HEAT TRANSFER MEASUREMENTS OF A LOW-PRESSURE PAK-B GAS TURBINE VANE UNDER SEPARATED FLOW CONDITIONS

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Abstract
With increased interest in high-altitude flight for Unmanned Aerial Vehicles and for more highly loaded low-pressure turbine vanes on commercial engines operating at lower altitudes, there is a need to understand the separated flow conditions occurring on engines operating under these conditions. This paper examines the separated flow behavior of a Pak-B low-pressure turbine vane in the Baylor University Turbine Suction Surface Wind Tunnel. The test section of this tunnel measures 12 in x 8 in x 48 in, and the facility is capable of speeds up to 25 m/s. This facility uses a contoured upper surface to reproduce the static pressure distribution from the suction surface of the turbine blade on a 33.5-inch long flat plate. Heat transfer measurements are made on this plate using a steady-state gold-deposited Mylar film technique. This gold Mylar surface is coated with thermochromic liquid crystals, which enables the determination of a detailed heat transfer distribution over the plate. Measurements are made for a Reynolds number of 100,000. The data gathered from this research will help turbine designers in the future.

Key Words: Low Pressure Turbine, Turbine Flow Separation, Low Pressure Turbine Heat Transfer, Pak B Turbine Blade
Nomenclature

\[c\] Axial chord length
\[C_p\] Pressure coefficient
\[\mu\] Dynamic viscosity
\[P_s\] Static pressure
\[P_t\] Total pressure
\[Re\] Reynolds number
\[\rho\] Density
\[SSL\] Suction Surface Length
\[T_{ls}\] Lower surface temperature
\[T_s\] Upper surface temperature
\[T_\infty\] Freestream temperature
\[T_u\] Freestream turbulence level (%)
\[V_\infty\] Freestream velocity

Introduction

Current trends in military Unmanned Aerial Vehicle (UAV) and commercial jet design are requiring much greater efficiency from low-pressure turbine stages. The mission of the UAV has been more clearly defined in recent years, calling for gas turbine engines designed to operate at altitudes in excess of 50,000 feet; this condition results in a significant loss of overall engine efficiency due to the low Reynolds number conditions at higher altitudes as shown in Figure 1.

![Figure 1 Efficiency Loss at High Altitude/Low Reynolds Number Condition](image)

Figure 1 Efficiency Loss at High Altitude/Low Reynolds Number Condition [1]
Furthermore, in an attempt to reduce weight and, thus, increase overall fuel efficiency, gas
turbine engine designers are developing turbines with fewer, more highly-loaded vanes,
requiring increased efficiency and enhanced performance of the newly-designed blades. As a
result of these current and projected demands, the flow and heat transfer characteristics over low-
pressure turbine blades, particularly the Pak-B blade, have been investigated over the past decade
to explore sources of inefficiency. A significant contributor to these losses in efficiency is the
flow separation characteristic of the low Reynolds number flows across low-pressure turbine
vanes at high altitudes. Separation typically occurs on the suction surface of a turbine blade,
which is the convex surface that experiences lower static pressures as the flow over it accelerates
and then decelerates toward the trailing edge due to the presence of an adverse pressure gradient.
This region of adverse pressure gradient often leads to separation, particularly for low Reynolds
number, laminar flow. To characterize this flow separation on the Pak-B profile, Lake
determined the static pressure coefficients at various locations along the Pak-B surfaces in a
cascade wind tunnel [2]. Lake’s data indicate a significant laminar separation region along the
aft section of the blade suction surface with an ensuing transition and turbulent reattachment
region near its trailing edge, such as is seen in Figure 2.

![Diagram](image)

**Figure 2 Flow Over the Suction Surface of a Pak-B Turbine Vane [2]**

It is the goal of the present research to add insight to this data with a characterization of the
effect of the separation region on heat transfer from the blade by obtaining a distribution of local
heat transfer coefficients over the suction surface of the Pak-B blade. Separated flow results in a
significant decrease in the local heat transfer coefficients near the thin aft section of the vane,
which can result in high thermal stresses. These higher stresses could lead to increased thermal
fatigue and, thus, a lower lifecycle of the turbine blades. Typically, low-pressure turbine blades
and vanes are not cooled making it even more important to improve the heat transfer distribution
by eliminating separation. Therefore, reduction of the separation region due to low Reynolds
number conditions is beneficial both for the improved lifecycle of low-pressure turbine vanes as
well as the improved performance of highly-loaded blades enhanced by continuous flow attachment.

