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Effect of Impinging Jet Excitation on Curved Surface Heat Transfer

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Introduction

THE overall efficiency of gas turbine engines is directly dependent upon the turbine inlet temperature of the working fluid. In today's engines, metallurgical limitations restrict the fluid temperature to approximately 1300°C, which is below the adiabatic flame temperature of most hydrocarbon fuels. For over 10 yr, engineers have sought ways to circumvent these design restrictions by developing more advanced methods of turbine blade cooling. One of the more generally accepted methods for enhanced cooling utilizes impinging jet heat transfer. In this approach, highly disturbed fluid emanating from the compressor is transmitted through a complex array of ductwork before impinging onto the blade surface. Yet little attention has been given to the state of the fluid impinging on the internal blade structure.

Previous research has indicated that changes in heat transfer are possible under harmonic excitation. Gutmark et al.[1] demonstrated that low level harmonic excitation of a jet impinging on a flat plate did enhance cooling. However, 18 yr earlier, Nevins and Ball[2] investigated the average heat transfer between a flat plate and a pulsating impinging jet and reached the opposite conclusion. They concluded that, for the range of variables covered, the heat transferred to the jet was independent of both frequency and amplitude of the disturbance. These studies reveal a major difference between an excited jet, in which disturbances have a negligible effect upon the steady mass flow rate, and a pulsating jet in which the mass flow is unsteady.

Time independent studies in the open literature include work by Gardon and Cobonque,[3] who examined the average heat transfer coefficients as well as their variations from point-to-point on a cooled flat surface using impinging jets. Metzer et al.[4] studied the heat transfer between a single jet and a concave cylindrical surface. Tabakoff and Clevenger[5] compared the thermal effectiveness of three different systems of air jets impinging on the inside surface of a half-circular cylinder. Hrycak[6] recently measured average and local heat transfer coefficients from a row of impinging jets to concave cylindrical surfaces.

When examining the fundamental fluid dynamics of the exiting jet, one notes that in the natural (unexcited) free shear layer, the fluid which separates from the nozzle boundary layer tends to "roll up" and form discrete vortices. If periodic excitation is applied to the shear layer, it is found to cause a two-dimensional undulation of the separating boundary layer. This undulation causes the agglomeration of several of these discrete vortices into a large, isolated vortical structure downstream from the separation lip. That is, excitation has been found to organize and generate larger vortical structures than would otherwise exist in a naturally occurring shear layer. Moreover, Hussain[7] demonstrated that under certain conditions excitation can also suppress the turbulent intensity of an axisymmetric jet, extending as far downstream as eight jet diameters. Since there are no experiments that investigated the effects of a simple periodic disturbance on blade cooling, the following program was conducted.

Experimental Setup

The implementation of this experiment required a test facility which would simulate a nominal surface arrangement within the turbine blade. This facility consisted of a 0.180-mm-thick nickel-chromium plate curved to form a long semicylinder with a 12.70-cm arc length which served as the inner blade contour. This contour was mounted in a wooden cell (43.2 cm wide × 44.5 cm deep × 30.5 cm high), and insulated with styrofoam (Fig. 1). The air jet emanated from a rectangular nozzle mounted above the plate with a 3.18-mm width and an aspect ratio of 44. Upstream of the nozzle was a settling chamber containing a 21-cm loudspeaker, oriented in the streamwise direction. This device provided periodic excitation of the exiting flow. The plate was heated by a resistive heating element, providing a constant heat flux per unit area. The plate temperatures were measured by nine miniature, fast responding, copper-constantan (type T) thermocouples located between the plate and the heater. To minimize lead conduction errors, the leads were placed parallel to the axis of the semicylinder. This ensured that the thermal gradient along the leads was approximately zero.

The data taking was carried out using a computer-controlled data acquisition system. Specifically, 1000 samples were acquired for each of the nine thermocouples at time increments of 125 ms. Using the pressure difference obtained across a sharp-edge orifice plate the mass flow rate was calculated.

Results

In the first phase of the experiment, the heat loss through the insulated test cell was determined over the temperature

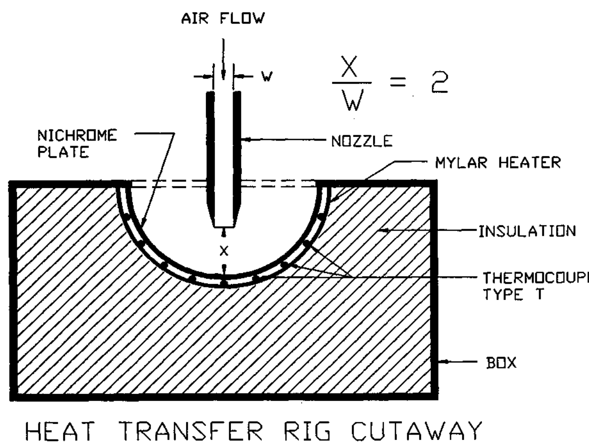

Fig. 1 Schematic of test cell.

