Engineering Notes

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Cross-Flow Influence on Slot Cooling Effectiveness

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Introduction

ONE of the main problems for airplanes flying in the Mach number range between 4 and 6, is the aerodynamic heating. It is of great importance to develop practical cooling techniques which allow the airplane to maintain structural integrity under the severe heating of hypersonic flight, without the necessity of introducing new materials and new "hot" structure designs.

One of the promising ways to solve this problem is the slot cooling technique. A coolant gas is injected into the boundary layer of the surface to be cooled, with the purpose of creating a cold film layer of gas between the surface and the hot mainstream. The film, acting as a protection, can reduce the heating process sufficiently to maintain the surface of the vehicle below the maximum allowable temperature of the material used. Recent investigations[1] at high Mach number show that the slot injection cooling scheme is much more effective than expected from preceding investigations.

All the previous slot injection studies were done on cylinders and flat plates. Pressure variations on the surface, three-dimensional effects and cross-flow phenomena can strongly influence the cooling capacity of slot injection. The purpose of the present investigation is to study the application of the slot cooling scheme to a body of practical configuration, simulating the fuselage of a high-speed airplane and particularly to study three-dimensional and cross-flow effects on the cooling effectiveness for different angles of attack.

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Index categories: Aircraft Aerodynamics (including Compoent Aerodynamics); Boundary Layers and Convective Heat Transfer-Turbulent.

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Experimental Equipment and Techniques

The experiments were performed in the New York University Mach 4 two-dimensional wind tunnel. The tunnel stagnation pressure was maintained at about 200 psia, the stagnation temperature was 530°R, the corresponding Reynolds number per foot was about 5×10^6. An axisymmetric body simulating the fuselage of a high-speed airplane was used for testing. The angle of attack range for the test was from 0-8° (Fig. 1).

The three slots used to cool the body had individualized mass flow control systems, so that a variety of possible conditions could be obtained. The instrumentation consisted of thermocouples located on the inside surface of the model skin, to determine the heat transfer to the body as well as the wall temperature distribution on the surface, and of pressure taps and thermocouples inside the slot chambers to determine the conditions of the slot injection and to check the mass flow injected. The injected coolant was air passed through a coil of tubing partially immersed in a bath of liquid nitrogen. The injected air temperature was in the range of 280-350°R. The model was precooled before the test to reach a difference in temperature between the adiabatic temperature and the wall temperature $(T_{ad} - T_w)$ which gives significant heat transfer and sufficiently accurate measurements.

The heat transfer on the wall is determined by the transient method from the measurement of the slope of the temperature with respect to time. If the shimstock skin is thin and all the other sources of heat are negligible, the aerodynamic heating can be calculated from the temperature increase, assuming that each element of the skin, to which the thermocuple is attached, behaves like a calorimeter. From the heat transfer and wall temperature distribution and knowing the heat transfer coefficient, it is possible to calculate the value of the adiabatic temperature by the Newton's law of cooling

$$q = h(T_w) \, |T_{ad} - T_w| \tag{1}$$

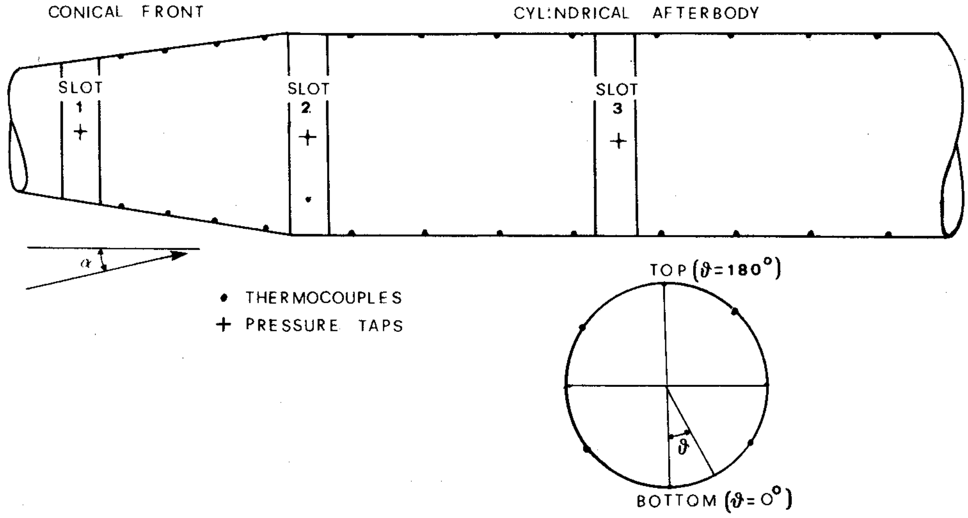

Fig. 1 Sketch of model configuration, slot positions, and instrumentation.