**Theory and Experimental Methods**

An effective method for characterizing flow over the Pak-B turbine blade is to record and plot the distribution of the static pressure coefficients over the surfaces of the blade. This was the approach taken by Lake, yielding pressure plots at different Reynolds numbers that clearly show the acceleration, deceleration, and separation of the flow at various locations along the blade surfaces. The nondimensional coefficient of pressure is defined by Equation (1), where $P_{0,\infty}$ is the total freestream pressure, and $P_{s,x}$ is the local static pressure at distance $x$ along the surface.

$$C_P = \frac{(P_{0,\infty} - P_{s,x})}{\frac{1}{2} \rho V_{\infty}^2}$$  \hspace{1cm} (1)

Although Lake’s data is based on experiments performed using a large-scale turbine vane model tested in a cascade wind tunnel, the Baylor University Turbine Suction Surface Wind Tunnel emulates these pressure coefficient distributions on a flat plate by varying the contour of the upper surface of the test section to alter the flow over the plate, which subsequently affects the local static pressures on the plate. The plate then accurately simulates the suction surface of the Pak-B blade. Thus, in order to validate the heat transfer results of the current research, a pressure coefficient plot matching that of Lake had to be obtained. This step would validate the flow field expected on the suction surface. To accomplish this step, several variable features of the Baylor tunnel were adjusted, including the upper surface contour and the application of different levels of suction on the upper surface to induce and control the separation region. However, Lake’s pressure coefficients were plotted against percent axial chord of the Pak-B profile as opposed to the percent suction surface length on which the current research is based. Therefore, it was necessary to use the modified Lake pressure coefficient locations determined by Erwert [3] in order to establish the model used to set the Baylor wind tunnel. The pressure coefficient distributions are shown in Figure 3 below.
In order to achieve a Reynolds number of 100,000 in the Baylor wind tunnel, the required velocity had to be determined from this Reynolds number as well as the density and dynamic viscosity of the air and the characteristic length. Since Lake defined Reynolds number with the axial chord as the characteristic length, an overall transformation ratio from suction surface length to axial chord of 0.754 was introduced. Equation (2) shows the definition of the Reynolds number used for this research. The required tunnel velocity was determined from Equation (2) and then was used to determine the required upstream dynamic pressure, which would be used to set the tunnel fan speed.

\[
Re_c = \frac{\frac{\rho V_{SSL}(c/SSL)}{\mu}}{\frac{\rho V_{SSL}(0.754)}{\mu}} = \frac{\rho V_{SSL}(c/SSL)}{\mu} = \frac{\rho V_{SSL}(0.754)}{\mu} \tag{2}
\]

The characterization of heat transfer along the plate, and, thus, over the suction surface of the Pak-B blade, is achieved using the application of a gold-deposited Mylar film method to determine the local heat transfer coefficients along the streamwise direction. A flat plate was prepared by adhering a gold-deposited Mylar sheet onto the surface with the gold side facing upwards. Thermochromic liquid crystals were applied to the black-painted gold side of the Mylar film to determine the surface temperature of the locations along the plate on which isotherms are present. This method involves applying electrical power to the gold-Mylar sheet, which dissipates the power as a uniform heat flux due to the uniform resistance of the gold-Mylar film. Neglecting the effective radiation from the plate, heat transfer from the electrical power dissipated across the plate is described by the energy balance represented by Equation (3).
The electrical power supplied to the gold-deposited Mylar sheet is calculated by the product of the measured current, $I$, and voltage, $V$, supplied by the power source and represents the total power converted to heat on the top surface of the plate. The total heat flux, $q_{tot}$, is then determined by dividing this power over the area, $A$, of the gold-Mylar test section on the plate. The conductive heat flux, $q_{cond}$, through the plate cannot be neglected. The value of $k$ used for Plexiglas in this experiment is an average value of $0.188 \, \text{W/mK}$ for acrylic [4]. Using a thermocouple to measure the temperature of the lower surface of the plate, the heat flux lost by conduction through the plate of thickness $dx$ is calculated by Equation (4).

$$q_{cond}'' = \frac{k(T_s-T_{\infty})}{dx}$$  \hspace{1cm} (4)

