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Experimental Investigation of Film Cooling Effectiveness of a Highly Loaded Turbine Blade Under Steady and Periodic Unsteady Flow Conditions

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ABSTRACT

This paper describes the experimental investigations of film cooling effectiveness on a highly loaded low-pressure turbine blade under steady and periodic unsteady wake induced flow condition. The cascade facility in Turbomachinery Performance and Flow Research Lab (TPFL) at Texas A&M University was used to simulate the periodic unsteady flow condition inside gas turbine engines. Moving wakes that are originated from upstream stator blades are simulated inside the cascade facility by moving rods in front of the blades. The flow coefficient is maintained at 0.8 and the incoming wakes have a reduced frequency of 3.18. There are a total of 617 holes on the blade, which are distributed along 13 different rows. 6 rows cover the suction side, 6 other rows cover the pressure side and one last row feeds the leading edge. Each row has a twin row on the other side of the blade with exact same number of holes and arrangement (except for leading edge). They both are connected to the same cavity. Coolant is injected from either sides of the blade through the 6 cavities to form a uniform distribution along the span of the blade. In order to study the film cooling effectiveness under periodic unsteady flow condition, the blade surfaces were covered with Pressure Sensitive Paint (PSP) and were excited with green light. Experiments were performed for Reynolds number of 150,000 and approximate blowing ratio of coolant was maintained at one, based on equal mass flux distribution, for all rows throughout the experiments. Experimental investigations were performed to determine the effect of flow separation, and pressure gradient on film-cooling effectiveness in the absence of wakes. Moreover, the effect of impinging wakes on the overall film coverage of blade surfaces was studied.

NOMENCLATURE

A_{foil}	Area of Inconel foil (mm^2)
c	Blade chord (mm)
C	Concentration of oxygen
c_{ax}	Blade axial chord (mm)
h, HTC	Heat transfer coefficient (W/m^{2}K)
h_B	Blade height (mm)
I	Electric Current (ampere)
I	Image intensity
L_{ss}	Blade suction surface length (mm)
p_s,p_t	Static and total pressure (Pa)
PSP	Pressure sensitive paint
P_i	Static pressure taps, i=1, 2, …, 48
$P_{t,s}$	Total and static pressure
Q	Heat flux (W/m^2)
Re	Blade Re-number
S_B	Blade spacing (mm)
S_R	Rod spacing (mm)
T	Temperature (K)
Tu	Inlet turbulence intensity
V	Velocity (m/s)
V	Voltage (volt)
V_{belt}	Belt velocity (m/s)
W	Nozzle width (mm)
α_1	Inlet air angle to the cascade (deg)
α_2	Exit air angle from the cascade (deg)
ε	Emissivity of liquid chrystal ε=0.85
η,	Film cooling effectiveness
σ	Cascade solidity $\sigma=c/S_B$
σ	Stefan-boltzamn constant σ=5.667×10^{-8} (W/m^{2}K)
υ	Velocity fluctuation (m/s)
ϕ	Cascade angle (deg)
Φ	Flow coefficient $\Phi=V_{in}/V_{belt}$
Ω	Reduced Frequency $\Omega=(\sigma/\Phi)\times(S_B/S_R)$
$C_p=(P_i-P_s)/(P_t-P_s)_{inl}$	Pressure coefficient, $C_p=(p_i-p_s)/(p_t-p_s)$

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Subscript

air	Mainstream air along with air as coolant
blk	Image without illumination
c	Coolant
cond	Conductive heat transfer
conv	Convective heat transfer
f	Film
Inl	Inlet
m	mixture
mix	Mainstream air along with air/nitrogen mixture as coolant
N_2	Mainstream air along with nitrogen as coolant
rad	Radiative heat transfer
ref	Reference condition for calibration
yb	Yellow band

