INFLUENCE OF THE HOLE LENGTH-TO-DIAMETER RATIO ON FILM COOLING WITH CYLINDRICAL HOLES

Ewald Lutum and Bruce V. Johnson
ABB Corporate Research Ltd.
CH-5405 Baden-Dättwil, Switzerland

ABSTRACT
Film cooling experiments were conducted to investigate the effects of coolant hole length-to-diameter ratio on the film cooling effectiveness. The results from these experiments offer an explanation for the differences between the film cooling results for cylindrical hole injection configurations previously reported by Goldstein et al. (1974), Pedersen et al. (1977) and Sinha et al. (1991). The previously reported injection configurations differed primarily in coolant hole length-to-diameter ratio. The present experiments were conducted with a row of cylindrical holes oriented at 35 degrees to a constant-velocity external flow, systematically varying the hole length-to-diameter ratios (L/D=1.75, 3.5, 5, 7 and 18), and blowing rates (0.525 ≤ M ≤ 1.56).

Results from these experiments show in a region 5 ≤ X/D ≤ 50 downstream of coolant injection that the coolant flow guiding capability in the cylindrical hole was apparently established after 5 hole diameters and no significant changes in the film cooling effectiveness distribution could be observed for the greater L/D. However, the film cooling effectiveness characteristics generally decreased with decreasing hole L/D ratio in the range of 1.75 ≤ L/D ≤ 5.0. This decrease in film cooling performance was attributed to (1) the undeveloped character of the flow in the coolant channels and (2) the greater effective injection angle of the coolant flow with respect to the external flow direction and surface. The lowest values of film cooling effectiveness were measured for the smallest hole length-to-diameter ratio, L/D=1.75.

NOMENCLATURE
D coolant hole diameter, [m]

DR density ratio = \frac{\rho_c}{\rho_\infty}

L length of coolant passage, [m]
M blowing rate = \frac{\rho_c U_c}{\rho_\infty U_\infty}

P hole pitch, distance between holes in lateral direction, [m]
P/D dimensionless lateral-spacing, pitch to diameter ratio
T temperature, [°C]
Tu turbulence intensity, [percent]
U mean velocity, [m/s]
X streamwise coordinate, origin at film hole center, [m]
X/D dimensionless streamwise coordinate
Z lateral coordinate, [m]
Z/D dimensionless coordinate in lateral direction
k thermal conductivity, [W/m/K]

Greek
\alpha injection angle of the fluid, [°]
\rho fluid density, [kg/m^3]
\eta_{ad,c} centerline adiabatic film cooling effectiveness
\eta_{ad,l} lateral averaged adiabatic film cooling effectiveness

Subscripts
c coolant fluid
\infty free-stream fluid
TLC thermochromic liquid crystal indication

INTRODUCTION
The review of film cooling technology by Goldstein (1971) delineates much of the physics of film cooling, especially the interactions between the free-stream and the film cooling jets.
Film cooling through discrete holes has been recognized as a three-dimensional phenomena with complex interactions as the coolant and the external flow initially interact. Much of the early experimental work was focused on the effects of the coolant to external gas path velocity and density ratio using cylindrical holes at various angles to the external surface.

Geometric effects have also been investigated as the film cooling technology developed and as the manufacturers sought explanations for engine performance that was different than the laboratory data. Effects of geometry include coolant hole exit geometry with the shaping of the hole, the angles at which the coolant penetrates the gas path, the hole diameter to boundary layer thickness, the angle of coolant jet to the surface, the angle of the coolant jet to the gas stream, airfoil surface conditions including surface roughness and curvature of the external wall. In addition to the conventional effects of coolant to free-stream blowing rate and density ratios, the effects of gas stream Mach number and free-stream scale and intensity of turbulence have also been investigated and reported. In addition to the published experimental studies on film cooling, additional film cooling technology is believed to have been developed experimentally by the industrial and aircraft gas turbine engine companies and not publicly published.

The numerical modeling of film cooling and some of the aforementioned effects have also been conducted for the past 20 years. Recent numerical modeling contributions include Leylik and Zerkle (1994), Vogel et al. (1995) and Walters and Leylik (1996 and 1997).