Knowing $q_{tot}$ and $q_{cond}$, it is possible to determine the energy convected from the top surface of the plate, $q_{conv}''$. The convective heat flux, $q_{conv}$, is defined by Equation (5),

$$q_{conv}'' = h_x(T_s - T_{\infty})$$  \hspace{1cm} (5)

where $h_x$ is the local heat transfer coefficient at a distance $x$ along the plate. Using these measurements and equations, the local heat transfer coefficients are calculated by Equation (6).

$$h_x = \frac{q_{tot}'' - q_{cond}''}{(T_s - T_{\infty})}$$  \hspace{1cm} (6)

The surface temperature, $T_s$, is found using the calibrated liquid crystal isotherm, and $T_{\infty}$ is the freestream temperature. The distribution of local heat transfer coefficients along the streamwise direction of the plate is obtained by varying the location of the isotherms by altering the electrical power settings and applying the new power and lower surface temperature to Equation (6).

**Apparatus and Experimental Procedure**

3.1 **Apparatus**

The primary experimental apparatus for this research was the Baylor University Turbine Suction Surface Wind Tunnel, a low-speed wind tunnel with a test section consisting of a flat plate and a contoured upper surface. The test section is 12 in wide by 8 in high by 48 in long.
adjustable ceiling profile is made of 1/8-in ABS plastic, measuring 12 in wide to match the width of the test section and flat plate. This contoured upper surface enables the static pressure profiles of the Pak-B blade and other turbine blades to be distributed on the flat plate. The shape of the profile is altered by adjusting the vertical position of five bars pressed against the top of the upper surface, as shown in Figure 4.

![Figure 4 Suction Surface Wind Tunnel](image)

A suction manifold is included in the ceiling profile at 60% suction surface length to help prevent flow separation from the ceiling profile and to induce the pressure gradient necessary to cause flow separation from the aft section at the appropriate location on the flat plate to match that of Lake (see Figure 5). The manifold is constructed from a 2-in aluminum beam cut at an angle to match the slope of the upper profile at its installation point. A 2-in pipe is attached to the manifold and runs through a hole in the top of the tunnel test section. Suction is applied to the manifold by means of a shop vacuum with the vacuum hose attached to the top of the pipe. The level of suction is controlled by adjusting the voltage of the power supplied to the vacuum using two Staco Energy Variac variable autotransformers. To ensure uniform pressure drop across the suction area in the upper profile, a steel mesh is stretched over the opening of the manifold.
Two 0.5-in thick Plexiglas plates were utilized for the experiment: a pressure plate and a heat transfer plate. Both plates are 12 in wide by 33.5 in long with a 4:1 elliptical leading edge. The pressure plate has sixteen staggered pressure taps distributed lengthwise along the plate to record the streamwise pressure distribution. More pressure taps are concentrated after 50% suction surface length since the separation region is expected to be present on the aft section of the plate, thus, requiring a finer set of pressure measurements to better characterize the separated flow. The pressure port locations along the plate are shown in Table 1 below.

<table>
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<tr>
<th>Port</th>
<th>Plate Distance From the Leading Edge (in)</th>
<th>% SSL</th>
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<th>Plate Distance From the Leading Edge (in)</th>
<th>% SSL</th>
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<td>33.4688</td>
<td>99.91</td>
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</table>

Table 1 Flat Plate Pressure Port Locations

Pressure measurements were made between the upstream static pressure and the local static pressure using an MKS Instruments 223BD-000.2ABB Pressure Transducer, serial #: 0006927880, and an MKS Instruments type PDR-D-1 Power Supply/Digital Readout, serial #: 000532287. The MKS Pressure Transducer has a range of 0-0.2 torr.
On the upper surface of the heat transfer plate, a 10.5-in by 32-in piece gold-deposited Mylar film was carefully adhered to the surface, gold-side facing upwards. The sheet width was centered laterally, and its length was positioned between the edge of the elliptical nose and 0.5 in from the aft edge of the plate. Copper tape was laid along the lengthwise edges of the plate on either side of the gold Mylar, and silver paint was applied to the small gap between them to ensure electrical conduction. Then, the entire gold-Mylar test section was spray-painted black to mitigate the effects of radiation from the surface. An airbrush was used to apply Hallcrest SPN/R25C1W liquid crystals to the spray-painted gold-Mylar surface. Finally, wires were soldered to the copper strips on the aft 0.5 in of the plate and run outside the test section to two BK Precision Model 1761 DC power supplies connected in parallel.