INTRODUCTION

One of the major parameters for increasing the thermal efficiency of gas turbine engines is the turbine inlet temperature (TIT). With increasing TIT, more advanced cooling techniques are required to reduce the blade temperature well below the melting point of the turbine blades. External and internal cooling techniques are employed to protect the blade, shaft and housing materials. Film cooling through holes is an effective method of external cooling. Understanding the effect of the complex geometry of cooling holes, their arrangement on the turbine blades and the interaction of jets and boundary layer have required detail boundary layer, film-cooling effectiveness and heat transfer measurements. Nirmalan et al [1] studied the effect of downstream film cooling on turbine vane external heat transfer. Heidmann and co-workers [2, 3] used IR-thermography, liquid crystal thermography, near wall thermocouple and hot wire anemometry to measure surface and flow parameters on a large-scale model of an inclined row of film-cooling holes. Volino and co-workers [4] produced unsteady wakes using a spoked wheels and utilized IR camera along with thermocouples and cold wire to find film cooling effectiveness and heat transfer coefficient on a flat plate. He later used the same method to find the effect of unsteady wakes and jet pulsing on film cooling in a series of publications [5-7]. Abuaf and co-workers [8] simultaneously determined the gas side heat transfer coefficient and film cooling effectiveness on the suction surface and in the leading edge showerhead region of a vane under both steady and unsteady conditions. Takeishi [9] performed low speed film-cooling effectiveness measurement on a stationary cascade and a rotating blade. It was found that the upstream unsteady wakes that are originated from upstream blades trailing edges have strong effects on aerodynamics, surface heat transfer and film coverage distribution. McQuilling et al [10] investigated the suction surface flow features associated with a pack B LPT using stress sensitive film method in a low speed wind tunnel and successfully produced a two-dimensional shear field for a range of flow velocities. Slojander and co-workers [11, 12] studied laminar separation and transition phenomenon on suction surface of a high-lift low-pressure turbine blade in steady and unsteady flow condition and presented their findings in a two-part paper. Schobeiri and co-workers [13] have investigated the periodic unsteady effects in absence of film-cooling holes. They concluded that unsteady wakes enhanced turbine blade heat transfer and caused earlier boundary layer transition. Polanka et al [14] conducted heat transfer and surface pressure measurement on turbine tip and shroud in a full scale rotating rig that operates at flow conditions that are consistent to true turbine environment. Abhari and Epstein [15] performed heat transfer measurements on a film-cooled turbine blade in a turbine facility and concluded that heat transfer coefficient could drop up to 60% on suction surface on film-cooled blades compared to the uncooled ones. Wittig and his co-workers [16] investigated the effects of free-stream turbulence and wake characteristics on the heat transfer along a cooled gas turbine blade. They also used a rotating spoked wheel type wake generator to produce unsteady wakes over a linear blade cascade. Han and co-workers [17, 18] measured film-cooling effectiveness on low-pressure turbine blade in unsteady periodic wake flow condition. He later presented the results of their study on the compound effect of unsteady wakes and coolant density on turbine blade for a variety of blowing ratios in a fully attached flow condition [19]. Heidman et al [20] investigated the wake passing on showerhead film cooling performance in an annular turbine cascade. Haas et al [21] also researched the effect of coolant density on film cooling performance under freestream turbulence intensity. Bons [22] reviewed the mixed effects of surface roughness on gas turbine heat transfer and film-cooling. He summarized that surface roughness at high blowing ratios can actually improve film-cooling effectiveness since it prevents jet lift-off from the surface. At low blowing ratios it can however help jet lift-off through producing thicker boundary layer and lower near-wall velocities. Ames [23, 24] performed extensive film cooling research on a turbine blade and found for low turbulence intensities the heat transfer augmentation is generally higher, especially if the coolant is injected into laminar region compared to turbulent region. Diganta et al [25] studied the effect of compound shaped holes on high pressure turbine blades in a linear cascade under unsteady conditions. Gomes and Niehus [26] experimented on film cooling effectiveness in periodic and steady inflow condition on a high pressure turbine blade and in presence of flow separation on pressure side.

The present study aims at investigating the effect of unsteady wakes on aerodynamics, heat transfer and film cooling effectiveness of a low pressure turbine (LPT) blade. The temperature at the low-pressure section hardly reaches critical temperature and cooling is not as necessary as it is in medium and high-pressure stages, yet the authors decided to perform measurements on this type of blade for the following reasons:

(1) The suction surface of a low-pressure turbine blade is subject to a strong negative pressure gradient followed by an equally strong positive pressure gradient. After reaching the minimum pressure point, the laminar boundary layer could potentially separates forming a separation bubble. Separation bubbles are not typical to LPT blades and engine designers try to avoid suction surface separation as much as possible in order to minimize loss. Yet in considerable number of designs separation bubbles become unavoidable especially in off-design conditions. As the comprehensive boundary layer measurement

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reported in Ref [27, 28] show, the onset, the size and the location of this bubble change, whenever wakes impinge on it. While the aerodynamic investigations in [27, 28] explains the dynamics of the flow separation, they do not treat the question of how the separation dynamics impacts the heat transfer and film coverage.

(2) The ever-increasing turbine inlet temperature, with the aim of increasing the efficiency of gas turbines, will eventually force aerodynamicists to design engines in which blade cooling even in low-pressure section is mandatory. More importantly, recent publications regarding an Ultra-High Efficiency Gas Turbine Engine (UHEGT) [29, 30] have unveiled an state-of-the-art design in which blades even in Low-Pressure stage are exposed to a relatively high temperatures.

(3) This study provides researchers with a benchmark example for future reliability analysis of commercial computational codes as well as design methods. The numerical model could then be extended to a comprehensive model where mixing of the two fluid with different density is modeled and compared to experimental results [31]. Also such studies can be used to develop analytical models that can serve as a quick tool for preliminary design of cooled gas turbine engine elements [32].

The Reynolds number in which these measurements were performed (Re=150,000) is based on suction surface length and exit velocity of cascade. It corresponds to cruise condition in which there exists a major separation region on the suction surface of the blade. This phenomenon as studied before in [13, 27], has a significant influence on heat transfer and aerodynamics of the blade. In this paper, the authors studied the effect of wake impingement on heat transfer coefficient and film cooling effectiveness. Hot wire anemometry was applied to perform boundary layer measurements, liquid crystal technique has been used to measure the heat transfer coefficient around the blade and finally pressure sensitive paint (PSP) was used for film-cooling effectiveness measurement. For the aerodynamics and heat transfer study reported in this paper, the unsteady cascade facility described in [33-35] was used.

Table 1-Cascade Geometry and Parameters

Parameters	Values
Inlet Velocity	$V_{in} = 6.02$ m/s
Nozzle width	$W = 200.0$ mm
Blade chord	$c = 203.44$ mm
Blade axial chord	$c_{ax} = 182.85$ mm
Blade suction surface length	$L_{ss} = 270.32$ mm
Inlet air angle to the cascade	$\alpha_1 = 0$ deg
Inlet turbulence intensity	$Tu_{in} = 1.9\%$
Blade Re-number	$Re = 150{,}000$
Blade height	$h_B = 200$ mm
Cascade solidity	$\sigma = 1.248$
Cascade angle	$\varphi = 55$ deg
Belt velocity	U=7.52 m/s
Exit air angle from the cascade	$\alpha_2 = 90$ deg
Flow coefficient	$\phi = 0.8$
Reduced Frequency	$\Omega = 3.18$

EXPERIMENTAL PROCEDURE

Experimental Facility

To investigate the effect of unsteady wake flow on turbine and compressor cascade aerodynamics, particularly on unsteady boundary layer transition, a multipurpose, large-scale, subsonic research facility was designed and has been in operation since 1993 [27]. Since the facility in its original configuration is described extensively in Ref [28, 34], only a brief description of the modifications and the main components is given below.

