uniform. This may be partially due to the conduction effect of the aluminum blade. The center line film cooling effectiveness (Z/D=0) for the two media progressing longitudinally down the blade for the five different thermocouple positions and different values of the blowing rate results are shown in Figures 7 through 12. It is seen that the steam cooling effectiveness is approximately double that of air. The explanation of this phenomena is that steam has a larger specific

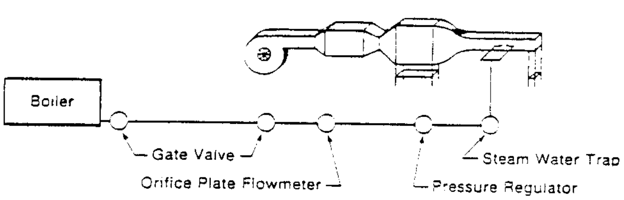

Figure 5 Piping Network Schematic

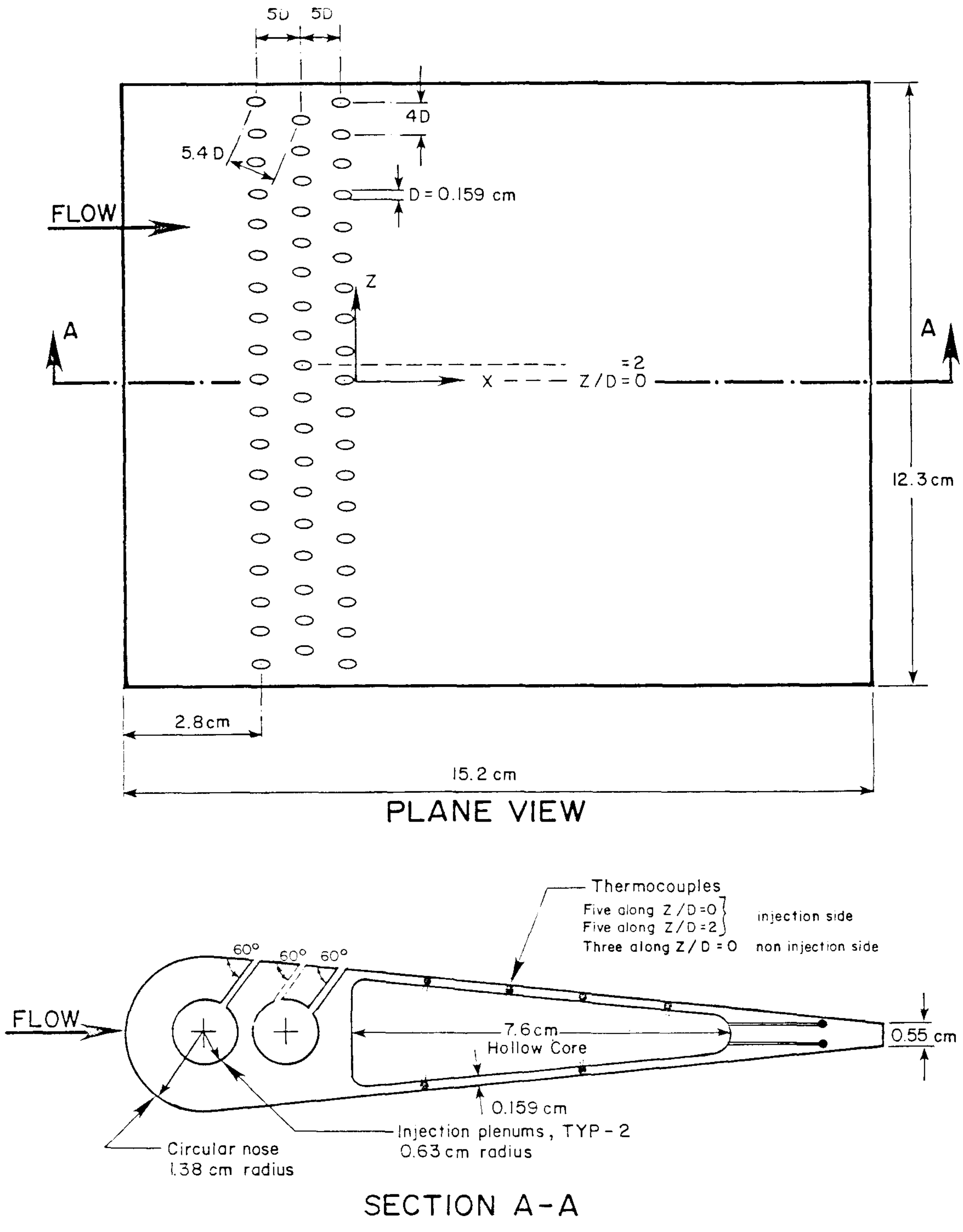

Fig. 4 Sketch of present Injection Geometry

Table 1 Typical Air Film Cooling Tested

Run	M	T_∞	T_2
1	.342	285°F (140°C)	95°F (35°C)
2	.532	285°F (140°C)	95°F (35°C)
3	.844	285°F (140°C)	95°F (35°C)
4	1.04	283°F (139°C)	95°F (35°C)
5	1.50	285°F (140°C)	95°F (35°C)
6	1.80	285°F (140°C)	95°F (35°C)

Table 2 Typical Steam Film Cooling Tested

Run	M	T_∞	T_2
1	.296	274°F (134°C)	218°F (103°C)
2	.330	276°F (135°C)	218°F (103°C)
3	.520	285°F (140°C)	218°F (103°C)
4	.84	282°F (139°C)	218°F (103°C)
5	1.20	273°F (134°C)	218°F (103°C)
6	1.786	285°F (140°C)	218°F (103°C)

