UNSTEADY WAKE OVER A LINEAR TURBINE BLADE CASCADE WITH AIR AND CO₂ FILM INJECTION: PART I — EFFECT ON HEAT TRANSFER COEFFICIENTS

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ABSTRACT

The effect of unsteady wake flow and air (D.R.=1.0) or CO₂ (D.R.=1.52) film injection on blade heat transfer coefficients was experimentally determined. A spoked wheel type wake generator produced the unsteady wake. Experiments were performed on a five airfoil linear cascade in a low speed wind tunnel at the chord Reynolds number of \(3\times10^5\) for the no wake case and at the wake Strouhal numbers of 0.1 and 0.3. Results from a blade with three rows of film holes in the leading edge region and two rows each on the pressure and suction surfaces show that the Nusselt numbers are much higher than those for the blade without film holes. On a large portion of the blade, the Nusselt numbers ‘without wake but with film injection’ are much higher than for ‘with wake but no film holes’. An increase in wake Strouhal number causes an increase in pressure surface Nusselt numbers; but the increases reduce at higher blowing ratios. As blowing ratio increases, the Nusselt numbers for both density ratio injectants (air and CO₂) increase over the entire blade except for the transition region where the effect is reversed. Higher density injectant (CO₂) produces lower Nusselt numbers on the pressure surface, but the numbers for air and CO₂ injections are very close on the suction surface except for the transition region where the numbers for CO₂ injection are higher. From this study, one may conclude that the additional increases in Nusselt numbers due to unsteady wake, blowing ratio, and density ratio are only secondary when compared to the dramatic increases in Nusselt numbers only due to film injection over the no film holes case.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>C</td>
<td>blade chord</td>
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<td>d</td>
<td>wake generator rod diameter</td>
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<td>D</td>
<td>film hole diameter</td>
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<td>D.R.</td>
<td>density ratio, (\rho_p/\rho_m)</td>
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<td>h</td>
<td>local heat transfer coefficient</td>
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<td>H</td>
<td>blade radial (spanwise) length</td>
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<td>I</td>
<td>momentum flux ratio, ((\rho V_h^2)/(\rho V_m^2))</td>
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<td>k</td>
<td>local thermal conductivity</td>
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<td>M</td>
<td>blowing ratio (secondary to mainstream mass flux ratio), ((\rho V_p)/(\rho V_m))</td>
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<tr>
<td>n</td>
<td>number of rods in the wake generator</td>
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<tr>
<td>N</td>
<td>wake generator rotation speed (rpm)</td>
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<tr>
<td>Nu</td>
<td>Nusselt number based on blade chord, (hC/\kappa)</td>
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<tr>
<td>(\bar{Nu})</td>
<td>spanwise averaged Nusselt number</td>
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<td>P</td>
<td>film hole pitch</td>
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<td>q''_n</td>
<td>net forced convection heat flux</td>
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<td>q''_con</td>
<td>local conduction heat loss flux</td>
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<td>q''_f</td>
<td>foil generated wall heat flux</td>
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<td>q''_l</td>
<td>local total heat loss flux</td>
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<tr>
<td>q''_rd</td>
<td>local radiation heat loss flux</td>
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<tr>
<td>e</td>
<td>distance between the wake generator shaft center and the cascade midspan</td>
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<tr>
<td>Re</td>
<td>Reynolds number based on the blade chord, (V_C/\nu)</td>
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<tr>
<td>S</td>
<td>wake Strouhal number, (2\pi N d/60V_C)</td>
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<td>T_w</td>
<td>local adiabatic wall temperature</td>
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<td>T_f</td>
<td>secondary flow temperature within the injection cavity</td>
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<td>T_\in</td>
<td>local wall temperature</td>
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<tr>
<td>T_c</td>
<td>mainstream temperature at the cascade inlet</td>
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<tr>
<td>U_r</td>
<td>rotational velocity at the cascade midspan</td>
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<tr>
<td>V</td>
<td>local mainstream velocity</td>
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<tr>
<td>V_e</td>
<td>local mainstream velocity at the cascade exit</td>
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<tr>
<td>V_c</td>
<td>mean mainstream velocity at the cascade inlet</td>
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<tr>
<td>V_c_2</td>
<td>mean mainstream velocity at the cascade exit</td>
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<td>X</td>
<td>blade surface coordinate from stagnation in the streamwise direction</td>
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<td>X/C</td>
<td>dimensionless blade surface coordinate in the streamwise direction</td>
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<tr>
<td>Y</td>
<td>blade radial (spanwise) coordinate</td>
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<tr>
<td>Y/H</td>
<td>dimensionless blade radial (spanwise) coordinate</td>
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<tr>
<td>(\nu)</td>
<td>local kinematic viscosity</td>
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<tr>
<td>(\rho_s)</td>
<td>secondary density</td>
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<tr>
<td>(\rho_m)</td>
<td>mainstream density</td>
<td></td>
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<tr>
<td>(\rho V_h)</td>
<td>local secondary mass flux</td>
<td></td>
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<tr>
<td>(\rho V_m)</td>
<td>local secondary momentum flux</td>
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INTRODUCTION