Figure 1-Turbine cascade test section at TPFL with components and adjustable test section as described in Ref [13, 27, 33-37]

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The research facility consists of a large centrifugal compressor, a diffuser, a settling chamber, a nozzle and a turbine cascade test section, as shown in Figure 1. The compressor with a volumetric flow rate of $15\ m^3/s$ is capable of generating a maximum mean velocity of $100\ m/s$ at the test section inlet. The settling chamber consists of five screens and one honeycomb flow straightener to control the uniformity of the flow. To account for a high flow deflection of the LPT cascade the entire test section unit, including the traversing system, was modified to allow a precise angle adjustment of the cascade relative to the incoming flow. This is done by a hydraulic platform, which simultaneously lifts and rotates the wake generator and test section unit. The unit is then attached to the tunnel exit nozzle with an angular accuracy of less than 0.05 degree, which is measured electronically.

Two-dimensional periodic unsteady wakes are simulated by translational motion of a wake generator. Wake generator consists of a series of cylindrical rods attached to two parallel timing belts driven by an electric motor and a frequency controller. The rod diameter, its distance from blade leading edge, wake width and corresponding drag coefficient are chosen according to the criteria outlined by Schobeiri et al [38].

Aerodynamic measurements

The cascade test section shown in Figure 1 located downstream of the wake generator includes five identical "Pak B" LPT blades designed by Pratt and Whitney and manufactured in TPFL. The aforementioned blades have a height of 200.0 mm and chord of 203.44 mm. More information regarding cascade geometry and other flow parameters are given in Table 1.

This blade number is necessary and sufficient to secure a spatial periodicity for the cascade flow. The blade geometry resembles essential features such as the laminar boundary layer separation that is very likely to happen to typical LPT blades. The blade geometry was made available to NASA researchers and academia to study the specific problems of LPT flow separation, its passive, active control and its prevention.

In order to obtain surface pressure distribution around the LPT-blade, an instrumented blade with static pressure taps placed at the midsection all around the blade was used in the cascade facility along with pneumatic pressure transducers. To ensure that the periodicity requirement is fulfilled, second and fourth blades were also instrumented each with 48 static pressure taps. Deviation of less than 2% in pressure coefficient distribution of neighboring blades confirms the periodicity for steady and periodic unsteady inlet flow conditions. A computer controlled three-axis traversing system is used to measure the inlet velocities and turbulence intensities, as well as the boundary layers on suction and pressure surfaces. The traversing system moving streamwise through a slot parallel to the suction surface was designed to reach all stream wise positions along the suction and pressure surfaces. The three-axis (x, y, θ) traversing system is vertically mounted on the Plexiglas sidewall. Each axis is connected to a stepper motor with an encoder and decoder. The optical encoder provides a continuous feedback to the stepper motor for accurate positioning of the probes. The x-y-axes are capable of traversing along the suction and pressure surfaces in small steps down to 1 micron. This accuracy is specifically required for boundary layer investigations, where the measurement of the laminar sub-layer is of particular interest [39].

The θ-axis is capable of rotating the probe axis with an angular accuracy of less than 0.05 deg. The data acquisition system used to perform the investigations present in this paper is the same one described in previous articles [27, 40]. Two adjacent blades are used for boundary layer measurements. The instantaneous velocity, ensemble-averaged and time-averaged velocities are determined using the standard procedure described in many papers, among others, in Refs [36, 41].

Aerodynamics Data Analysis

For the steady state case, the instantaneous velocity components are calculated from the temperature-compensated instantaneous voltages by using calibration coefficients. Instantaneous velocity can be represented in the following form:

$$V = \overline{V} + v \tag{1}$$

Where $\overline{V}$ is the mean (time-averaged) velocity and v is the turbulent fluctuation component. The mean velocity, also known as the time average, is given by:

$$\overline{V} = \frac{1}{N}\sum_{j=1}^{N} V_j \tag{2}$$

Where N is the total number of samples at one boundary layer location. The root mean square value of the turbulent velocity fluctuation is

$$v = \sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(V_j - \overline{V}\right)} \tag{3}$$

And the local turbulence intensity is defined as:

$$Tu_{loc} = \frac{v}{\overline{V}} \times 100 = \frac{1}{\overline{V}}\sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(V_j - \overline{V}\right)^2} \times 100 \tag{4}$$

For unsteady cases, the ensemble-averaged velocity, fluctuation velocity and turbulence intensity were calculated from the instantaneous velocity samples by:

$$V_i(t_i) = \langle V_i(t_i)\rangle = \frac{1}{N}\sum_{j=1}^{N} V_{ij}(t_i) \tag{5}$$

$$v_i(t_i) = \langle v_i(t_i)\rangle = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[V_{ij}(t_i) - \langle V_i(t_i)\rangle\right]^2} \tag{6}$$

$$Tu_i(t_i) = \langle Tu_i(t_i)\rangle = \frac{\langle v_i(t_i)\rangle}{\langle V_i(t_i)\rangle} \times 100 \tag{7}$$

Where N is the total number of wake generator periods and M is the number of samples taken per period. $\langle V_i(t_i)\rangle$ is the ensemble-averaged velocity for the particular boundary layer traverse.