As stated above, there have been extensive studies on film cooling. However, most of these studies have focused on the gas path characteristics and the coolant flow ratios. The effects of the cooling hole inlet conditions and length and the control of the film cooling effectiveness through the variation of the hole inlet geometry and inlet flow conditions have not been systematically investigated in detail. Exceptions include: 1) the experimental studies from Papell et al. (1982) and Papell (1984), where efforts to control the vorticity from the coolant hole were made, 2) the numerical and experimental results from Vogel et al. (1995) which showed effects of coolant hole inlet conditions on the near jet film cooling aerodynamic and 3) the experimental study from Burd and Simon (1997) who investigated the influence of coolant supply geometry and hole length on the film coolant exit flow and film cooling effectiveness.

However, there have been several experiments with coolant holes at the same angle to the flow with similar gas path and coolant flow conditions but with various values of coolant hole L/D which present different results. These include Goldstein et al. (1974) with a coolant hole L/D=5.2, Pedersen et al. (1977) with a L/D=40, and Sinha et al. (1991) with L/D=1.75. Table 1 summarizes the related geometrical and experimental boundary conditions of the referred investigations, as far as available from the publications and those of the present study. Except for the experiments by Goldstein et al. (1974), all previous investigations mentioned were conducted at density ratios slightly above unity. A comparison of their results at two coolant blowing rates showed significant differences in both the centerline film effectiveness and the laterally averaged film effectiveness, especially at the higher blowing ratios. These significant differences in the results with moderate differences in the free-stream test conditions were the basis for pursuing the present study.

Objectives

The principle purposes of this investigation and paper are to show the effects of coolant hole L/D on the experimental film cooling performance, to compare results of the present experiments with the results of previous and to discuss possible mechanisms for the differences in the performance of the various length coolant holes.

### Table 1. Comparison of the geometrical and experimental conditions.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Channel width</th>
<th>Channel height</th>
<th>Number of holes</th>
<th>P/D</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldstein et al. (1974)</td>
<td>250</td>
<td>130</td>
<td>11</td>
<td>3.0</td>
<td>5.2</td>
</tr>
<tr>
<td>Pedersen et al. (1977)</td>
<td>610</td>
<td>305</td>
<td>15</td>
<td>3.0</td>
<td>40</td>
</tr>
<tr>
<td>Sinha et al. (1991)</td>
<td>610</td>
<td>610</td>
<td>7</td>
<td>3.0</td>
<td>1.75</td>
</tr>
<tr>
<td>Present Study</td>
<td>80</td>
<td>60</td>
<td>7</td>
<td>2.86</td>
<td>1.75</td>
</tr>
</tbody>
</table>

### Fluid Boundary Condition

<table>
<thead>
<tr>
<th>Reference</th>
<th>T(_{u_0})</th>
<th>U(_{max})</th>
<th>DR</th>
<th>T(_{\infty})</th>
<th>T(_{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldstein et al. (1974)</td>
<td>low</td>
<td>20-55</td>
<td>0.90</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Pedersen et al. (1977)</td>
<td>0.4</td>
<td>15-27</td>
<td>1.18</td>
<td>heat-mass transfer</td>
<td></td>
</tr>
<tr>
<td>Sinha et al. (1991)</td>
<td>0.2</td>
<td>20</td>
<td>1.20</td>
<td>27</td>
<td>-23</td>
</tr>
<tr>
<td>Present Study</td>
<td>3.5</td>
<td>115</td>
<td>1.15</td>
<td>64</td>
<td>20</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL APPARATUS**

The adiabatic film cooling experiments were conducted in a subsonic open-circuit wind tunnel with a straight channel test section shown in Figure 1. Ambient air was compressed by an electrical blower. The free-stream mass flow was determined by a calibrated orifice with a measurement uncertainty of 2.5 percent. Free-stream air was heated in a range of 60°C to 70°C by an electrical heater before it entered into the settling chamber. The hot air path and the settling chamber were insulated in order to minimize temperature differences of the incoming flow. An assembly of honeycomb and a series of screens homogenized the flow inside the settling chamber. The flow accelerated through the nozzle with a 10:1 contraction ratio into the test section.
A turbulence grid was placed at the test section entrance to increase the free-stream turbulence intensity. This turbulence grid consisted of 3 x 3 mm rectangular holes that were spaced, from hole center to hole center, 4 mm in width and height. The streamwise decay of the free-stream turbulence intensity was determined in previous measurements on this test facility (Tu = 5.0% at X/D = -18, Tu = 3.5% at X/D = 0 and Tu = 2.0% at X/D = 40). The approaching boundary layer was turbulent with a boundary layer thickness of about 4 mm at the injection location. The displacement thickness at this location was determined to be 0.5 mm. The free-stream velocity level was about U = 115 m/s.