For the calculation of electrical power supplied to the heat transfer plate, two Newport Electronics HHM290/N TrueRMS Supermeters were used to determine the current and voltage applied to the plate. The Supermeter used to measure the current was placed in series with the power supply whereas the Supermeter used to measure the voltage was placed in parallel by connecting its two leads to the soldered connection at the aft end of the plate inside the tunnel. This allowed for the direct measurement of the voltage at the plate without the losses through the wires from the power supplies.

Two Omega Wire-K thermocouples used for the heat transfer experiment: one to measure the inlet freestream temperature, \( T_\infty \), and one to measure the temperature of the lower surface of the heat transfer plate, \( T_{ls} \), to account for the conductive heat loss through the plate. To display the temperatures from these two thermocouples, an additional Supermeter and an Altek Model 322-1 thermocouple calibrator were used. Figure 6 shows the experimental setup.
3.2 Experimental Procedure

To obtain a pressure coefficient plot that matched Lake’s data, the Reynolds number of 100,000 had to be established before any plate pressure measurements could be recorded. The upstream Pitot-static tube was initially connected to the MKS Instruments pressure transducer with the upstream total pressure, $P_{0,∞}$, on the high pressure side and the static pressure, $P_{s,∞}$, on the low pressure side. This differential pressure represents the dynamic pressure defined by Equation (7). The required velocity, as determined by rearranging Equation (2), yields the dynamic pressure necessary to achieve the appropriate Reynolds number. The Baylor wind tunnel fan motor frequency was adjusted accordingly until the digital readout displayed the necessary dynamic pressure.

\[ P_{0,∞} - P_{s,∞} = \frac{1}{2} \rho V_{∞}^2 \quad (7) \]

Once the tunnel Reynolds number was set, the total pressure from the upstream Pitot-static tube was directed to the high pressure side of the pressure transducer while the low pressure side received the static pressure from each port on the pressure plate in sequence. In effect, the digital readout displayed the differential pressure, $P_{0,∞} - P_{s,x}$, that forms the numerator of the pressure coefficient defined by Equation (1). The differential pressure was recorded for each static pressure port three times and averaged in order to mitigate the influence of random error. Each average was then divided by the dynamic pressure, according to Equation (1), to calculate the static pressure coefficient at that plate location. These pressure coefficients were then plotted against percent suction surface length and compared with Lake’s plot as transformed by Erwert from axial chord to suction surface length.
Before the heat transfer plate could be tested, the liquid crystal had to be calibrated in order to establish the temperature represented by the yellow-green hue of the one-degree wide color spectrum. To accomplish this calibration, a thin foil (0.005 inch thick) K-type thermocouple was attached to the surface of a small sample Plexiglas plate, which was then spray-painted black and overlaid with the same liquid crystals, as seen in Figure 7. A hot-air blow dryer was slowly passed onto this plate until the crystals activated, and the yellow-green hue within the isotherm produced was centered on the thermocouple as the temperature was recorded. This process was repeated twenty times, and the temperatures were averaged to establish the temperature the isotherm represents on the heat transfer plate. This temperature, which represents the gold-Mylar surface temperature, \( T_s \), at the location of the isotherm, was determined to be 32.965 °C, despite the fact that the liquid crystal used is designed to activate at 25 °C. This difference in calibration temperature was due to the age of the crystal and in no way changed the response of the crystal to temperature changes.

![Figure 7 Liquid Crystal Calibration](image)

Having validated the pressure coefficient plot against that of Lake and calibrated the liquid crystals, the gold-Mylar heat transfer plate was then installed into the Baylor wind tunnel in place of the pressure plate. The tunnel was restarted and adjusted until the dynamic pressure reading from the Pitot-static tube again represented a Reynolds number of 100,000. Both power supplies were turned on and set to be current-controlled. The current was gradually increased until the liquid crystals were activated in the separated region. Once the crystals were activated, two isotherms formed bounding a blue region that represented the separated region containing low local heat transfer coefficients. At this point, measurements were taken and recorded. Using a yardstick attached to the side of the test section, the streamwise locations of the two isotherms were observed and recorded. The current and voltage supplied by the power sources were read from the Supermeters and recorded as well as the lower surface and freestream temperatures (\( T_{ls} \) and \( T_\infty \)). The current was then increased slightly to produce a higher power setting and, thus, more heat flux from the plate. This resulted in the liquid crystal isotherm to adjust to a new...
location. New data were taken from the new power setting after allowing the plate to reach a steady-state condition. This process was repeated until the isotherms had extended beyond the plate edges. Ten minutes were allotted between each power increase to achieve the steady state.