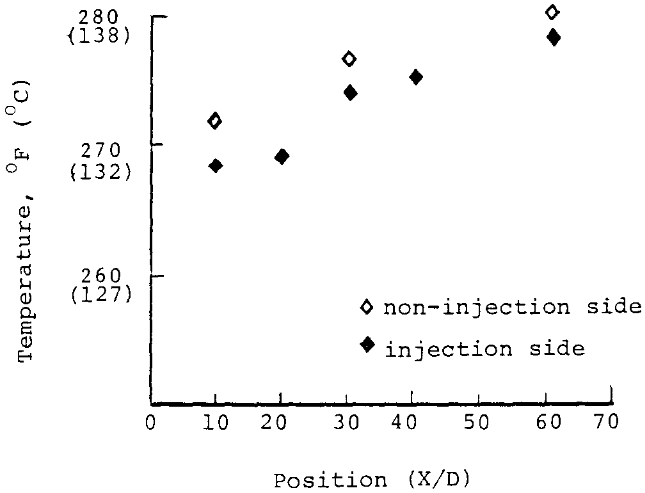

Figure 6 Thermocouple Correlation for an Uncooled Blade

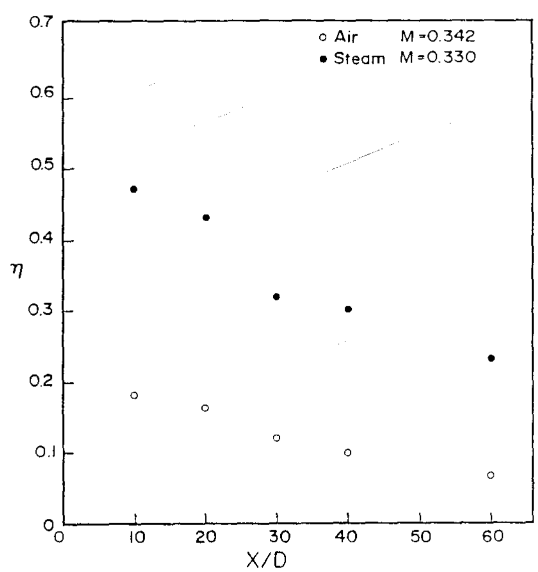

Fig. 7 Steam and Air Effectiveness for Blowing Rates at Different Positions

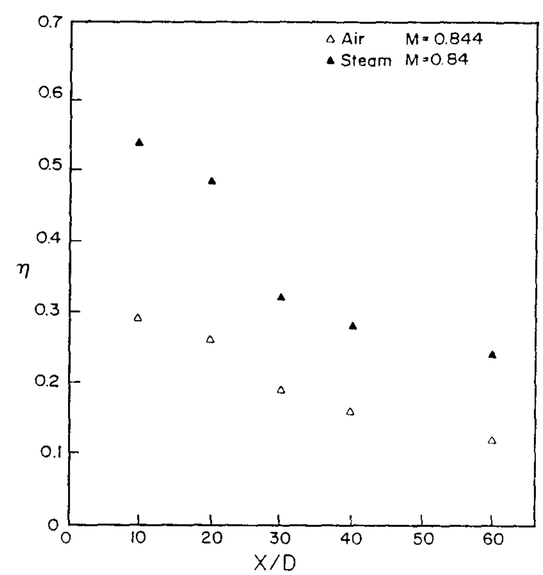