A second pressurized air supply system of the lab delivered the cooling mass flow at ambient temperature level of about 20°C. The cooling mass flow was accurately determined by means of a turbine wheel meter (1 percent measurement uncertainty) and piped into the cooling air settling chamber, where the air passed through a set of flow straightening devices to minimize flow disturbances. The cooling air was finally injected into the heated free-stream flow through a single row of cylindrical holes at selected blowing rates in the range of 0.52 ≤ M ≤ 1.56. The typical density ratio for all experiments conducted was DR = 1.15.

The dimensions of the straight test section were 80 mm in width and 60 mm in height with top and side walls constructed of polycarbonate material. The polycarbonate walls allowed optical access to the test surface. A color CCD camera was arranged to observe the test surface through the top wall of the test section. Secondary air was injected after 100 mm of the total length of 600 mm. The bottom wall of the straight channel, the actual test surface, held the different injection configurations investigated. The use of low conductivity material (Necurom, k = 0.1 W/m/K) and additional thermal insulation applied below this test surface kept the heat losses to low values. Temperature measurements errors due to heat losses were determined by a two dimensional heat conduction analysis to be less than 0.05°C.

Figure 1. Straight channel test facility.

Figure 2. Injection configurations (P/D=2.86).
with diameter, \( D \), equal 4 mm. The hole spacing in lateral direction was \( P=11.43 \) mm and corresponded to a pitch-to-diameter ratio of \( P/D=2.86 \). The hole channels were inclined at \( \alpha=35^\circ \) to the free-stream flow direction. The hole length-to-diameter ratio of the injection channels was systematically varied, \( L/D=1.75, 3.5, 5, 7, 18 \), by variation of the test plate thickness as shown in Figure 2.

**Data Analysis**

Adiabatic film cooling data was obtained by use of the well established thermochromic liquid crystal (TLC) technique to measure the adiabatic wall temperature distribution. Isothermal temperature patterns due to film cooling on the adiabatic test plate were indicated by a mixture of up to 6 narrow-banded thermochromic liquid crystals and were recorded by a color CCD camera in conjunction with a color image processing system. All additional experimental data, i.e., temperature, pressure and mass flow information of the main and secondary flow, were stored by a separate data acquisition system for later data reduction purposes.

To achieve accurate measurement of the wall temperature using the TLC’s, a special apparatus was built to conduct the temperature calibration of the TLC indication temperatures inside the film cooling test section. The calibration was conducted by interchanging the test plate with a copper calibration plate. A linear temperature distribution was achieved by heating at one end of this plate and cooling at the other end. Determination of the TLC temperature indications on the copper surface was obtained with the same color image processing system used later for the film cooling measurements. Thermocouples, embedded in the copper surface, were used to measure the temperature distribution over the plate length. The experimental uncertainty of the local film cooling effectiveness values was determined by an uncertainty analysis to be not higher than 0.008.

During the experiments, the TLC data was captured using a color CCD camera in conjunction with a color image processing system. A complete data set was compiled using up to six adjacent smaller images. The camera was mounted above the experimental apparatus on a traverse system controlled by a step motor, allowing all pictures to be taken with the same reference points. Using multiple images to build up the final picture allowed higher resolution and better isotherm definition of the adiabatic wall temperature distributions. The temperature indications of the TLC’s were assumed to be the adiabatic wall temperatures. The free-stream temperature was measured by a total temperature probe at \( X/D=10 \) upstream of the injection location. The coolant temperature was measured by a thermocouple in the coolant settling chamber. With the additional information of the coolant and free-stream temperatures, these isothermal contour lines were recalculated to adiabatic film cooling effectiveness contours as shown in Figure 3 by the following equation:

\[
\eta_{lad} = \frac{(T_w-T_{TL,C})/(T_w-T_c)}{1}.
\]  

(1)

For the calculation of the lateral averaged film cooling effectiveness values, a special interpolation technique was used. The field of interpolation was determined in lateral direction over a range of two pitches (3 holes) and in streamwise direction, dependent on the input data set respectively. The interpolation was done by a stepwise interpolation technique using the following steps:

1) Interpolation in streamwise direction with a power fit \( (Y=AX^B) \) based on the detected effectiveness contour lines. This interpolation was performed to form skeleton lines, that define the shape of the effectiveness hills and produce more input data for the following interpolation in lateral direction.

