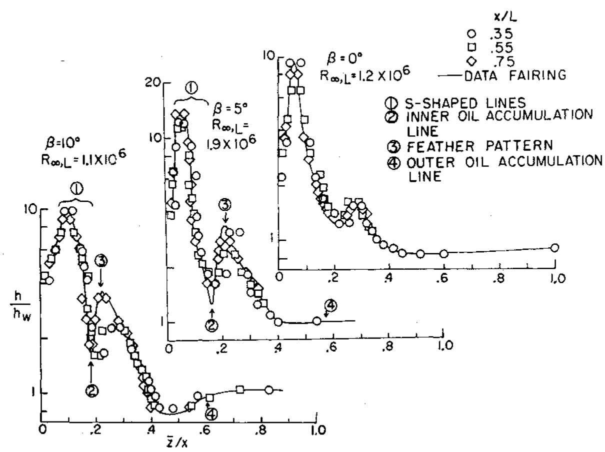

Fig. 4 Comparison of heat-transfer data for various vertical wedge angles.

mixture of silicone oil and lampblack distributed over the model surface in a random dot pattern.

Oil-flow patterns on the vertical wedge surface are shown in Fig. 2 for β angles of 5° and 10°. In both symmetrical and asymmetrical cases, the flow can be divided into similar regions. *S*-shaped lines (area 1) indicate a vortex near the corner (see Ref. 4 for a more detailed discussion of this vortex). A featherlike pattern (area 3) is separated from the *s*-shaped pattern by a thin oil accumulation line (area 2). Outside of the feather pattern a region of strong crossflow terminates in a heavy oil accumulation line (area 4), and beyond this the flow gradually approaches two-dimensional, undisturbed wedge flow. Near the top of the wedge the flow is not two-dimensional due to the projection of the wedge into the tunnel-wall boundary layer. One significant difference in the symmetrical and asymmetrical oil-flow pattern occurs in the region between area 1 and the corner juncture. For the $\beta = 10°$ case, the flow appears to be approximately radial from the tip of the model; for the $\beta = 5°$ case, the flow is turned toward the corner juncture. A possible explanation for this effect is that the vortex on the horizontal wedge moves toward the corner as β decreases.

Isoheating lines obtained from sequential photographs of the melting point boundary are shown in Fig. 3 for the $\beta = 10°$ corner. Data are presented as ratios of local to maximum heating measured on the vertical surface. The previously discussed flowfield regions from Fig. 2 are also shown. From a comparison of Figs. 2 and 3 it is apparent that the maximum heating is associated with the vortex in the near corner region.

A summary of the heating data for the three corner configurations is presented in Fig. 4 as the ratio of experimental to theoretical heat-transfer coefficients. Theoretical values were calculated for a given β from local similarity laminar boundary-layer theory, including the effects of boundary-layer self-induced pressures.[6,7] The nearly conical nature of the flow is evident from the correlation of data at different x locations when plotted in $\bar{z}/x$ coordinates. Oil-flow results show the flow to be nonconical for x/L less than about 0.35.

Peak heating near the corner (relative to undisturbed heating on the vertical wedge) is higher at $\beta = 5°$ than at $\beta = 10°$ due to the strong influence of the horizontal wedge on the 5° vertical wedge flow. At $\beta = 0°$, however, the peak heating level decreases to approximately 10 times local flat-plate heating. Evidently, the vortex system which influences peak heating is weaker at $\beta = 0°$ than at $\beta = 5°$. It is possible that the internal structure of the flow field changes between the $\beta = 5°$ and $\beta = 0°$ cases, however, this seems unlikely since the general shape of the heat-transfer distribution remains the same. A second lower peak in heating corresponds closely to the center of the feather pattern (area 3), and has been related to the presence of an internal shock in the flowfield.[4] Finally, heating rates approach the undisturbed two-dimensional wedge value outside the region where the outer oil accumulation line (area 4) occurs.

In general, the results of this investigation have shown that the surface flowfield and heating in asymmetrical corners are similar to that observed in symmetrical corners.[4] One exception, however, is the higher heating measured on the vertical wedge due to the asymmetry of the vortex system of the corner.