It is well known that gas turbine performance improves with an increase in turbine inlet temperature. This has caused a continuing trend towards higher gas turbine inlet temperatures and resulted in higher heat loads on turbine components. Hence, turbine blade external and internal cooling techniques must be employed in order to maintain the performance requirements.

There have been many studies to investigate the effect of unsteady wake on the downstream blade (without film holes) heat transfer coefficient distribution, which is caused by the relative motion between the upstream nozzle vanes and the downstream blades. It is clear from published results that this unsteady wake enhances the leading edge heat transfer and causes an earlier and longer laminar-turbulent transition on the suction surface. This elongated transition zone causes increased heat transfer over a larger area. Many investigations have been made to study the effect of unsteady wake and mainstream turbulence on the flow field and heat transfer coefficients of a downstream turbine blade. Abhari et al. (1992), Abhari and Epstein (1992), Blair et al. (1989a, 1989b), Blair (1992), Camci and Arts (1990), Dunn (1986), Dunn et al. (1986, 1989, 1992), and Nirmalan and Hylton (1990) conducted experiments in actual gas turbine engines; whereas, Doorly (1988), Dullenkopf et al. (1991), Dullenkopf and Mayle (1992), Liu and Rodi (1989, 1992), O'Brien and Capp (1989), Priddy and Bayley (1988), Wittig et al. (1987, 1988), and Han et al. (1993) did laboratory simulations of upstream unsteady wake conditions. Two techniques to produce unsteady wake have been used in laboratory simulations. Liu and Rodi (1989, 1992), and Priddy and Bayley (1988) used a squirrel cage type wake generator; whereas, Doorly (1988), Dullenkopf et al. (1991), Dullenkopf and Mayle (1992), O'Brien and Capp (1989), Wittig et al. (1987, 1988), and Han et al. (1993) used a spoked wheel type wake generator. Mayle and Dullenkopf (1990) and Mayle (1991) recently developed a theory to incorporate unsteady effect into a steady flow analysis by introducing a time-averaged intermittency factor.

Mick and Mayle (1988) studied the heat transfer coefficient distributions on a leading edge model with film injection. Mehendale and Han (1992), and Ou and Han (1992) studied the effect of high mainstream turbulence on a leading edge model with film injection. They reported that film injection alone enhances the 'no film holes' surface heat transfer coefficients by 2-3 times. They noted that high mainstream turbulence increases surface heat transfer coefficients at all blowing ratios, but the increases reduce at higher blowing ratios.

Teekaram et al. (1989) studied the effect of secondary to mainstream density ratio on heat transfer coefficients over a flat plate with film injection. They used air and CO₂ at the same density for film injection. Densities of both injectants were made equal by controlling their temperatures. They reported that the film cooled heat transfer coefficients were independent of the gas used for injection (air or CO₂) as long as their densities were maintained the same. Ammari et al. (1990) studied the effect of density ratio on flat plate heat transfer coefficients with air or CO₂ film injection.

This study focuses on the effect of incident unsteady wake conditions on heat transfer coefficient distribution on a model turbine blade with air or CO₂ film injection through three rows of film holes in the leading edge region and two rows each on the pressure and suction surfaces. The objectives of this study are to determine: (1) the enhancement in blade heat transfer coefficients solely due to the upstream unsteady wake for the no film holes conditions, (2) the enhancement in blade heat transfer coefficients solely due to film injection for the no wake condition, (3) the effect of density ratio on blade heat transfer coefficients with air or CO₂ film injection, and (4) the combined effect of upstream unsteady wake and injectant density ratio on blade heat transfer coefficients.

