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Vortex-Induced Heating to Cone Flaps at Mach 6

JERRY N. HEFNER* AND ALLAN H. WHITEHEAD JR.†
NASA Langley Research Center, Hampton, Va.

EXPERIMENTAL studies[1,2] have shown that vortices, generated over the leeward surfaces of hypersonic configurations at angle of attack, can significantly influence lee-surface heating. The interaction of these vortices with the leeward surface can generate heating peaks of greater magnitude than that found in the same area at zero incidence. Localized high heating regions might be anticipated on control surfaces that protrude into the lee-side flow since these vortices could interact with the deflected control surface. The present Note discusses results of an experimental investigation conducted in the Langley 20-in. Mach 6 wind tunnel[3] to ascertain the effects of lee-side vortices on control surface heating at angle of attack. A critical feature of the experiment was an attempt to alleviate the interaction between the vortices and the control surfaces by judicious location of the control flaps.

The basic configuration was a sharp $8\frac{1}{2}°$ half-angle right circular cone, 30.5 cm long. Two flap configurations, each deflected into the lee-side flow 25° relative to the cone centerline, were attached to the base of the cone. One configuration used a single flap which was 3.56 cm wide and 5.08 cm long and centered about the vertical plane of symmetry. The other configuration used a pair of flaps which were each 1.78 cm wide and 5.08 cm long and mounted 1.27 cm outboard of the plane of symmetry. A flat surface, parallel with the cone centerline, extended 8.47 cm ahead of the cone base and allowed a straight hinge line for the flaps. The tests were conducted at a freestream Reynolds number based on cone length ($R_{\infty,L}$) of 7×10^6. Results for selected angles of attack (α) are presented in this Note ($\alpha = 10°$, 14°, and 20°) although the angle of attack was varied between 0° and 20°.

Surface oil flow patterns on the cone with single flap are presented in Fig. 1 to illustrate the formation of the lee-side vortices with angle of attack. Oil flow studies, not shown herein, were obtained on the cone without flaps and showed essentially the same oil flow patterns as found on the cone with the flaps. Consequently, the basic lee-surface flow phenomena are concluded to be independent of the existence of the flap. Featherlike oil smears indicate the scrubbing action of the vortices on the surface.[4] Paired lee-side vortices are generated on the upper cone surface when it is aligned with or slightly shielded from the freestream ($\alpha \simeq 8\frac{1}{2}°$–9°). At $\alpha = 10°$, these primary vortices are not well established and appear to be confined to a small region near the cone apex; however, the flow expanding around from the windward surface separates along the contour defining the flat surface ahead of the flap hinge line and forms vortices which interact with the flap. As the angle of attack increases to 14° and 20°, the flow on the leeward surface separates over the entire length of the cone and the primary vortices become well established and interact more extensively with the lee surface of the cone; secondary vortices, smaller in size than the primary vortices, are generated on either side of the primary vortex pair. Unpublished schlieren photography and vapor screen studies together with the oil flow patterns indicate that although these primary and secondary vortices interact with the single flap at $\alpha = 14°$, the vortices at $\alpha = 20°$ are probably "lifted" over the flap. The interaction between the vortices and flap surface is therefore reduced at $\alpha = 20°$.

Centerline heat-transfer data obtained by the phase change paint technique[5] on the single flap are presented in Fig. 2 in