Received Jan. 17, 1989; revision received April 26, 1991; accepted for publication Aug. 3, 1993.

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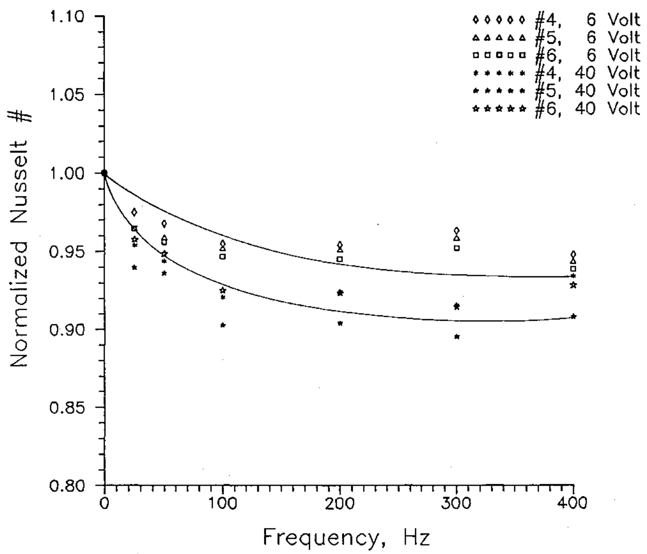

Fig. 2 Normalized stagnation zone Nusselt number variations under flow excitation.

range of interest. The cell heat loss was then correlated to each thermocouple. The effects of acoustic excitation on the local surface heat transfer was then carried out in the second phase of the experiment. These effects were studied at an approximate jet Reynolds number of 10,000 (based on slit width), under unexcited (or naturally disturbed) conditions, and with applied sinusoidal disturbances with amplitudes of 6 and 40 V, peak-to-peak. This corresponded to 80 dB for the unexcited case, and 150 dB when excited at the maximum excitation level. The ratio of jet height to slit width l/w was held constant at 2.0.

For each test, the plate was allowed to reach equilibrium, then subjected to a disturbed flowfield with selected frequencies of oscillation ranging from 25 to 400 Hz with unexcited reference cases taken at the beginning and end of each test. The recorded temperatures for each thermocouple were then used to compute the Nusselt number Nu at each thermocouple location. Plotted in Fig. 2 is the observed Nu variations for thermocouples 4, 5, and 6 located in the stagnation zone.

In order to determine the effect of periodic excitation on the streamwise turbulence level, energy spectrums were acquired from hot wire anemometry signals for each frequency setting.

Discussion

The present experiment examined an excited jet impinging on a curved plate with a constant surface heat flux and two levels of excitation. Whenever the plate was subjected to an excited flowfield, the surface temperature rose when compared to the unexcited reference case. In repeated tests, the greatest percent decreases in Nu appeared to occur in the 100–400-Hz range. In repeated tests at the 6-V excitation level, the maximum drop in Nu was nominally 5%. At 40 V, a drop of approximately 10% in local Nu at the stagnation zone was observed (Fig. 2).

Similarly, energy spectrums acquired under maximum excitation showed a drop in turbulent intensity between unexcited and excited cases. The unexcited streamwise turbulent intensity was determined to be 13.2%, while under excitation values as low as 6% were found.

It appears that the larger vortical structures generated by the undulation of the separating boundary layer did not increase heat transfer within the confined environment of the simulated turbine blade, as surmised by Gutmark et al.[1] Rather, these vortices apparently re-entrained the already warmed air within the inner-blade environment. By re-entraining the warmed air, and the suppression of the turbulent intensity, the temperature difference between the jet and the blade was reduced, therefore, the cooling efficiency decreased.

Summary

While the generation of large isolated vortical structures by acoustic excitation is not a new concept, it is one which has serious implications within the gas-turbine industry. Although past experiments have demonstrated that periodic excitation could enhance heat transfer, the results presented above suggest that the development of large vortical structures coupled with the drop in turbulence intensity, within the confined turbine blade geometry, can lead to a reduction in cooling efficiency.

Acknowledgments

The author wishes to gratefully acknowledge the Charles A. Lindbergh Fund for its financial support, Dave Paule for the data acquisition, and Robert Annan for facility development.

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