A five blade linear cascade with an instrumented blade at its center was used for this study. Two instrumented blades, one without film holes and the other with film holes, were used. The cascade was mounted in a low speed wind tunnel at the Turbine Heat Transfer Laboratory of Texas A&M University. The upstream unsteady wake was produced by a spoked wheel type wake generator similar to the ones used by Dullenkopf et al. (1991), O'Brien and Capp (1989), Wittig et al. (1987), and Han et al. (1993). The blade with film holes was connected to air and CO₂ supply lines. Both test blades were instrumented with the thin foil-thermocouple technique similar to that used by Mehendale and Han (1992) and Han et al. (1993).

TEST APPARATUS AND INSTRUMENTATION

A schematic of the test apparatus is shown in Fig. 1. The test apparatus consisted of a low speed, low turbulence wind tunnel with an inlet nozzle, a spoked wheel type wake generator, a linear turbine blade cascade with an instrumented blade at its center, and a suction type blower. The wind tunnel was designed for a blade turning angle of 107.49°. The nozzle had a contraction ratio of 3:1.5. The wake generator was covered with a casing to prevent leakage flow and its shaft was located below the bottom wall of the wind tunnel. The five blade cascade was installed downstream of the wake generator.

![Fig. 1 Schematic of the linear turbine blade cascade with a spoked wheel type wake generator](http://proceedings.asmedigitalcollection.asme.org/10.1115/1.4030845)
a similar velocity ratio distribution as in a typical advanced high pressure turbine blade row. The selected blade had a 107.49° turning with relative flow angles of 35° and -72.49° at the blade inlet and exit, respectively. A five times scaled up model was used to simulate the engine Reynolds number. The cascade had five blades, each with a chord length of 22.68 cm and a radial span of 25.2 cm. The blades were spaced 17.01 cm apart at the cascade inlet. The cascade leading edge was 8.82 cm downstream of the wake generator. All blades were made of high quality model wood. Only the center blade was instrumented and was either the blade without film holes or the blade with film holes.

The spoked wheel type wake generator had 32 rods, each 0.63 cm in diameter to simulate trailing edge of an upstream blade. The wake generator was driven by a 2.2 kW (3 hp) D.C. motor. Its shaft was located 20 cm below the bottom wall of the wind tunnel. The wake Strouhal number was adjusted by controlling the motor speed. The wake generator rotation speed was accurately measured by a Pioneer DT-36M digital photo tachometer.

Using non-linear rotating rods with a linear blade cascade causes the wakes at the top of the cascade to pass by the blades faster than the wakes at the bottom of the cascade. This error was small in the 7.6 cm midspan region where the thermocouples were located, as indicated by tests on a no film holes blade. Heat transfer coefficient tests for the no film holes blade indicate that for the 0.00378 cm thick foil, with negligible lateral conduction, spanwise thermocouple readings in the 7.6 cm midspan region were off by only about ±0.5%.

Four slots were machined in the top wall of the wind tunnel, two near the leading edge and two near the trailing edge, in the middle of flow passages as shown in Fig. 2. Hot wire probes were inserted through the leading edge slots to measure the oncoming flow velocities, wake profiles, turbulence fluctuations, and to check the flow periodicity between the two adjacent flow passages. The trailing edge slots were used to measure the exit flow velocities.

A calibrated single hot wire was used to measure the instantaneous velocity profile. It was connected to a 3 channel TSI IFA 100 hot wire anemometer. The analog signal from the anemometer was converted to digital by a DATA TRANSLATION 250 kHz A/D board in a 386SX 20 MHz machine. The anemometer output was also connected to a NICOLET 446A spectrum analyzer that displayed the instantaneous wake profile and frequency distribution.