References

[1] Charwat, A. F. and Redekopp, L. G., "Supersonic Interference Flow Along the Corner of Intersecting Wedges," *AIAA Journal*, Vol. 5, No. 3, March 1967, pp. 480–488.

[2] Stainback, P. C. and Weinstein, L. M., "Aerodynamic Heating in the Vicinity of Corners at Hypersonic Speeds," TN D-4130, Nov. 1967, NASA.

[3] Bertram, M. H. and Henderson, A., Jr., "Some Recent Research with Viscous Interacting Flow in Hypersonic Streams," Presented at the *Symposium on Viscous Interaction Phenomena in Supersonic and Hypersonic Flow*, Sponsored by Hypersonic Research Laboratories, Wright-Patterson Air Force Base, Ohio, May 7–8, 1969.

[4] Watson, R. D. and Weinstein, L. M., "A Study of Hypersonic Corner Flow Interactions, AIAA Paper 70-227, New York, 1970.

[5] Jones, R. A. and Hunt, J. L., "Use of Fusible Temperature Indicators for Obtaining Quantitative Aerodynamic Heat-Transfer Data," TR R-230, Feb. 1966, NASA.

[6] Bertram, M. H., "Hypersonic Laminar Viscous Interaction Effects on the Aerodynamics of Two-Dimensional Wedge and Triangular Planform Wings," TN D-3523, Aug. 1966, NASA.

[7] Bertram, M. H. and Feller, W. V., "A Simple Method for Determining Heat Transfer, Skin Friction, and Boundary-Layer Thickness for Hypersonic Laminar Boundary-Layer Flows in a Pressure Gradient," Memo 5-24-59L, June 1959, NASA.

A Correlation of the Minimum Thermal Resistance at Soldered Joints

M. Michael Yovanovich*
University of Waterloo, Waterloo, Ontario, Canada

In an earlier Note[1] this author reported that thermal resistances for soldered joints ranged from 0.025°C-cm²/w for the best joint (brass/brass) to 0.14°C-cm²/w for a badly soldered joint. These values considerably exceed the theoretical value of 0.00246°C-cm²/w calculated for an average solder thickness of 15 μ. All the tests were performed with identical surfaces. Correlation of all of these data is very difficult because of the many parameters, both geometric and physical, that play a part in the resistance. This Note reports the results of a preliminary analysis and further experimental work done to obtain a correlation.

Thermal Analysis

It is assumed that the best soldered joints can be modeled as shown in Fig. 1. The solder (k_2) of average thickness e separates two solids (k_1,k_3) and is assumed to be homogeneous, devoid of gas cavities and scale. There is metal-to-metal contact between the solder and the solids at every point of the

Received April 24, 1970. This work was supported by Canadian National Research Council Grant A7445.

* Associate Professor of Mechanical Engineering. Member AIAA.

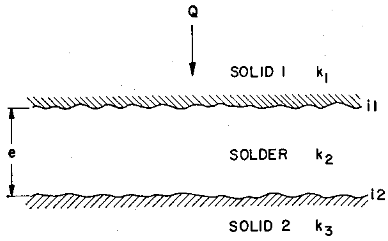

Fig. 1 Soldered joints.

two interfaces $i1$ and $i2$. The surfaces of two solids are nominally flat but rough and the thickness of the solder is much larger than the surface roughness.

The temperature fields far from the interfaces are unidirectional, parallel to the planes of the interfaces. In the vicinities of the interfaces and within the solder the temperature field is no longer unidirectional because of the waviness of the interfaces and the discontinuity of the thermal conductivity across the interfaces. The net result of this nonuniformity of temperature field is a measurable temperature drop ΔT_j at the joint. The thermal resistance at the joint is defined as $R_j = \Delta T_j/(Q/A)$ and can be written as $R_j = R_{i1} + R_{i2}$ where R_{i1} and R_{i2} are the interface resistances.

The thermal resistance at interface $i1$ is $R_{i1} = \psi_{i1}/k_{i1}$, where $k_{i1} = 2k_1k_2/(k_1 + k_2)$. The parameter ψ_{i1}, based upon current thermal constriction theory,[2-4] has the dimension cm and consists of a dimensionless geometric parameter and some characteristic dimension of the interface such as the surface roughness and the number of elemental heat flow channels available for heat conduction across the interface. The parameter ψ is assumed to be independent of thermal properties of the joint as well as the local heat flux. It will depend upon the surface roughness. The thermal resistance at the other interface can similarly be written as $R_{i2} = \psi_{i2}/k_{i2}$ where $k_{i2} = 2k_2k_3/(k_2 + k_3)$.