2) Interpolation in lateral direction using a cubic spline for each streamwise position, based on both the detected effectiveness contour lines and the results of the streamwise interpolation carried out just before. This interpolation was continued in the streamwise direction downstream of the injection location as far as sufficient input data was available. These results were also stored for the final interpolation step.

3) To obtain smooth contours, the data was again interpolated in the streamwise direction, similar to the first interpolation step for all lateral positions based on the results of the two previous interpolation steps. Because of the additional created effectiveness values, continuous interpolation was possible for the desired range of two pitches in lateral direction (Figure 4).

\[
\begin{align*}
\eta_{lad} & = 0.10 \\
& = 0.22 \\
& = 0.34 \\
& = 0.47 \\
& = 0.65 \\
& = 0.77
\end{align*}
\]  

**Figure 3.** Typical TLC contours of film cooling effectiveness values at low blowing rate.

**Figure 4.** Typical interpolated film cooling effectiveness data at low blowing rate.

The typical interpolation accuracy was within 2.5 percent of the local effectiveness values. Finally, an integration in lateral direction was performed to determine the lateral averaged film cooling effectiveness data at each streamwise position. The estimated integration error based on the experimental and interpolation uncertainty was about 1 to 3 percent of the streamwise local lateral averaged film cooling effectiveness. The
uncertainty depended on the effectiveness level, with the higher uncertainty related to lower effectiveness values.

PRESENT RESULTS

Measurements of adiabatic film cooling effectiveness values at selected length-to-diameter ratios, L/D=1.75, 3.5, 5, 7 and 18, are presented in the Figures 5a through 8b. Centerline (a) and laterally averaged (b) film cooling results are shown, as a variation with the dimensionless streamwise coordinate, X/D, at four blowing rates, M=0.52, 0.81, 1.15 and 1.56.

The centerline film cooling effectiveness distributions at a low blowing rate (M=0.52) with the long holes (L/D=5, 7 and 18) show small differences along the streamwise distance shown in Figure 5a. The film cooling effectiveness distribution obtained close to the injection location for L/D=3.5 was similar to that obtained for longer injection holes. With increasing distance downstream, a larger decrease in film cooling effectiveness was measured for the L/D=3.5 holes, compared to the effectiveness results for the longer holes. The results with L/D=1.75 indicate about 20 to 25 percent lower film cooling effectiveness compared to the results of the long holes. The corresponding distributions of the lateral averaged film cooling effectiveness are shown in Figure 5b. Highest lateral averaged film cooling effectiveness values are achieved with the long injection holes, L/D=5 and 7. However, for holes with the longest length, L/D=18, slightly lower values of film cooling effectiveness are obtained in the near injection region (X/D<35). Lower lateral averaged film cooling effectiveness values are generally obtained with the shorter injection holes compared to the long injection holes. The decrease of film cooling effectiveness is about 10 percent with L/D=3.5 and about 20 percent with L/D=1.75.

Figures 6a and 6b present the film cooling effectiveness values for the different hole length-to-diameter ratios at a blowing rate of M=0.81. The centerline and lateral averaged film cooling effectiveness distributions with the injection holes, L/D=5, 7 and 18, indicated very little variation in the effectiveness and are higher than the film cooling performance with the shorter injection holes. The decrease of film cooling performance with the L/D=3.5 injection holes is about 20 percent and about 40 percent with the L/D=1.75 injection holes compared to the longer holes.

The centerline film cooling effectiveness distributions, at a moderate blowing rate, M=1.15, indicate the same trends as seen at the lower blowing rate, M=0.81 (Figure 7a). Compared to the film cooling effectiveness values obtained at the lower blowing rate, the decreases in the film cooling effectiveness values are attributed to a strong jet separation with the L/D=1.75 hole at M=1.15. The lateral averaged results shown in Figure 7b indicate again higher levels of film cooling effectiveness for the longer injection holes. However, the distribution for holes with L/D=5 shows a 10 to 15 percent decrease in film cooling performance compared to holes with L/D=7 and 18 for X/D>15. With the shorter injection holes, approximately 25 to 35 percent less film cooling effectiveness with L/D=3.5 and about 30 to 50 percent less film cooling effectiveness with L/D=1.75 is obtained compared to the values with L/D=7 and 18.