Heat Transfer Measurements

Figure 2 shows the details of the heat transfer blade. This blade is specially manufactured from a nonconductive material with a thin Inconel heater foil attached to its surface via a two-sided temperature resistant adhesive tape. On top of this tape, a sheet of liquid crystal is attached for temperature measurements. The power required for heating the heat transfer blade is supplied by a Sytron 10 V–200 A DC- power supply. The current passing through the test blade is measured with a multimeter connected across a shunt resistor. Two separate multimeters are used to measure the voltages in the circuit. One

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multimeter is connected across the output leads of the power supply to measure the voltage output, and the other is connected across the blade terminals. These two measurements are used to calculate the power losses in the cable resistance.

The yellow band of the liquid crystal is used to record the data. The location of the yellow band is controlled through the power supply to the blade, and the voltage and the current readings across the blade terminals are recorded for different locations of the yellow band on the turbine blade. The collected data are reduced based upon a constant heat flux analysis, which entails determining all the energy losses on a flux basis and subtracting them from the heat flux of the Inconel foil. Details of heat transfer measurements using the liquid crystal technique are presented in Ref [13, 42].

Heat Transfer Data Analysis

Steady state liquid crystal method was used to measure the Heat Transfer Coefficient of the Low-Pressure Turbine blade under steady and unsteady flow condition. Liquid crystal method had been previously used by numerous researchers in turbomachinery field [42, 43]. For this purpose, a separate blade is manufactured from non-conductive material and is instrumented with thin Inconel foil heater and liquid crystal sheet. Using a two-sided adhesive tape the Inconel foil and liquid crystal sheet were attached to the blade (Figure 2). The Inconel foil heater is powered by a Sytron 10V-200A power DC supply. Current passing through the heater and voltage across the heater were measured using multiple multimeter. Freestream air temperature is measured by a type-E thermocouple. Another thermocouple is mounted on the blade for the purpose of calibration. At the beginning of each test, the yellow band of the liquid crystal is calibrated for temperature. Calibration is done by adjusting the power until the location of the yellow band falls on top o the surface mounted thermocouple. Calibration is done under no flow condition for a number of times before the test is run. The yellow band temperature was found to be almost 47.5^{o}C (for more information regarding yellow band method calibration please see Ref [13, 42, 43]). The yellow band is chosen since it occurs over narrowest temperature band and has a good uniformity characteristic. After voltage and current supplied to Inconel foil heater is recorded, the location of yellow band is read. The power is then changed to move the location of yellow band. The process is repeated for other locations after waiting until steady-state operation condition is achieved. Yellow band tracking is continued until the full longitudinal lengths of blade surfaces are completely mapped. After subtracting all energy losses (on flux basis) from the heat flux of Inconel foil, convective portion of heat flux will remain.

Figure 2- heat transfer blade covered with liquid crystal sheet [13]

$$Q_{conv} = Q_{foil} - Q_{rad} - Q_{cond} \quad \textbf{(8)}$$

Where Q_{foil} and Q_{rad} are calculated from Equation (9) and (10) respectively.

$$Q_{foil} = \frac{VI}{A_{foil}} \quad \textbf{(9)}$$

$$Q_{rad} = \varepsilon\sigma\left(T_{yb}^4 - T_{\infty}^4\right) \quad \textbf{(10)}$$

Heat transfer coefficient can be obtained from equation (11).

$$h = \frac{Q_{conv}}{\left(T_{yb} - T_{\infty}\right)} \quad \textbf{(11)}$$

The emissivity of liquid crystal is about 0.85 and the heat loss due to conduction was found to be negligible.

Film Cooling Measurements

Figure 3 shows the film-cooled blade. This blade is manufactured using 3D printing technique and has six coolant passages inside. Coolant is being injected into each passage. Each passage feeds one row of holes on the suction side and one row on the pressure surface of the blade. There are total of 617 holes on the blade, which are distributed along 13 different rows. 6 rows cover the suction side, 6 other rows cover the pressure side and one last row feeds the leading edge. The holes are shaped holes to provide better and more effective film coverage. It is obvious that passage and horseshoe vortices deflect the coolant flow toward the blade midpsan, especially on the suction surface [44, 45]. In order to counter this and provide more coverage for the end-wall regions of the blade that are most susceptible to this effect, nearby holes have compound angle as well.

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Figure 3- Film cooled blade covered with PSP inside the test facility(top) and the cross section of the blade(Bottom)

The surfaces of the blade are covered with base coat (white color) and nine layers of Pressure Sensitive Paint are sprayed on top of that using airbrush. The airbrush was held perpendicular to blade at a specified distance from it. It was then moved over the blade in a reciprocating manner at a constant and known speed to ensure about uniformity of thickness of the PSP coating. The number of coats needed to paint the blade depends on the type of paint that has been used. During numerous tests it has been determined that this number of layers provides acceptable sensitivity to get sufficient response in intensity for small pressure changes.

The surfaces of the blade were excited using strobe light fitted with a narrow bandpass interference filter with an optical wavelength of 520nm (this wavelength corresponds to green light). Upon excitation, the PSP coated surface emits red light with wavelength of minimum 600nm. In order to record the intensity, a CCD camera was used. This CCD camera fits with a 35 mm lens and was used along with a long-pass filter to record intensity images. The purpose of the filter is to block the reflected portion of light from the surface so that the recorded intensity is solely due to excitation of PSP molecules. A schematic and picture of data acquisition setup is shown in Figure 4.