A schematic of the top view of the blade without film holes is shown in Fig. 3. Twenty-six strips of stainless steel foil, each 25.4 cm long × 2 cm wide × 0.00378 cm thick, were cemented vertically on the test blade. They were separated by 0.8 mm gaps that were filled with wood putty and made flush with the foil surface. All foils were connected in series by copper bus bars. The foils produced an almost constant wall heat flux boundary condition when electrically heated. Thirty-six gage copper constantan thermocouples were cemented on the undersides of the foils. There were 11 rows of thermocouples on the pressure surface and 15 rows on the suction surface. Each row had 3 thermocouples spaced 2.52 cm apart in the radial midspan region of the blade.

A schematic of the top view of the blade with film holes is shown in Fig. 4. The first cavity supplied three rows of film holes - one near the leading edge, and one each on the pressure and suction surfaces. The second cavity supplied one row each on the pressure and suction surfaces. The third and fourth cavities supplied one row of film holes on the pressure and suction surfaces, respectively. Depending on its location, each row had 8 to 10 film holes between 30% and 70% of the radial blade span. Some of the film holes had a compound angle (radial and tangential) relative to the blade surface as seen in Fig. 4. Radial angle is defined as the angle between the film hole axis and the local radial (spanwise) direction. Tangential angle is defined as the angle between the film hole axis and the local streamwise tangential direction. Details of the film hole configuration (streamwise location, diameter, length, spanwise spacing, and compound angle) for this 5X model blade were specified by General Electric - Aircraft Engine Division. Each cavity was supplied by an individually controlled injection (air or CO₂) flow...
rate. This blade was instrumented with thin foils and thermocouples similar to the blade without film holes, except that the foils did not cover the film hole region. Each thermocouple row had 4 thermocouples placed at strategic locations in the radial midspan region. Thermocouples were also mounted in the injection cavities to measure the secondary flow temperature. All thermocouples were connected to a 100 channel FLUKE 2280A data logger interfaced with the 386SX machine. Input voltage and line current for both test blades were measured with FLUKE multimeter and current clamp.

According to O’Brien and Capp (1989), the wakes Strouhal number (S) is defined as

\[ S = \frac{2\pi n N d_n}{(60 V_{\text{avg}})} \]

where \( N \) is the number of rods in the wake generator, \( d \) is the wake generator rod diameter, \( n \) is the number of rods in the wake generator, and \( V_{\text{avg}} \) is the mainstream velocity at the cascade inlet. Three upstream unsteady wake conditions were studied - (1) the no wake condition where all rods from the wake generator were removed, (2) the medium wake respectively.

For the blade with film holes, the secondary (injectant) mass flux rate for a given row of injection holes was determined by knowing the local mainstream velocity at that location (as measured with a pressure tap instrumented blade - Han et al., 1993) and the desired blowing ratio. Tests were conducted at the blowing ratios of 0.4, 0.8, and 1.2. During the tests, the injectant temperature (air or CO\(_2\)) was maintained the same as the ambient mainstream temperature.

The mean velocity and turbulence intensity are time dependent and periodic in nature due to the periodic nature of wake shedding and passing. An analysis of the unsteady random signal indicates that the behavior cannot be characterized only by the time mean average. In order to calculate the time dependent periodic mean velocity and turbulence intensity of the wake flow, the phase-averaged (ensemble-averaged) method suggested by O’Brien and Capp (1989), Dullenkopf et al. (1991), and Han et al. (1993) was adopted. Several wake passing periods were selected for data analysis. Each one of the selected wake passing periods was divided in the same number of bins. Data from the same bin in different periods were added. The phase-averaged mean velocity for that bin was then obtained by dividing the sum by the number of selected periods. This process was repeated for all other bins. The phase-averaged turbulence intensity of the wake flow was obtained in a similar manner. For higher accuracy in obtaining phase-averaged mean values, a digital record of 100 rod passing periods with 150 samples per period was made.

The local heat transfer coefficient with film injection is defined as

\[ h = \frac{q''}{T_w - T_{aw}} \]

where \( h \) is the local heat transfer coefficient, \( q'' \) is the net local convective heat flux, \( T_w \) is the local heated wall temperature, and \( T_{aw} \) is the local film temperature due to the mixing of mainstream and secondary flows.