Fig. 8 Steam and Air Effectiveness for Blowing Rates at Different Positions

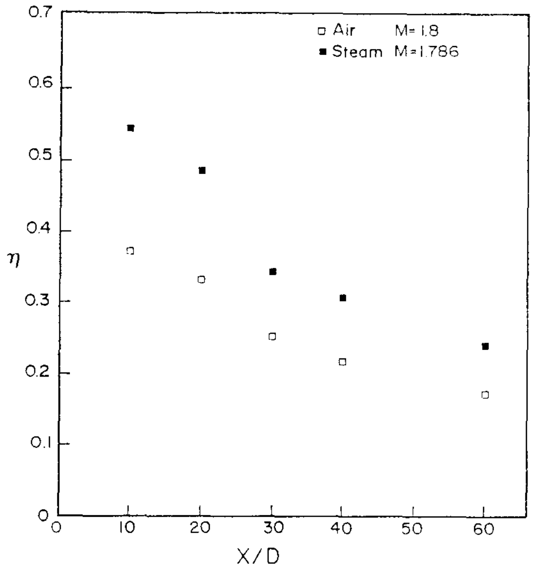

Fig. 9 Steam and Air Effectiveness for Blowing Rates at Different Positions

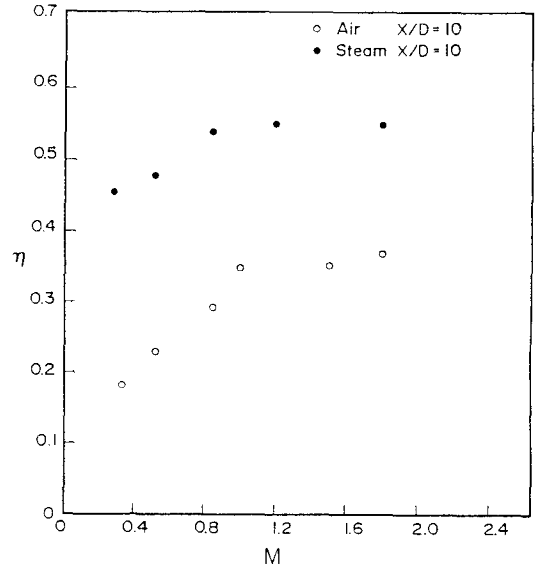

Fig. 10 Steam and Air Cooling Effectiveness Versus Blowing Rate for Position X/D=10