Since the blade is relatively large (C_{ax}=182mm), illuminating the whole surface with the strobe light uniformly is impossible. Also due to the same problem, the whole blade could not be captured within one shot with all the details that are subject to study. In order to solve this problem, the research team illuminated different locations on the blade surfaces individually and took pictures of different regions, applied perspective corrections on pictures and merged all pictures to obtain the whole film cooling process on the blade surfaces. A total of 100 pictures were captured for each single region with air and nitrogen as coolant and pixel intensities for all images were averaged. A computer program was used to convert pixel

Figure 4-Data acquision system

intensities into pressure using previously obtained calibration curve and then into film cooling effectiveness. The coolant flow rate was controlled using rotameter based on prior calculation for desired blowing ratio. The blowing ratio is the mass flux ratio between the coolant flow and the mainstream gas flow ($M=\rho_c V_c/\rho_a V_a$). It reduces to the ratio between the velocity of cooling jets and the free-stream velocity for cases in which density of coolant and mainstream air is almost similar. Approximate blowing ratio for all locations on the blade was maintained at one using the control valves placed to limit the

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coolant flow rate for each passage in the blade. The blowing ratio value is based on equal mass flux distribution assumption. Average velocity of coolant is used to calculate this ratio and this velocity is obtained from coolant volumetric flow rate and total area of cooling holes. Mainstream velocity is measured using a carefully calibrated five-hole probe located upstream of the wake rods.

Film Cooling Effectiveness And Data Analysis

The definition of adiabatic film cooling effectiveness is:

$$\eta = \frac{T_f - T_m}{T_f - T_c} \tag{12}$$

In this equation, T_f is temperature inside the film, T_c is the temperature of the coolant and T_m is the mainstream air temperature. PSP method uses heat (thermal) and mass transfer analogy to find out the film-cooling effectiveness on the surface. This analogy enables us to measure the effectiveness without directly measuring temperatures.

PSP technique has been described extensively in many publications such as Ref [42, 46-48] hence here a brief description is given. PSP is photo-luminescent material that emits light when excited by a light with certain wavelength. The amount of light intensity emitted from PSP is directly proportional to partial pressure of Oxygen. Any pressure variation on the surface that is coated with PSP will result in emitting light intensity to change due to oxygen quenching process. Higher pressure results in low intensity and vice versa. Normally PSP material has sensitivity to temperature as well so in order to keep the deviations caused by temperature variations low; it was ensured that all measurements were done under the same thermal condition.

A calibration was performed prior to the actual measurements. It was done on a specimen with the same material and same surface finish of the blade in order to find the relationship between the light intensity ratio and pressure ratio. Base paint and Pressure Sensitive Paint were sprayed on top of the sample in order to produce the same thickness of paint layers as on the blade. Calibration was done using a vacuum/pressure chamber. Pressure inside the chamber was varied from 0 to 2 atm and the intensity at different points was recorded using CCD camera. It was observed that if the emitted light intensity at some certain temperature is normalized with reference light intensity at the same temperature, the effect of temperature is eliminated. Hence during the experiments, reference images were captured immediately after the experiments were completed in order to avoid temperature effects. The calibration curve is shown in Figure 5.

Figure 5-Pressure Sensitive Paint calbration curve

During calibration process and also the experiments the image intensity obtained from camera is normalized with a reference picture taken at no flow condition. In order to remove the back-ground noise another picture is taken at no flow condition and no excitation. Then by further subtracting the intensity of this picture from the other two sets of pictures, one can remove the effect of inherent back-ground noise in an optical system. The resulting intensity ratio was then converted to pressure ratio using the previously obtained calibration curve.

$$\frac{I_{ref} - I_{blk}}{I - I_{blk}} = f\left(\frac{\left(P_{O_2}\right)_{air}}{\left(P_{O_2}\right)_{ref}}\right) = f\left(P_{ratio}\right) \tag{13}$$

In this equation, I stands for Intensity value recorded by each pixel and the right hand side is the equation that is obtained from calibration curve.

To obtain film-cooling effectiveness, air and nitrogen were used as coolant separately. Blowing nitrogen instead of air as coolant from the holes will cause less oxygen partial pressure in the cooled regions. By comparing the images obtained from these two sets of pictures, one can determine the film cooling effectiveness through the following equation:

$$\eta = \frac{C_{air} - C_{mix}}{C_{air}} = \frac{\left(P_{O_2}\right)_{air} - \left(P_{O_2}\right)_{mix}}{\left(P_{O_2}\right)_{air}} \tag{14}$$

Since the molecular weight of air and nitrogen are almost the same, concentration of air (C_{air}), concentration of nitrogen (C_{N_2}) and concentration of air/nitrogen mixture (C_{mix}) on the test surface are directly proportional to partial pressure of oxygen. The reliability of this method has been investigated in numerous publications. Wright et al [49] and also Rallabandi et al [50] compared the film cooling effectiveness results obtained by this method with results of conventional measurement techniques such as steady-state and transient liquid crystal, IR-thermography, naphthalene mass transfer and traditional foil heater with thermocouples. They demonstrated that among all measurement methods, PSP technique demonstrates most reliability and accuracy.

Uncertainties

Uncertainty method of Coleman and Steele [51] was used to determine the uncertainty of aerodynamics parameters as well as heat transfer coefficient and film-cooling effectiveness. All uncertainty calculations were performed based on confidence level of 95%. Uncertainty of velocity for single wire probe after data reduction is 2.1%. This level of uncertainty causes 1.7% uncertainty in calculating Reynolds number which

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is reflective of cumulative result of uncertainty in calibration and data acquisition. The same procedure was applied to calculate the uncertainty of HTC. The cumulative uncertainty of HTC, which combines the bias and random error, varies along the blade surface. At $S/S_0=0.3$ the maximum uncertainty in determining HTC is calculated to be 6.2%.

Uncertainty of FCE also varies along the blade surface. For regions with effectiveness magnitude of 0.8 and higher uncertainty drops below 1% while for regions with effectiveness of 0.07% uncertainty can be as high as 10.3%. Again this number is cumulative result of bias and random errors. However this should be noted that there are only a few data points on the whole span of the blade that could potentially have very high uncertainty magnitudes.