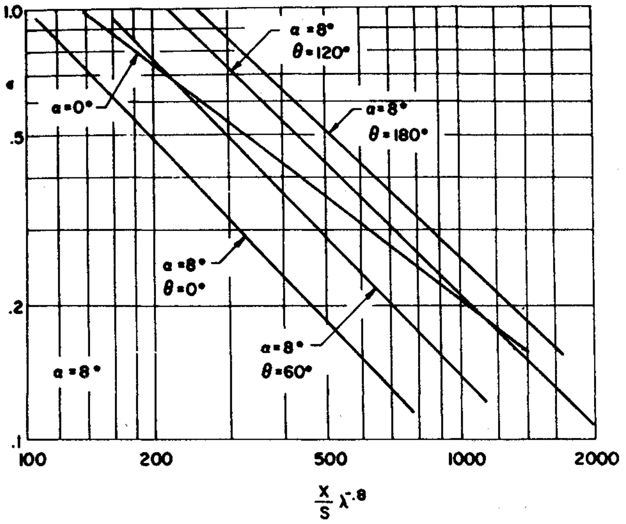

Fig. 2 Effectiveness correlations at $\alpha=8°$ for different azimuthal angles θ.

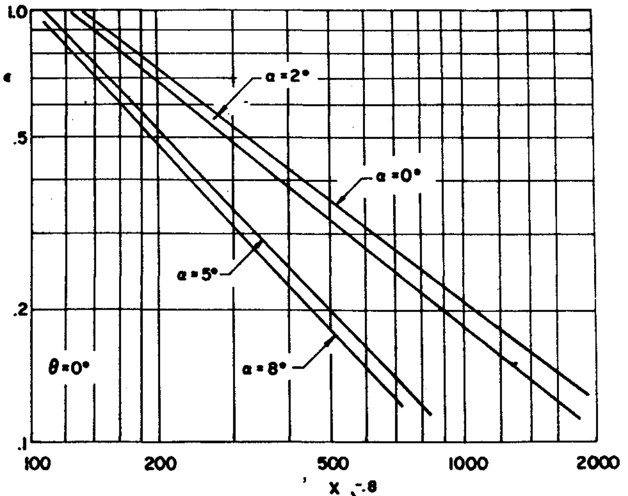

Fig. 3 Comparison of effectiveness correlations at $\theta=0°$ for different angles of attack.

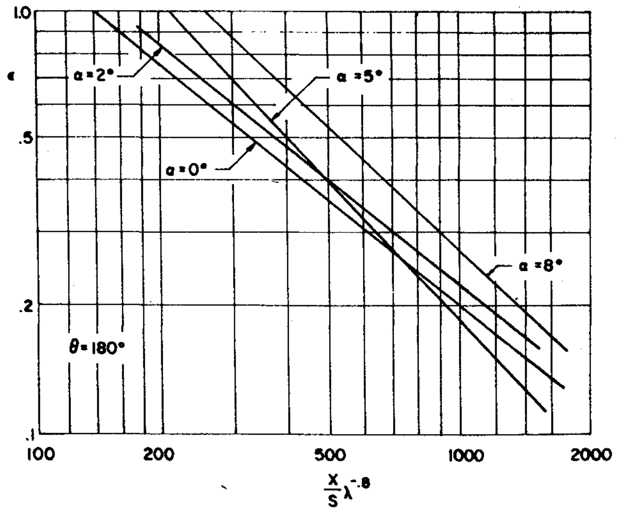

Fig. 4 Comparison of effectiveness correlations at $\theta=180°$ for different angles of attack.

The value of the heat transfer coefficient $h(T_w)$ was deduced for each thermocouple position and each precooling temperature from a series of no-injection tests. In the no-injection case, the adiabatic temperature is known, T_w and q can be measured; thus $h(T_w)$ follows from Eq. (1).