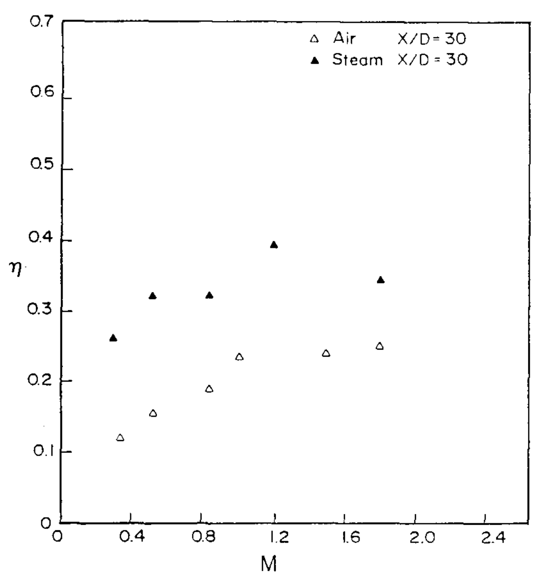

Fig. 11 Steam and Air Cooling Effectiveness Versus Blowing Rate for Position X/D=30

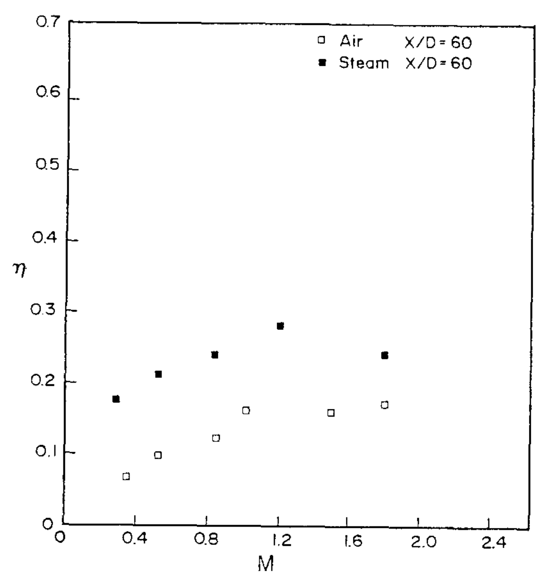

Fig. 12 Steam and Air Cooling Effectiveness Versus Blowing Rate for Position X/D=60

heat and a larger Prandtl number than those of air. The results generally support the previous analytical prediction [18]. Upon examination of Figures 7 through 9 from the first position to the trailing edge, the effectiveness for steam is seen to decrease at a more rapid rate than air, although still maintaining the much higher effectiveness for each point. A plausible explanation for this phenomena is that steam has a smaller viscosity than air. This will cause a greater mixing with the mainstream air and reduce the cooling effectiveness along the blade at a given blowing rate. Analyzing the effectiveness of the coolant against the blowing rate at the different blade positions, as shown in Figures 10 through 12, a positive slope is noted for the effectiveness. Again, the approximate doubling of the effectiveness is seen. The slope of both steam and air curves begin to decrease around a blowing rate of M=1.0, which implies that after M=1.0, the effectiveness increases at a slower rate. Also, the effectiveness slope does not increase as rapidly for steam as it does for air. This implies that the steam is not as dependent upon blowing rates as is air.

CONCLUSIONS

An experimental investigation of film cooling effectiveness downstream of injection through three staggered rows of 60 degree inclined holes over a straight airfoil with a circular leading edge indicates that steam provides a higher effectiveness than air at all points on the blade for similar blowing rates. Also, a higher effectiveness is seen for steam at all the blowing rates considered. The film cooling effectiveness following injection steam or air through three staggered rows increases with increasing blowing rate, and it reaches a plateau at the blowing rate of about 1.0.

Comparing the slopes of Figures 10 through 12, it shows steam to be less dependent on blowing rates than air. Reviewing Figures 7 through 9, it is seen that at a blowing rate of M=0.33, steam has an effectiveness 2.5 times greater than that of air. However, as the blowing rate is increased to M=0.84 and M=1.8, the steam effectiveness is 1.75 times and 1.4 times greater than air, respectively. These facts suggest that at small blowing rates, steam has a much higher effectiveness than air, but as the blowing rates are increased, the difference between the steam and air effectiveness is gradually decreased. However, these conclusions are based on the present data of aluminum blade with high thermal conductivity and its particular injection geometry. Therefore, in order to confirm the present observations and to provide more information for the steam film cooling, it is planned to take data based on the conventional adiabatic flat plate injection geometry.