Figures 8a and 8b show the results for the highest blowing rate (M=1.56) investigated during this film cooling study. All film cooling effectiveness distributions shown in Figure 8a indicate that a strong jet separation from the test plate occurred at this high blowing rate. The highest film cooling performance obtained with M=1.56 was with the longest injection hole (L/D=18). The two other long hole injection configurations, L/D=7 and 5, resulted in 10 percent lower lateral film cooling effectiveness values compared to the values with L/D=18. The shorter injection holes caused about 35 to 45 percent less film cooling effectiveness with L/D=3.5 and about 45 percent less film cooling effectiveness with L/D=1.75 compared to the values with L/D=18.

The lateral film cooling effectiveness values from Figures 5 through 8 for selected values of X/D are re-plotted in Figure 9 to show the influence of hole length-to-diameter ratio on the film cooling performance. The variations of lateral averaged film cooling effectiveness values with the hole length-to-diameter ratio, L/D, are shown for four streamwise locations, X/D= 10, 20, 30 and 40. At each streamwise location, the results are presented for the four investigated blowing rates, M=0.52, 0.81, 1.15 and 1.56. Small effects of hole length-to-diameter ratio on the film cooling performance are measured for the well-developed coolant flows in the longer holes (i.e., L/D=7 and 18). Small to moderate effects of hole length-to-diameter ratio on the film cooling performance are obtained with a L/D=5 hole. For M=0.81, a small (0.01) increase in effectiveness was measured compared to L/D=7 and 18 holes. This is attributed to an unknown but beneficial interaction of the coolant jet and cross flow for those conditions. The film cooling effectiveness decreases clearly with decreasing hole length-to-diameter ratio in the range of 1.75≤L/D≤5. This decrease in film cooling effectiveness is attributed to (1) the underdeveloped character of the coolant flow and (2) the greater effective injection angle of the coolant flow, with respect to the external flow direction and surface, due to jetting of the coolant flow on the upstream edge of the film cooling holes (Burk and Simons 1997).

The minimum film cooling effectiveness values are obtained for the coolant hole length-to-diameter ratio, L/D=1.75. The decreases in film cooling performance are about 25 percent for the low blowing rate results (M=0.52), about 40 percent for the moderate blowing rate results (M=0.81) and about 30 to 45 percent for the high blowing rate results (M=1.15 and 1.56), compared to the corresponding results measured with the longer coolant channels. These results show that for injection configurations with the short coolant hole lengths, significant decreases in the film cooling effectiveness can occur and that the coolant hole L/D must be added to the long list of geometrical and flow characteristics which influence film cooling performance.

Comparison with Previous Results

The comparison of the present results with data from Goldstein et al. (1974) at a blowing rate M=0.5 indicates higher film effectiveness values from the present experiment in the near-injection region and identical values further downstream (Figure 10a). These differences are attributed to the higher momentum flux.
ratio due to the lower density ratio of the experiments conducted by Goldstein et al. (1974). Results from Pedersen et al. (1977) and Sinha et al. (1991) indicate higher values of centerline film cooling effectiveness for X/D<40 and identical values further downstream, compared to the present results. The agreement between the present lateral averaged results for a blowing rate M=0.5 shown in Figure 10b with results from Pedersen et al. (1977) is good. Results from Sinha et al. (1991) indicate significantly lower lateral averaged film cooling effectiveness values in the near injection region, compared to the present results. These differences between these two measurements decrease with downstream distance, if the data from Sinha et al. (1991) are extrapolated to higher X/D values.

The agreement between the present results and data from Pedersen et al. (1977) at the higher blowing rate M=1.0 is reasonably good for the centerline film cooling effectiveness (Figure 11a). The centerline values from Goldstein et al. (1974) indicate lower values close to the injection holes and similar values for X/D>30 compared to the corresponding present results. The centerline values from Sinha et al. (1991) indicate lower values compared to the corresponding present results. The lateral averaged film cooling effectiveness values from Pedersen et al. (1977) are less compared to the comparable present data (Figure 11b).