Since both mainstream and secondary flows (air or CO\(_2\)) are at the same ambient temperature \( (T_a) \) and since Mach Number < 1 \( (T_w = T_{aw}) \), equation (1) can be modified to

\[ h = \frac{q''}{T_w - T_{aw}} = \frac{q''}{T_w - T_{aw}} \]

where \( T_w \) is the ambient temperature and \( T_{aw} \) is the local adiabatic wall temperature.

Since the foil heated blades experienced heat loss during tests, the local heat transfer coefficient was calculated as

\[ h = \frac{q''_{gen} - q''_{loss}}{T_w - T_{aw}} = \frac{q''_{gen} - (q''_{cond} + q''_{rad})}{T_w - T_{aw}} \]

where \( q''_{gen} \) is the generated surface heat flux, \( q''_{loss} \) is the local total heat loss flux, \( q''_{cond} \) is the local conduction heat loss flux, \( q''_{rad} \) is the local radiation heat loss flux, \( T_w \) is the local wall temperature with foil heat, \( T_{aw} \) is the ambient mainstream temperature, and \( T_{aw} \) is the local adiabatic wall temperature without foil heat. Equation (3) was also used to calculate the local heat transfer coefficients for the blade without film holes. Heat loss tests were performed to estimate the total heat loss in equation (3) above.

During the heat transfer coefficient tests, \( T_w \) was in the 40-50°C range and \( T_{aw} \) was about 25°C. The measured total heat loss was about 10% of the foil generated heat. The conduction and radiation heat losses were 4% and 6%, respectively, of the heat.
generated. Heat loss through the tiny thermocouple wires was estimated to be very small (less than 0.1%), and axial and lateral conduction through the thin foil was also found to be negligible. The above mentioned thin foil-thermocouple technique and the related data analysis method are the same as in Mehendale and Han (1992) and Han et al. (1993).

The local Nusselt number (\(\text{Nu}\)) was then calculated from \(\text{Nu}=hC/k\) where \(h\) is the local heat transfer coefficient, \(C\) is the blade chord length, and \(k\) is the local thermal conductivity. The local Nusselt numbers at a given streamwise location were averaged to obtain the spanwise averaged Nusselt number (\(\text{Nu}\)) at that location. An uncertainty analysis as in Kline and McClintock (1953) showed the uncertainty in Nusselt numbers to be ±5% based on 20:1 odds.

RESULTS AND DISCUSSION

Flow Conditions

Velocity profiles in the radial direction at the inlet and outlet of the left and right flow paths were recorded. The dimensionless velocity profiles at the inlet and outlet of both the flow paths are shown in Fig. 5. The results indicate that the inlet and outlet velocity profiles in both the flow paths are essentially uniform in the 50% midspan region. Also, the flow direction at the inlet and outlet of both flow paths was uniform. Thus, the Nusselt numbers are free from the top and bottom wall boundary layer effects. The phase-averaged velocity profiles in both the flow paths were found to be very similar.

A pressure tap instrumented blade was used to measure the surface static pressure distribution which was converted to local mainstream velocity distribution around the blade (Han et al., 1993). The distribution of local exit velocity ratio (\(V/V_\text{2}\)) around the blade is shown in Fig. 6. The solid line is a pre-test prediction based on \(\text{Re}=2\times10^5\) provided by General Electric - Aircraft Engine Division. The measured local mainstream velocity on the pressure surface is a good match; whereas on the suction surface, the measured local mainstream velocity is higher than the predicted value on the upstream side.

![Fig. 5 Inlet and outlet velocity profiles for no wake and \(\text{Re}=3\times10^5\)](image)

Typical instantaneous velocity profile, typical phase-averaged mean velocity profile, and typical phase-averaged turbulence intensity.

![Fig. 6 Velocity distribution on the model blade for no wake and \(\text{Re}=3\times10^5\)](image)