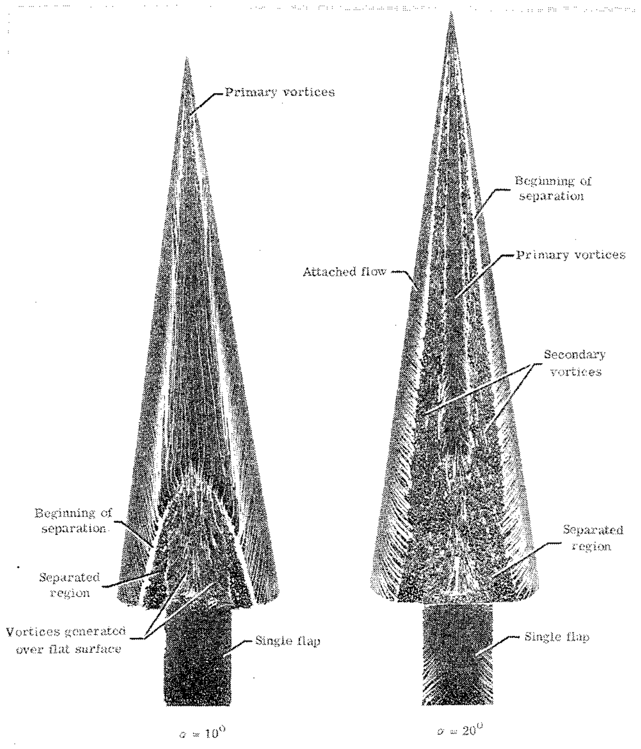

Fig. 1 Surface oil flow patterns on $8\frac{1}{2}°$ cone with single flap at angle of attack.

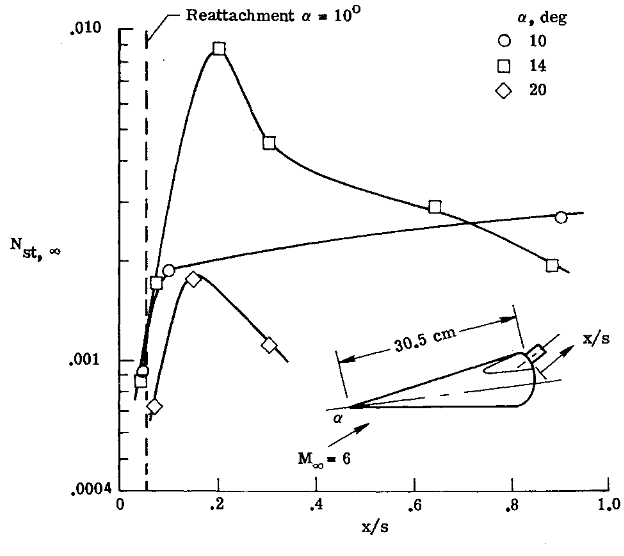

Fig. 2 Centerline heating on single flap at angle of attack.

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* Aerospace Engineer, Analytical Fluid Mechanics Section, Hypersonic Vehicles Division. Member AIAA.
† Technical Assistant to Director for Aeronautics. Member AIAA.

terms of freestream Stanton number ($N_{St\infty}$) as a function of angle of attack and the ratio of the longitudinal surface distance measured from the flap hinge line (x) divided by the flap chord (s) for three angles of attack. The maximum peak flap heating for these angles of attack occurs at $\alpha = 14°$ because both the primary and secondary vortices interact with the single flap surface. This peak heating exceeds the vortex-induced peak heating on the cone forebody at the same angle of attack (e.g., at $\alpha = 14°$, $N_{St\infty} \simeq 0.0014$ on the cone forebody whereas on the flap the peak heating was 0.00879). Moderately high heating occurs on the single flap just downstream of flow reattachment at $\alpha = 10°$, probably because only the vortices formed along the contour defining the flat surface interact with the flap surface. At $\alpha = 20°$ the peak flap heating decreases because the vortices are "lifted" over the flap.

The phase change paint heat-transfer data for $\alpha = 14°$ are presented in Fig. 3 and show the significant effect of dividing the single flap and moving each half 1.27 cm outboard of the vertical plane of symmetry (the axis of the flap remains parallel with the vertical plane of symmetry). As was found for the single flap, the maximum peak flap heating at angle of attack for the paired flaps occurs at $\alpha = 14°$. Splitting the flaps reduces this maximum vortex-induced peak heating by more than 60%. This reduction in heating occurs because only the secondary vortices formed ahead of the flat area interact with the flap surface; the primary vortices pass between the flaps. The maximum peak flap heating at angle of attack for the paired flaps is not only less than that for the single flap but is also less than the maximum flap heating at zero angle of attack (i.e., $N_{St\infty} = 0.00341$ for paired flaps at $\alpha = 14°$, compared to $N_{St\infty} \simeq 0.009$ for paired flaps at $\alpha = 0°$). Splitting the flaps and moving them outboard from the plane of symmetry alleviates considerably the severity of the vortex-induced heating to the