RESULTS AND DISCUSSION

Aerodynamic, heat transfer and film-cooling effectiveness measurements were performed at Reynolds number of 150,000 and turbulence intensity of 1.9%. Reynolds number is calculated based on suction surface length and exit velocity of the cascade. This Reynolds number pertains to cruise condition and ensures the presence of a rather large separation region on the suction surface of the blade.

Aerodynamics

Figure 6 shows the static pressure coefficient distribution around the blade. Surface static pressure distribution around the blade is obtained using a blade instrumented with static pressure taps that are placed at the midsection all around the blade. The pressure taps are connected to pneumatic pressure transducers. Because of the internal pneumatic damping effect, the results are inherently time averaged. At the Reynolds number in which experiments were performed; there exists a rather large separation bubble on the suction surface of the blade which occupies about 20% of the suction surface length (separation starts from S/S_0=0.58 and extends upto S/S_0=0.82 where the flow re-attaches). The negative pressure gradient on suction surface accelerates the flow until it reaches an inflection point at which the pressure gradient changes sign and forces the flow to separate. This region is identified by constant pressure plateau and is clearly seen in Figure 6. Also this figure depicts that unsteady wake flow can cause a reduction in length of the separation zone. This can be seen by a shorter separation plateau.

Figure 7(a) and (b) exhibits velocity as well as velocity fluctuations for different locations on suction surface of the blade. Inside the laminar region, fluctuation magnitudes are very small. As flow enters transitional region and finally separation zone, the fluctuation magnitudes tend to increase until flow re-attaches to the surface. Unsteady wakes cause periodic disturbance of stable laminar boundary layer upstream of separation. This fact results in early transition and separation of the flow. The effect of unsteady wake frequency on boundary layer separation is distinctly illustrated in Figure 7. Inside laminar region, introduction of wakes cause significant increase in fluctuation levels. Wakes also move the velocity distribution further away from separation as seen at $S/S_0=0.77$. Passing through the separation zone, the reattached flow still shows the unsteady wake effects on the velocity and fluctuation profiles. The fluctuation profile at $S/S_0=0.85$ depicts a decrease

Figure 6-Static Pressure Coefficient distribution around the blade

of turbulence fluctuation activities caused by unsteady wakes compared to the steady case. This decrease is due to the calming phenomenon [52].

Heat transfer

Heat transfer coefficient distribution is shown in Figure 7(c). The laminar boundary layer that is characterized by the lack of significant lateral turbulence fluctuations is not capable of transferring mass, momentum, and energy to the blade surface, resulting in a steep drop of HTC from leading edge to $S/S_0=0.494$, where the pressure gradient changes the sign. The HTC drops further at a larger slope and assumes a minimum at the start of the separation bubble. From this point on, the turbulence activities outside the bubble continuously increase, causing the heat transfer coefficient to rise. On the pressure surface, the HTC first drops sharply due to the governing laminar non-turbulent boundary layer and reaches a minimum at the start of the transition region. During the transition process, characterized by intermittent changes of the flow pattern from laminar to turbulent and vice versa, the random fluctuations in longitudinal as well as lateral directions continuously increase leading to a lateral exchange of mass, momentum, and energy with the boundary layer, thus, increasing the HTC. In unsteady situation only marginal changes in HTC are depicted especially in laminar region. Inside separation region due to suppression of velocity fluctuation HTC also drops. On the pressure surface, however, noticeable changes are observed within the transitional region, where the transition start and end move upstream. [53]

Film Cooling Effectiveness

For Film cooling measurements the approximate blowing ratio, based on equal mass flux distribution, for all locations on the blade were kept at 1. Coolant flow rate for each passage was independently controlled by a separate set of valve and rotameter. This blowing ratio was chosen since the mixing losses are minimum in this condition. All experiments were performed in presence and absence of wakes. In unsteady case, the rod velocity was maintained at 7.52 m/s corresponding to Φ=0.8.

The film-cooling effectiveness resulting from PSP for steady and unsteady cases on pressure and suction surfaces are shown in Figure 8. This figure shows the entire span of the blade in stream-wise direction in unsteady flow (top) and

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steady flow (bottom) condition. Aforementioned figure however shows only one-half of the blade in lateral direction. The top limit of this contour plot represents the sidewall of the cascade facility, where light source and camera were installed. The bottom axis represents the mid-line of the blade.

Near end-wall regions: In this region, close to sidewall of the facility, the effect of passage vortices is vividly seen on suction surface contours. The passage vortex as described by Sharma and Butler [54] is originated from pressure-side leg horseshoe vortex of the neighboring blade and then becomes passage vortex. It travels in the lateral direction due to pressure difference between pressure and suction sides of adjacent blades, until the suction side horseshoe vortex wraps itself around the passage vortex. This vortex carries the inlet boundary flow away from the endwall. The complex nature of the secondary flow in near end-wall region has a significant impact on film-cooling characteristics of film injection. This flow is strong enough to deviate the cooling jets in near endwall regions towards the middle section of the blade eventhough in this neighborhood jets have compound angle of 20°. This region is identified as the region with least effective film coverage near side-walls of suction surface in both conditions. Unsteady flow condition causes weaker coverage in this region compared to steady flow condition as it causes more diffusion of coolant into this zone. Unsteady wakes have unfavorable effect in terms of film-cooling in near end-wall region and that is because they can make the passage flow more turbulent [55], which eventually can lead to better mixing of coolant and mainstream air.