REFERENCES.

1. Goldstein, R. J., "Film Cooling", Advances in Heat Transfer, vol, 7, p. 321, Academic Press, New York and London, 1971.
2. Weighardt, K., "Hot-Air Discharge for De-Icing", AAF Translation No. F-TS-919-RE, 1946.
3. Seban, R. A., "Effects of Initial Boundary Layer Thickness on a Tangential Injection System", J. of Heat Transfer, 82, p. 392, 1960.
4. Goldstein, R. J., Shavit, G., and Chen, T. S., "Film-Cooling Effectiveness with Injection Through a Porous Section", J. of Heat Transfer, 87, p. 353, 1965.
5. Stollery, J. L. and El-Ehwany, A. A., "A Note on the Use of a Boundary-Layer Model for Correlating Film-Cooling Data", Intern. J. Heat Mass Transfer, 8, p. 55, 165.
6. Burns, W. K. and Stollery, J. L., "The Influence of Foreign Gas Injection and Slot Geometry on Film Cooling Effectiveness", Intern. J. Heat Mass Transfer, 12, p. 935, 1969.
7. Metzger, D. E., Carper, H. J., and Swank, L. R., "Heat Transfer with Film Cooling Near Nontangential Injection Slots", J. Engr. for Power, 90, p. 157, 1968.
8. Seban, R. A. and Back, L. H., "Effectiveness and Heat Transfer for a Turbulent Boundary Layer with Tangential Injection and Variable Free-Steam Velocity", J. Heat Transfer, 84, p. 235, 1962.
9. Escudier, M. P. and Whitelaw, J. H., "The Influence of Strong Adverse Pressure Gradients on the Effectiveness of Film Cooling", Intern. J. Heat Mass Transfer, 11, p. 1289, 1968.
10. Goldstein, R. J., Eckert, E. R. G., and Ramsey, J. W., "Film Cooling with Injection Through Holes: Adiabatic Wall Temperature Downstream of a Circular Hole", J. Engr. for Power, 90, p. 384, 1968.
11. Metzger, D. E., Takeuchi, D. T., and Kuntsler, P. A., "Effectiveness and Heat Transfer with Full-Coverage Film Cooling", J. Engr. for Power, P. 180, 1973.
12. Mayle, R. E. and Camarata, F. J., "Multihole Cooling Film Effectiveness and Heat Transfer", J. of Heat Transfer, p. 534, 1975.
13. Liess, C., "Experimental Investigation of Film Cooling with Ejection from a Row of Holes for the Application to Gas Turbine Blades", ASME Paper No. 74-GT-5, 1974.
14. Jabbari, M. Y. and Goldstein, R. J., "Adiabatic Wall Temperature and Heat Transfer Downstream of Injection Through Two Rows of Holes", J. Engr. for Power, 100, p. 303, 1978.
15. Foster, N. W. and Lampard, "The Flow and Film Cooling Effectiveness Following Injection Through a Row of Holes", J. Engr. for Power, 102, p. 584, 1980.
16. Afejuku, W. O., Hay, N., and Lampard, D., "The Film Cooling Effectiveness of Double Rows of Holes", J. Engr. for Power, 102, p. 601, 1980.
17. Rice, I. G., "Steam-Cooled Blading in a Combined Reheat Gas Turbine/Reheat Steam Turbine Cycle, Part I - Performance Evaluation", ASME Paper No. 79-JPGC-GT-2, 1979.
18. Han, J. C. and Jenkins, P. E., "Prediction of Film Cooling Effectiveness of Steam", ASME Paper No. 82-GT-100, 1982.
19. Goldstein, R. J., Rask, R. B., and Eckert, E. R. G., "Film Cooling with Helium Injection into an Incompressible Air Flow", Intern. J. Heat Mass Transfer. 9, p. 1341, 1966.
20. Nicoll, W. B. and Whitelaw, J. H., "The Effectiveness of the Uniform Density, Two-dimensional Wall Jet", Intern. J. Heat Mass Transfer, 10, p. 623, 1967.