Unsteady Wake Effect

The effect of wake Strouhal number on spanwise averaged Nusselt number distribution for the blade without film holes is shown in Fig. 8. This figure depicts solely the effect of upstream unsteady wake. Results for the no wake base condition show that Nusselt number on the suction surface decreases monotonically with increasing streamwise distance from stagnation due to laminar boundary layer growth; but past \(X/C=0.85\) (i.e. 85% chord), the Nusselt number increases sharply due to boundary layer transition. NuSSelt number on the pressure surface decreases sharply with increasing \(X/C\) for the same no wake condition, but starts to gradually increase from \(X/C=-0.2\) due to strong acceleration as seen from Fig. 6. The effect of upstream unsteady wake is very similar to that presented by Dullenkopf et al. (1991) and Han et al. (1993). As wake Strouhal number increases, the increased flow unsteadiness disturbs the boundary layer and causes an increase in the heat transfer coefficient distribution over the entire test surface. This effect is more severe on the suction surface than on the pressure surface. The upstream unsteady flow conditions cause an earlier laminar to turbulent boundary layer transition on the suction surface (at only half the distance for the no wake case) and the transition length increases with increasing wake Strouhal number. These observations are consistent with those of Mayle (1991). The increases in heat transfer coefficients from the no wake case to \(S=0.3\) vary from 15% near the leading edge to as high as 235% at \(X/C=0.85\) on the suction surface; whereas, the increases vary from 30% near the leading edge to 85% at \(X/C=-0.2\) on the pressure surface. The increases in heat transfer coefficients from \(S=0.1\) to 0.3 vary from 0% to 15% over the entire test surface. Past the leading edge, the decrease in Nusselt number on the pressure surface is
Fig. 7 Typical wake flow profiles for $S=0.1$ at $Re=3\times10^5$

steeper than on the suction surface due to a much lower velocity on the pressure surface as seen from Fig. 6.

**Film Injection Effect**

The effect of film injection on spanwise averaged Nusselt number distribution is shown in Fig. 9. This figure depicts solely the effect of film injection, i.e., for the no wake condition. The sharp increases in heat transfer coefficients immediately downstream of the film hole row locations on the suction surface are caused by the highly disturbed boundary layer due to the injection jet (secondary)-mainstream interaction. Following such peaks, the boundary layer growth and stabilization cause the heat transfer coefficients to decrease. Since the boundary layer on the pressure surface is thicker than on the suction surface, the increases in heat transfer coefficients caused by flow disturbances due to film injection are less prominent on the pressure surface.

**Blowing Ratio Effect.** In general, an increase in blowing ratio causes an increased injection jet-mainstream interaction and results in an increase in heat transfer coefficients on the pressure surface and most of the suction surface, except the region just downstream of the last row of film holes, for both the density ratios (Fig. 9). The effect of blowing ratio decreases farther downstream of the rows of film holes due to film dilution and a growing boundary layer. In the
region just downstream of the last row of film holes on the suction surface, the heat transfer coefficients increase with a decreasing blowing ratio. This is because a lower blowing ratio with its lower momentum flux ratio, the accumulated effects of upstream film jets, and the significantly higher local mainstream velocity force an earlier and shorter boundary layer transition to a turbulent boundary layer. This earlier and shorter boundary layer transition results in higher heat transfer coefficients. An increase in blowing ratio causes an increase in penetration and lesser cumulative effects. This causes a lesser impact on the boundary layer and results in a delayed transition and hence lower heat transfer coefficients with increasing blowing ratio.

**Density Ratio Effect.** For a given blowing ratio, as the density ratio increases the momentum flux ratio decreases. Hence, at the same blowing ratio, the lower density injectant jet (air, D.R.=1.0) penetrates further than the higher density injectant jet (CO$_2$, D.R.=1.52). This causes a higher jet-mainstream interaction for the lower density ratio injectant and results in higher heat transfer coefficients. The effect of density ratio is more pronounced on the pressure surface, where the heat transfer coefficients for air injection are higher than for CO$_2$ injection (Fig. 9). On the suction surface, the heat transfer coefficients for both density ratios are very close except for the transition region where the higher density ratio injectant (CO$_2$) produces higher heat transfer coefficients. On the pressure surface, the momentum flux ratios for lower density ratio injectant (air) are higher than those for the higher density ratio injectant (CO$_2$). This results in higher jet-mainstream interaction and higher heat transfer coefficients for air injection. In the suction surface transition region, the lower momentum flux ratio CO$_2$ injection stays closer to the blade and causes an earlier transition to turbulent boundary layer. Hence, the higher density ratio injectant (CO$_2$) produces higher heat transfer coefficients than the lower density ratio injectant (air) in the transition region.