Leading edge: Effective cooling of this zone is crucial in performance of a gas turbine engine. This region, as shown in Figure 7 has the highest heat transfer rate over the entire airfoil. Unsteady wakes have caused a significant drop in film coverage in this region, Figure 7. This finding is in agreement with measurements of Funzaki et al [56]. Unsteady wakes can cause the mainstream flow to penetrate the coolant film in this

Figure 7- Velocity profiles at different streamwise locations on suctions side of the blade(top left), velocity fluctuation magnitude at same streamwise locations on suction side of the blade(top right). Heat transfer coefficient and film-cooling effectiveness for entire span of the blade(bottom)

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region, especially since this region is the closest region of all locations on the blade to wake generators. This fact will translate into lower film cooling effectiveness under unsteady condition. In both cases it is observed that the portion of coolant that is being transferred downstream along the pressure side is producing better coverage than suction side although the negative pressure gradient on suction surface should accelerate the flow more in this direction while positive pressure gradient on the other side has the opposite effect. This is due to the effect of curvature that is going to be discussed in the following section.

Suction side: Figure 7(c) shows that film-cooling effectiveness on suction side is not as strong as pressure side. There are a number of reasons that lead to this behavior and here we intend to identify those reasons. The blade geometry in Figure 3 shows that each single channel inside the blade supplies coolant to one row on the suction side and one row on the pressure surface. Since the surface pressure on suction side is clearly lower than the pressure side, majority of the coolant has to be directed towards the holes on suction side. Higher static pressure difference between twin rows will cause more significant blowing ratio difference between twin rows. Even though more coolant is being injected through suction side holes, the overall effectiveness is generally lower than the identical location on pressure side. This could be attributed to slightly higher blowing ratio for suction side rows than their respective twin rows on pressure side. This results in having jets with relatively high momentum coming out of suction surface. These jets will lift off and hence we witness a sudden drop in film coverage immediately after injection. Different rows have different angles and having steep angle can clearly increase the tendency to lift off. Smaller angle can keep jets closer to surface for a longer time. The peak in film effectiveness on suction side occurs after second row. This row has the smallest angle among the first three rows as shown in Figure 3. It results in having jets closer to surface. Also curvature at this location is a slightly lower than the third row. This could increase the possibility of reattachment of the upstream jets as well [57]. This fact along with the ejection angle explains the higher effectiveness in regions downstream from second row compared to the third row. Although convexedness of suction surface acts against re-attachment but the combined effects of locally lower curvature and smaller ejection angle result in locally high film coverage after second row. Up to almost mid-span of the blade (*S/So=0.494*) boundary layer remains laminar, which is characterized by lower amount of fluctuation in lateral direction. Hence boundary layer would not be able to transfer mass, momentum and energy to blade surface resulting in a drop in HTC from leading edge along the suction surface. On the other hand the

Figure 8- Film-Cooling Effectiveness contours of unsteady wake flow condition (top) and steady (bottom) for the entire span of the blade at Turbulence intensity of 1.9% and *Ω* of 3.18

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same reason causes the jets to dissipate slower and having slightly higher FCE in regions prior to *S/So=0.494*. Transition is identified by increase in turbulence level of freestream. Figure 7a,b shows velocity and velocity fluctuation magnitudes at 6 different locations on Suction Surface of the blade. Elevated level of velocity fluctuation is observed in transitional regime. In transitional regime, the high level of turbulence will result in having faster and more rapid dissipation of the cooling jets. Table 2 lists the static pressure coefficient difference of the two outlets of each passage. Hence at this location the cooling jets that are being injected from fourth row on suction side will have the highest blowing ratio and momentum among all jets. Thus it will have considerably higher tendency to lift off from the surface, which results in poor film coverage in the area downstream from this location. This is accompanied by further reduction of HTC until it assumes the minimum value at the onset of separation (S/S_0=0.583). Figure 7 clearly shows unsteady wakes have caused a reduction in film effectiveness on this side. Unsteady wakes cause coolant jets to break down faster and hence reduce film coverage. This is seen more vividly in regions closer to leading edge.

In zones farther downstream on both sides wakes have to travel significantly longer distance. This fact translates into smaller difference between film cooling effectiveness of steady and unsteady cases than upstream regions. On suction surface

Table 2-Difference between static pressure coefficient of the two outlets of each passage

	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5	Hole 6
ΔC_P	2.17	4.38	6.18	6.66	5.93	4.32

transition starts at earlier location in unsteady case compared to steady flow condition since incoming wakes increase the level of turbulence in boundary layer. This fact is reported by Schobeiri et al [13]. It leads to having the separation and reattachment at slightly earlier locations. Film injection also increases local turbulence in boundary layer as well. Thus there will be even higher tendency to have earlier transition, separation and finally re-attachments in a film-cooled blade, which add to the reasons behind having less film cooling effectiveness in unsteady case.

Figure 9 and Figure 10 show periodic growth and contraction of separation bubble with freestream turbulence intensity of 1.9%. These figures display the full extent of the separation bubble and its behavior under periodic wake flow at different t/τ. The value of t/τ corresponds to the point in the rod-passing period at which the data acquisition system is triggered. Separation bubble is characterized by low velocity region on the suction surface as seen in Figure 9. By comparing Figure 9 and Figure 10 one can understand that there are in fact two distinctive zones within the separation bubble. Upstream portion of this zone that starts from approximately $S/S_0=0.583$

Figure 9-Ensemble Averaged Velocity Contours at t/τ=0, 0.25, 0.5, 0.75 and t/τ=1.0 for Ω of 3.18.