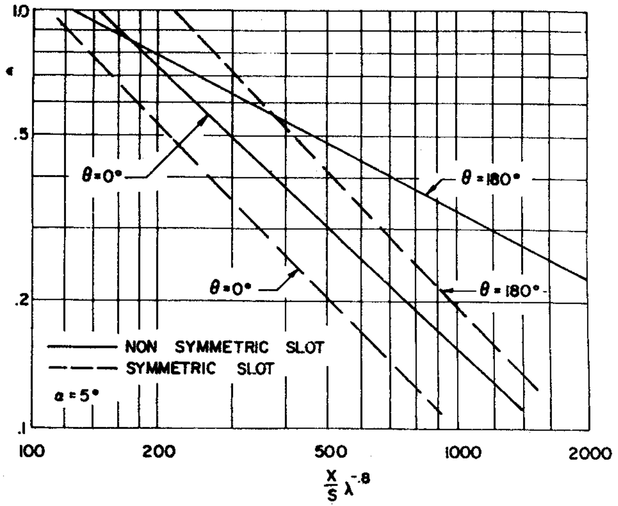

Fig. 5 Effectiveness correlations for symmetric and nonsymmetric slots at $\alpha=5°$.

Experimental Results and Discussion

The distribution of the adiabatic temperature is the most significant way of illustrating the results of the present study. The adiabatic temperature is considered in its nondimensional form

$$\epsilon = T_{ad} - T_o / T_{oj} - T_o \tag{2}$$

known as the cooling effectiveness. The effectiveness ϵ has been correlated[1] as a function of a combination of parameters

$$\epsilon = fn(x/s\lambda - 0.8) \tag{3}$$

where x/s is the streamwise distance measured in terms of slot heights and $\lambda = \rho_j u_j / \rho_e u_e$ is the mass flow ratio.

The results correlated according to the relation in Eq. (3) show a very regular trend, and the different cases can be easily compared. The cooling effectiveness is higher in the region immediately downstream of the slot since in this region the surface feels just the temperature of the injectant gas, while further downstream the effectiveness decreases due to the mixing of the hotter mainstream with the coolant gas. The results for the body at different angles of attack, in the range between two and eight degrees have been obtained. For each angle of attack the cooling effectiveness correlation has been made for different azimuthal angles θ (0°, 60°, 120°, 180°) corresponding to the thermocuple's positions on the cylinder skin.

Figure 2 show the results for 8° angle-of-attack and the four azimuthal angles. The four correlation slopes are reported together with the one obtained at 0° angle of attack for comparison. The values of the cooling effectiveness on the windward side ($\theta=0°$) are lower and on the leeward side ($\theta=180°$) higher than the values obtained at zero angle of attack ($\alpha=0°$). Thus the cooling effectiveness decreases from the leeward side to the windward side. These results can be explained by the presence of crossflow around the axisymmatric body at angle of attack. The crossflow carries away the coolant from the windward side toward the leeward side giving to the body a very nonuniform coolant protection.

Analogous considerations are valid for the lower angles of attack. The complete set of results is reported elsewhere.[2] The effect of the crossflow on the cooling characteristics of the injected gas is obviously smaller for lower angles of attack and as a result the effectiveness correlations are less differentiated at the various azimuthal angles. Comparisons for azimuthal angles θ, of 0° and 180°, for several angles of attack are displayed in Figs. 3 and 4. The coolant film, spreading nonsymmetrically over the surface becomes highly nonuniform at increasing body and angle of attack, generating a region of lower temperature on the leeward side and a region of higher temperature on the windward side. In practical applications a lower average temperature and then a higher average heat transfer rate are inevitable for the entire surface to maintain every point below the maximum permissible temperature for the material used.

To minimize the severe deterioration of the cooling capability of slot injection due to three-dimensional effects, new designs are required for the slot system which give a nonuniform peripheral distribution of the coolant. At this purpose a very simple slot system scheme which counters the cross-flow effects has been investigated in the present study. The scheme consists of nonsymmetric slots, higher on the windward side and lower on the leeward side which, maintaining the average height $S_{eq}=(S_L+S_w)/2$, i.e., the injection coolant mass flow, and producing a nonuniform injection pattern, act to prevent and reduce the negative cross-flow effects on cooling.