A comparison with Fig. 8 indicates that on the suction surface, the heat transfer coefficients for the "no wake but with film injection" case can be up to 1.7 times higher than those for the "no film holes but with strong wake" case in the 0≤X/C≤0.8 region. This behavior is observed on a smaller scale near the film holes (~0.2≤X/C≤0.4) on the pressure surface.

**Combined Unsteady Wake and Film Injection Effect**

The effect of wake Strouhal number on spanwise averaged Nusselt number distribution at the blowing ratios of 0.4, 0.8, and 1.2 is shown in Figs. 10, 11 and 12, respectively. The effect of unsteady wake in addition to film injection is depicted in these figures.

**Pressure Surface.** As the wake Strouhal number increases the unsteady flow fluctuations disturb the boundary layer and cause higher heat transfer coefficients at all locations. As the blowing ratio increases, the heat transfer coefficients near the film hole row locations for both density ratios and for all wake Strouhal numbers increase due to increased interaction between injection jet and mainstream. Downstream of X/C=0.4, the heat transfer coefficients for a given wake Strouhal number and a given injectant are almost exactly equal at all blowing ratios. This indicates that at these locations, the wake generated boundary layer disturbance is stronger than the injectant jet generated one. The no wake heat transfer coefficients increase by up to 8% when the blowing ratio increases from 0.4 to 1.2. As blowing ratio increases, the boundary layer disturbance increases, and hence the increases in heat transfer coefficients due to unsteady wake (from the no wake case to S=0.3) reduce. The increases reduce from a range of 42-24% at the blowing ratio of 0.4 to a range of only 23-14% at the blowing ratio of 1.2.

At the lowest blowing ratio of 0.4, both density ratios show same levels of heat transfer coefficients because the amount of injectant coming out and the momentum flux ratios are very small. At higher blowing ratios, the differences between the two density ratios become more significant near the film injection locations, with low density ratio injectant (air) producing higher heat transfer coefficients for the reasons explained before. At further downstream locations, the density ratio effect on heat transfer coefficients is very small due to film dilution.

**Suction Surface (except transition region).** An increase in wake Strouhal number increases the unsteady flow fluctuations, thus disturbing the boundary layer and causing higher heat transfer coefficients for both injectants at all blowing ratios. As the blowing
ratio increases, the heat transfer coefficients near the film hole row locations for both density ratios and for all wake Strouhal numbers increase slightly. The effect of unsteady wake is the greatest at the lowest blowing ratio of 0.4 where the jet is very weak. As blowing ratio increases, the boundary layer disturbance increases, and hence the increases in heat transfer coefficients due to unsteady wake (from the no wake case to S=0.3) reduce. The maximum increases in heat transfer coefficients due to the unsteady wake (from the no wake case to S=0.3) are about 15% at all three blowing ratios. Both density ratio injectants (air and CO₂) show similar levels of heat transfer coefficients for all wake Strouhal numbers.

Suction Surface (transition region). In this transition region, as the blowing ratio decreases, the lower momentum flux ratio causes lesser penetration. This effect and such accumulated effects from the upstream film jets, in addition to high local mainstream velocities promote an earlier and shorter boundary layer transition with higher heat transfer coefficients. For the higher density ratio injectant (CO₂), since the momentum flux ratios are lesser, the penetration is lesser. This results in earlier boundary layer transition and higher heat transfer coefficients than the lower density ratio injectant (air). The increases in heat transfer coefficients due to the unsteady wake (from the no wake case to S=0.3) are more significant at the highest blowing ratio of 1.2 (the lowest heat transfer coefficients). This is because at higher blowing ratios, the transition is delayed and the unsteady wake flow disturbances easily affect the transitional boundary layer. The maximum increases in heat transfer coefficients (from the no wake case to S=0.3) range from 15% at the blowing ratio of 0.4 to 31% at the blowing ratio of 1.2 for the low density ratio injectant (air). For the higher density ratio injectant (CO₂), an earlier transition makes the boundary layer highly disturbed and the effect of unsteady wake on heat transfer coefficients is not so severe but the trend remains the same as for the lower density ratio injectant (air).