Results and Conclusions

A key supposition that was made in predicting the results of the heat transfer experiment was that the region of low local heat transfer coefficients would correspond with the separated region indicated on the pressure coefficient plot. As seen in Figures 3 and 8, the separated region on the pressure coefficient plot is distinguished by a series of coefficients of nearly the same value from approximately 72% SSL to 86% SSL; it is characterized by a flat region on the plot. This indicates, based on Equation (1), that the static pressures on the surface of the plate do not vary with streamwise distance along the plate in that flat region. Using the current, voltage, and temperature data gathered for each power setting, the local heat transfer coefficients were computed by Equation (6) and plotted against their respective locations along the plate. This local heat transfer distribution was then superimposed on the pressure coefficient plot to yield a comparison of the separation regions, as shown below in Figure 8.

Figure 8 Pressure Coefficient ($C_p$) and Local Heat Transfer Coefficient ($h_x$) Distribution Along the Suction Surface of the Pak-B Profile

As Figure 8 shows, the local heat transfer coefficients decrease gradually with distance from the leading edge of the plate. This is the result of energy accumulation in the flow and boundary layer growth as the laminar flow progresses down the plate. The onset of the separation region is indicated by the sharp drop in $h$ starting at approximately 66% SSL. The sudden decrease in $h$ to a minimum within the separated flow region is due to the lack of bulk fluid motion on the surface.
of the plate necessary to facilitate convective heat transfer. At the end of the separation region, the local heat transfer coefficients begin to rise again, indicating flow reattachment and potential transition to turbulent flow. Indeed, turbulent reattachment would account for the sharp increases in $h$ that occur toward the end of the plate. The separated regions shown in both plots correspond as expected. The heat transfer plot is characterized by much lower local heat transfer coefficients within the approximately 72-84 % SSL separated region characteristic of the pressure coefficient plot.

Although the location of the separation region in the heat transfer plot was successfully corresponded with that of the pressure plot, the major implications of these results are manifested in the contrasting local heat transfer coefficients around the area of separated flow. The sharp increase in $h$ after reattachment to the trailing edge of the plate signifies a sharp gradient in the convective heat transfer and, thus, the temperatures on the thin trailing edge of the Pak-B turbine vane. This stark contrast between the heat transfer characteristics of the separated region and the reattachment region (as well as the section just before the separation) could create significant thermal stresses and thermal fatigue over the lifecycle of the blade that may lead to unexpected damage and potentially structural failure. Therefore, stopping separated flow across low-pressure turbine blades and solutions to reduce and eliminate this separation region have tremendous implications for heat transfer and thermal loading on these vanes, particularly on the aft section of the suction surface.

**Conclusions, Future Work and Recommendations**

This paper examined the simulated suction surface of a Pak-B gas turbine vane. A Reynolds number of 100,000 was tested and the top surface of the tunnel adjusted to match the velocity, and thus the static pressure profile, of the Pak-B vane. Under these conditions, a separated region was found to be between 72-84 % suction surface length. Heat transfer measurements under the same conditions showed a region of low heat transfer under the separated region. Toward the trailing the heat transfer has a very steep gradient indicating that a region of high thermal stress would exist near the trailing edge of the vane.

The current results establish a baseline characterization of heat transfer on a low-pressure turbine vane as well as the impact of separated flow on the thermal behavior of turbine blades. Similar experiments should be conducted to refine the current results by using a smaller width of gold-deposited Mylar film, thus requiring less power to activate the liquid crystals. Modifications to the plate to introduce flow control techniques would demonstrate the effect of forcing turbulent flow on reducing or even eliminating the separation region by maintaining flow attachment to the surface. The results of this will potentially show the benefits of mitigating the impact of separated flow on the heat transfer characteristics of the plate by reducing the thermal stresses.
due to large variations in local heat transfer coefficients. These flow-control measures include the application of various arrays of dimples and vortex generators to induce turbulent flow. Finally, the introduction of freestream turbulence using a turbulence grid will also provide insight into its impact on the separation region and the local heat transfer coefficients down the plate.

References