The experimental results (Fig. 5), compared with the previous symmetric slot results, generate a more uniform adiabatic wall temperature distribution and thus improve the cooling capability of the system. The results obtained with this primitive nonsymmetric slot scheme are only indicative, however they can suggest a possible direction of investigation.

References

[1]Zakkay, V., Sakell, L., and Parthasarathy, K., "An Experimental Investigation of Supersonic Slot Cooling," *Proceedings of the 1970 Heat Transfer and Fluid Mechanics Institute,* Stanford University Press, 1970.

[2]Piva, R. and Srokowski, A., "Three-Dimensional Effects on Slot Cooling," AFOSR-TR-73-1073, Feb. 1973, U.S. Air Force Office of Scientific Research, Arlington, Va.

Analysis of Predicted Aircraft Wake Vortex Transport and Comparison with Experiment

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Introduction

AN aircraft wake vortex transport model has been developed[1] which combines fluid mechanic representations of the various vortex-induced and atmospheric effects. A series of flight tests was conducted to verify the model using B-747, B-707, CV-880, and DC-6 aircraft (over 400 flybys) in which both the motion of the vortices and the attendant meteorological conditions were recorded. The tests were performed at the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey.

Vortex tracks were recorded photographically and by ground-wind sensors. NAFEC has a 140-ft tower instrumented with hot-film anemometers, colored smoke dispensers at 20-ft intervals, and meteorological instrumentation at five levels. The smoke was used to visualize the vortices. A 35-mm camera was positioned 2000 ft from the tower on a line nearly normal to the prevailing wind direction. Photographs were taken every second and the vortex tracks were obtained by examining each photo and locating the vortices by scaling photographic distances with known distances. Gill single-axis propeller anemometers were arrayed on a baseline near the 140-ft tower to measure the wind component perpendicular to the aircraft flight path. As a vortex moved through the anemometer system, it produced a distinctive signature superimposed upon the background wind. The digitized wind sensor data were processed to locate the most probable vortex location as a function of time.[2]

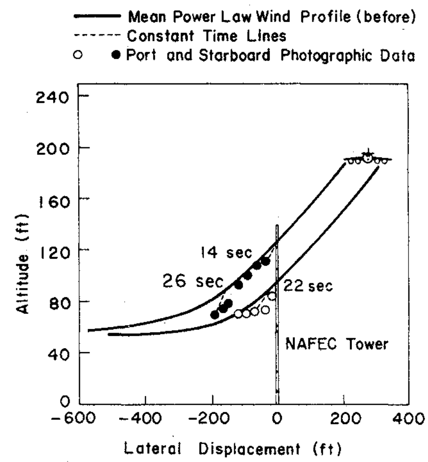

Fig. 1 Comparison of predicted vortex tracks with photographic data for a B-707 flyby (labeled times calibrate the constant time lines and align prediction and observation).

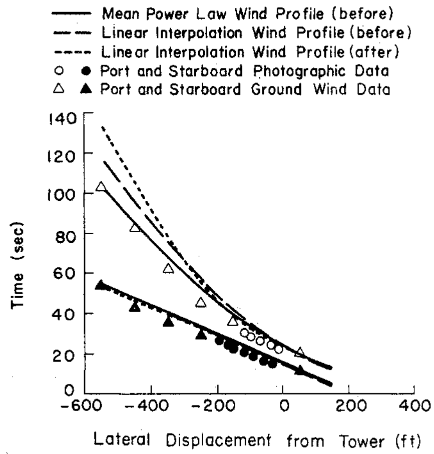

Fig. 2 Comparison of predicted vortex track with measured ground wind data for a B-707 flyby.

Analysis

Figure 1 shows a typical cross-sectional vortex track compared with a predictive track where the ambient wind was determined by a least-square polynomial fit to the mean wind field averaged for 2 min before the aircraft passage. Figure 2 shows the ground-wind track for the same flyby as in Fig. 1; three predictive tracks are shown: two linear interpolations of the five tower-measured average wind speeds ("before" denotes the mean for the two minutes prior to the aircraft flyby and "after" denotes the two minutes after the flyby),

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