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and extends up to almost $S/S_0=0.66$, is distinguished by a low turbulence intensity region which is surrounded and covered by a high turbulence intensity area. In further downstream section of the bubble turbulence intensity tends to rise. Separation bubble is also identified as the region in which the fifth and sixth row are located. The differences between static pressure where suction-surface rows are located and their respective pressure-side rows are still very high. Hence jets on suction side corresponding to these two rows have considerably high momentum and high tendency to lift off. As we know higher turbulence intensity causes higher Turbulence Kinetic Energy, which eventually results in higher Turbulence Eddy Dissipation. Fifth row is located in calm region of separation bubble and coolant enters a low intensity region which is positive for providing better film coverage, however large discharge angle of the jets favor the lift-off and eventually low film-coverage. Sixth row however constantly discharges the coolant into the more turbulent portion of the bubble that has unfavorable effect on film-cooling effectiveness (The locations of the holes are shown in Figure 6). This row that is placed just before the re-attachment location of the bubble, has the lowest angle and the least curvature of all rows on suction side. All these facts will result in a small boost in film effectiveness although boundary layer is fully turbulent. Outside the bubble the turbulence activities continuously increase and cause further dissipation of jets while for the same reasons HTC starts to rise until re-attachment of flow occurs. As a result of re-attachment the continuous increase in HTC ends and it experiences a peak at this location. From this point on turbulent boundary layer continues to grow and HTC reduces.

Pressure side: For the same reasons explained in previous section the blowing ratio for each row on pressure side is lower than their respective rows on suction side. Although static pressure forces acting on jets try to move jets away from the surface, the film coverage is generally higher on this side than the suction surface of the blade. The concavity of the blade not only results in having jets with smaller angles, but also acts in favor of re-attachment. This is clearly seen immediately downstream of the second row. This row is located where the curvature of the surface is maximum.

As stated earlier unsteady wakes cause earlier transition on both surfaces. On pressure side transition occurs at a location which is $\Delta S/S_0=0.064$ closer to leading edge compared to steady flow. Subsequently transition ends sooner as well resulting in noticeable change in HTC distribution. In terms of FCE, unsteady wakes have the opposite effect on pressure side as they had on suction surface except for the small region immediately downstream of leading edge. At this location, where boundary layer is laminar and also it is the closest location to wake generators, unsteady wakes cause increased turbulence level which helps dissipating the jets faster.

In locations downstream from this point unsteady wakes increase film effectiveness. It is obvious in Figure 8 that the jets are thicker in unsteady flow condition compared to steady flow. The concavity of the surface and low injection angle along with Blowing ratio of less than one, due to static pressure difference at the jet outlets of a single coolant passage, prevent jets from lifting off of the surface while higher lateral fluctuations in unsteady case cause diffusion of wakes in lateral direction. Hence an increase in lateral average of film-cooling

Figure 10- Ensembled Averaged Turbulence Intensity contours at t/τ=0, 0.25, 0.5, 0.75 and t/τ=1.0.

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effectiveness is observed.

Farther downstream regions receive less coolant as the pressure difference between the identical rows on suction and pressure increases. Also curvature tends to decrease until it is not effective enough to overcome the effect of positive pressure gradient of mainstream flow. The positive pressure gradient at these locations prevents re-attachment of the jets once they have lifted off of the surface. In this zone, which film coverage is minimum of all places on pressure side (except for the leading edge), the difference between steady and unsteady cases drops to zero that stresses out the strength of positive pressure gradient in dissipating jets into mainstream. Downstream from the last cooling row is the region where curvature is not present anymore and the smaller angles of jets cause them to remain on the surface that results in having an increase in film coverage. Again in this area unsteady wakes have positive effect on film-cooling effectiveness due to the same reason explained before.

CONCLUSION

This paper experimentally investigates the effect of upstream unsteady wakes on distribution of aerodynamics, heat transfer coefficient and more importantly film-cooling effectiveness. For this purpose, a linear cascade facility that has been in use since 1993 in Turbomachinery Performance and Flow Research Laboratory was used. Periodic Unsteady wakes were established by translational motion of rods with diameter of 2.5 mm. Experiments were performed for Reynolds number of 150,000. Turbulence intensity was maintained at 1.9% while the blowing ratio for all locations on the blade surfaces was kept at one. The main findings are:

1. Film Cooling Effectiveness on pressure side is stronger than suction surface of the blade, which could be attributed to the difference between blowing ratio of twin rows. The injection holes on suction surface have higher blowing since the coolant is being injected into lower pressure region than the pressure surface row, hence they have higher tendency to lift off. Also curvature of suction surface acts against re-attachment of the jets while curvature has opposite effect on pressure side. Not to mention higher relative angle of holes with respect to surface on suction side has negative effect on jet lift off as well.

2. HTC and FCE in majority of regions behave in opposite ways. This is can be justified from turbulence intensity and velocity fluctuation point of view. It is known that in regions with high turbulence intensity HTC tends to increase. Higher fluctuation in velocity will enhance energy transfer from mainstream flow in to the blade, which means HTC has to rise while for the same reason cooling jets that are being injected to the mainstream will dissipate faster and sooner.

3. When unsteady wake condition is imposed on top of film injection opposite effects are observed on suction and pressure side of the blade. On suction side unsteady wakes clearly have reduced the FCE. This is because unsteady wakes cause faster break down and dissipation of jets into mainstream. This is more apparent in zones close to leading edge where the effect of wakes is maximum. Inside the transitional and eventually separation region the difference between FCE in steady and unsteady conditions becomes less apparent. That is because in addition to high curvature of blade in this region and the maximum momentum of the jets in fifth row of suction surface, the separation causes high dissipation rate of the jets as the back flow opposes the injection of jets. On pressure side static pressure forces acting on the surface and concavity of the blade have opposite effects. The former will encourage the jets to lift off while the latter increases the tendency of jets to re-attach to surface. The higher film effectiveness under unsteady condition is a result of combination of effects. The significant increase in lateral fluctuations will cause diffusion of coolant i lateral direction while the curvature and low injection angles prevent jets form lifting off of the surface.

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