The results from the present experiments do not identify differences between experiments. These differences are mainly attributed to higher free-stream turbulence intensity at which the present experiments were conducted. However, the results show the significant effects of L/D ratios with the same trends as the previous experiments. In addition, the physical insight obtained from the experiments is useful in understanding some of the physical mechanisms governing film cooling.

CONCLUSIONS

Adiabatic film cooling experiments were conducted with a row of cylindrical holes oriented at 35 degrees to the external flow direction. The hole length-to-diameter ratios were systematically varied in the range of L/D=1.75, 3.5, 5, 7 and 18. The adiabatic film cooling effectiveness was determined for a range of blowing rates at a fixed free-stream velocity level (U∞=115 m/s). The purpose of these experiments was to systematically investigate the effects of coolant hole length to diameter ratio and explain the diverse film cooling results previously obtained by several investigators with different ratios of coolant hole L/D.

Small to moderate effects of hole length-to-diameter ratio on film cooling performance were measured for the long injection hole configurations (i.e., L/D=5, 7 and 18). The coolant flow characteristics in the cylindrical holes were apparently sufficiently established after 7 hole diameters so as to not significantly alter the film cooling effectiveness distribution for the greater value of hole L/D.

The film cooling effectiveness decreased with decreasing hole L/D ratio in the range of 1.75≤L/D≤5.0. This decrease in film cooling effectiveness was attributed to (1) the undeveloped character of the flow in the coolant channels and (2) the greater effective injection angle of the coolant flow, with respect to the external flow direction and surface.

The lowest values of the film cooling effectiveness were measured for the smallest hole length-to-diameter ratio, L/D=1.75. The decrease in film cooling performance was about 25 percent for the low blowing rate results (M=0.52), about 40 percent for the moderate blowing rate results (M=0.81) and about 30 to 45 percent for the high blowing rate results (M=1.15 and 1.56), compared to the corresponding results achieved with the longer coolant channels.

ACKNOWLEDGMENTS

The authors wish to acknowledge the help of Mr. S. Wolff and Mr. J. Wiegelmann for conducting the film cooling experiments described in this paper.

REFERENCES


Figure 5. a) Centerline and b) lateral averaged adiabatic film cooling effectiveness distributions at various length-to-diameter ratios obtained with M=0.52.

Figure 6. a) Centerline and b) lateral averaged adiabatic film cooling effectiveness distributions at various length-to-diameter ratios obtained with M=0.81.
Figure 7. a) Centerline and b) lateral averaged adiabatic film cooling effectiveness distributions at various length-to-diameter ratios obtained with $M=1.15$.

Figure 8. a) Centerline and b) lateral averaged adiabatic film cooling effectiveness distributions at various length-to-diameter ratios obtained with $M=1.56$. 
Figure 9. Lateral averaged adiabatic film cooling effectiveness distributions versus length-to-diameter ratio at 4 streamwise locations, $X/D$: a) = 10, b) = 20, c) = 30 and d) = 40.
Previous results: $M=0.5$
- i) $L/D=1.75$ $\eta=0.21$
- ii) $L/D=5.2$ $\eta=0.30$
- iii) $L/D=40$ $\eta=0.23$

Present results: $M=0.52$
- $L/D=1.75$ $\eta=0.24$
- $L/D=5.0$ $\eta=0.24$
- $L/D=18$ $\eta=0.24$

Previous results: $M=1.0$
- i) $L/D=1.75$ $\eta=0.83$
- ii) $L/D=5.2$ $\eta=1.13$
- iii) $L/D=40$ $\eta=0.93$

Present results: $M=1.15$
- $L/D=1.75$ $\eta=1.16$
- $L/D=5.0$ $\eta=1.16$
- $L/D=18$ $\eta=1.16$

Figure 10. Comparison of present a) centerline and b) lateral averaged adiabatic film cooling results with previous results from i) Sinha et al. (1991), ii) Goldstein et al. (1974) and iii) Pedersen et al. (1977).

Figure 11. Comparison of present a) centerline and b) lateral averaged adiabatic film cooling results with previous results from i) Sinha et al. (1991), ii) Goldstein et al. (1974) and iii) Pedersen et al. (1977).