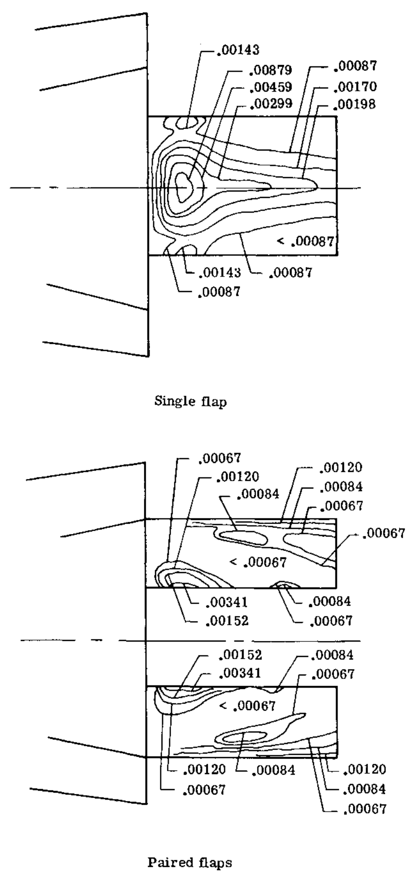

Fig. 3 Heat transfer in terms of freestream Stanton number on control flaps at $\alpha = 14°$.

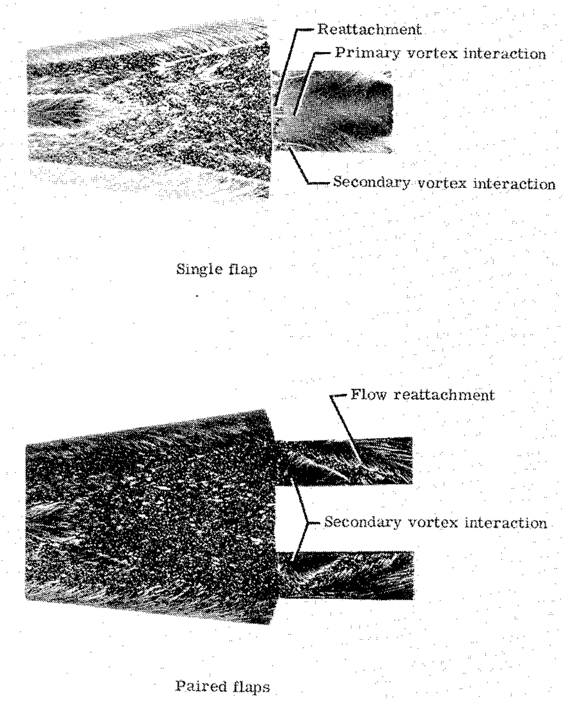

Fig. 4 Surface oil flow patterns on flaps at $\alpha = 14°$.

flaps; however, this technique for alleviating vortex-induced flap heating is not necessarily satisfactory. Limited measurements of the surface static pressures showed that the average pressure coefficient on the flaps was reduced by as much as 150% by moving them to an outboard position (i.e., the pressure coefficient for the paired flaps was −0.015 whereas the pressure coefficient for the single flap was 0.032). Furthermore, oil flow studies, similar to those presented in Fig. 4, show that the movement of the flaps significantly increased the complexity of the flow on the flaps by creating additional lines of separation and reattachment.

In summary, locally high heating due to vortices can occur on lee-side flaps at angle of attack. This heating is generally less than the maximum heating on the flap at zero angle of attack (for the same flap deflection) but can be greater than the vortex-induced heating on the configuration forebody at the same angle of attack. Splitting the flaps and moving them to positions away from the plane of symmetry can reduce this heating; however, reductions in the average flap pressure coefficient and increased flow complexity accompany this flap movement. The present results were obtained for a simplified geometry; therefore, care should be exercised in applying them to more complex configurations since lee-side vortices and vortex-induced heating are extremely sensitive to configuration geometry.[1]

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