The Prandtl numbers for both injectants are about the same. Since kinematic viscosity of CO₂ is only 53% that of air, the local Reynolds numbers for CO₂ injection can be as high as 89% over air injection, depending on the local CO₂ concentration in the boundary layer. But, the thermal conductivity of CO₂ is only 66% of air. If accounted for in the Nusselt number calculation, it will cause an increase of up to 51% in Nusselt numbers depending on the local CO₂ concentration in the boundary layer.

However, in this paper, the local values of air kinematic viscosity and air thermal conductivity were used for Reynolds number and Nusselt number calculations for both injectants (air and CO₂).

CONCLUDING REMARKS

The effect of upstream unsteady wake on surface heat transfer coefficient distribution of a test blade without film holes and a test blade with film injection in a linear cascade was investigated. A spiked wheel type wake generator was used. Tests were performed at the chord Reynolds number of 3×10⁶ for the no wake, and at the wake Strouhal numbers of 0.1 and 0.3. For tests with film injection, air (D.R.=1.0) and CO₂ (D.R.=1.52) were used as injectants at the blowing ratios of 0.4, 0.8, and 1.2.

The main findings are:

1. The unsteady wake by itself, i.e. for the no film holes case, promotes an earlier boundary layer transition and increases the transition length on the suction surface. The heat transfer coefficients on both the pressure and the suction surfaces increase with increasing wake passing frequency. These increases over the ‘no wake no film holes’ data are much higher on the suction surface (up to 235%) as compared to those on the pressure surface (up to 85%). Thus, by itself, the unsteady wake has a very dominant effect on heat transfer coefficients.

2. Film injection by itself, i.e. for the no wake condition, produces much higher heat transfer coefficients on the entire test surface; but the increases over the ‘no film holes’ data are much higher on the suction surface than on the pressure surface. At some locations on the suction surface, the increases in heat transfer coefficients with only ‘film injection but no wake’ are as high as 70% over those with ‘wake but no film holes’. Thus, by itself, film injection has even more dominant effect on heat transfer coefficients than by wake itself.

3. When unsteady wake condition is imposed on top of film injection, the effect is a further increase in heat transfer coefficients over the entire test surface. As blowing ratio increases, the increases in heat transfer coefficients due to the unsteady wake reduce, except for the transition region where they increase. The effect of unsteady wake is more pronounced on the pressure surface and in the transition region. On most of the suction surface (up to 80% chord length), however, the effect of unsteady wake in addition to film injection is secondary when compared with only the film injection effect.

4. In general, as blowing ratio increases, the surface heat transfer coefficients increase, except in transition region where an increase in blowing ratio causes a decrease in heat transfer coefficients and an increase in the transition length. On most of the suction surface (up to 80% chord length), however, the effect of increasing blowing ratio is secondary when compared with the blowing ratio of 0.4.

5. At the lowest blowing ratio of 0.4, both density ratio injectants (air and CO₂) produce almost same heat transfer coefficients except in the transition region where the values for the

NOTE

The effects of property differences between the higher density ratio injectant (CO₂) and the lower density ratio injectant (air) are discussed here.
lower density ratio injectant (air) are lower than those for the higher density ratio injectant (CO₂). At higher blowing ratios, air injection produces higher heat transfer coefficients than CO₂ injection on the pressure surface. On the suction surface, except for the transition region, air injection produces similar levels of heat transfer coefficients as CO₂ injection, at all blowing ratios. In the transition region, CO₂ injection produces higher heat transfer coefficients than air injection, at all blowing ratios. On most of the suction surface (up to 80% chord length), however, the effect of density ratio is secondary when compared with only the film injection effect.

The effect of several important parameters (unsteady wake, density ratio, and blowing ratio) on heat transfer coefficient for a turbine blade with film injection has been presented in this paper. The paper also indicates the relative strengths of these parameters. To the authors knowledge, such information about combined effects of the parameters has not been presented elsewhere in open literature. These results together with the adiabatic film effectiveness results in Part II (Mehendale et al., 1993) can be used in gas turbine blade design.

ACKNOWLEDGEMENT

The project was sponsored by the U.S. Naval Air Warfare Center through General Electric Aircraft Engines. The project managers for the Naval Air Warfare Center were Mr. M. Sautner and Mr. R. Petruska. Their support is greatly appreciated. Very special thanks are due to Mr. T. Thomas of General Electric Aircraft Engines for his suggestions and discussions throughout the project investigation.

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