The total or joint resistance being the sum of the two interface resistances can be written as $R_j = \psi_{i1}/k_{i1} + \psi_{i2}/k_{i2}$. For identical surface conditions $\psi_{i1} = \psi_{i2}$ and so the joint resistance reduces to $R_j = \psi_i/K_j$ where $K_j = 2/(1/k_1 + 2/k_2 + 1/k_3)$. Here K_j is the effective thermal conductivity of a soldered joint consisting of three different materials having thermal conductivities k_1, k_2 and k_3, respectively.

Experimental Verification of the Theory

A series of tests was performed to verify the results of the thermal analysis. These tests consisted of temperature measurements in brass (k_1 = 1.11 w/cm-°C) and stainless steel (k_3 = 0.162 w/cm-°C) soldered with pure tin (k_2 = 0.64 w/cm-°C). The procedure followed is fully described in Ref. 1.

The first tests using brass/brass joints (K = 0.405 w/cm-°C) yielded a minimum resistance of 0.0245°C-cm²/w. The brass/stainless steel joints (K = 0.198 w/cm-°C) yielded a minimum resistance of 0.052°C-cm²/w and the stainless/stainless steel joints (K = 0.131 w/cm-°C) yielded a minimum resistance of 0.0805°C-cm²/w.

From these series of tests the parameter $\psi_i = [\Delta T_j/(Q/A)]K_j$ is calculated to have the values 0.0099, 0.0103, and 0.0109 for the three types of joints investigated. These values of ψ_i represent the average for ten sets of measurements obtained for each of the brass/brass, brass/stainless, and stainless/stainless joints. There was no observable variation of joint resistance with contact pressure.

Conclusions

The excellent agreement between the values of ψ_i obtained for the three types of soldered joints is a verification of the validity of the assumptions used. In these experiments the thermal conductivities differed by a factor of seven while the values of the effective thermal conductivity of the joints differed by a factor of three. One can conclude that the thermal resistance of a soldered joint can be correlated by means of the parameter ψ_i provided that the solder is homogeneous devoid of cavities and scale, and that $\psi_i = 0.010$ when the surface roughness is about 0.3 μ.

References

[1] Yovanovich, M. M. and Tuarze, M., "Experimental Evidence of Thermal Resistance at Soldered Joints," *Journal of Spacecraft and Rockets*, Vol. 6, No. 7, July 1969, pp. 855–857.

[2] Yovanovich, M. M., "Overall Constriction Resistance Between Contacting Rough, Wavy Surfaces," *International Journal of Heat and Mass Transfer*, Vol. 12, 1969, pp. 1517–1520.

[3] Mikic, B. B., "On Mechanism of Dropwise Condensation," *International Journal of Heat and Mass Transfer*, Vol. 12, 1969, pp. 1311–1324.

[4] Cooper, M. G., Mikic, B. B., and Yovanovich, M. M., "Thermal Contact Conductance," *International Journal of Heat and Mass Transfer*, Vol. 12, 1969, pp. 279–300.

Incipient Cross-Stream Liquid Jet Atomization at High Altitude and Velocity

Paul B. Gooderum* and Dennis M. Bushnell†
NASA Langley Research Center, Hampton, Va.

Nomenclature

D_o = orifice diameter
Kn = Knudsen number, $M(\gamma\pi/2)^{1/2}/Re$
M = Mach number, $(Vg^2 + V_l^2)^{1/2}/a$
Re = Reynolds number, $\rho(Vg^2 + V_l^2)^{1/2}D_o/\mu$
Vg = gas velocity
V_l = liquid velocity at the orifice
We = Weber number, $\rho(Vg^2 + V_l^2)D_o/2\sigma$
μ = coefficient of viscosity
ρ = density, gas stream
σ = surface tension, liquid

A FLIGHT research project has been conducted to measure the effects of a liquid spray on the electron and ion concentrations in the flow field over the antenna of a reentering vehicle.[1] In the analysis of these results it is of fundamental importance to know whether or not the liquid jets were broken up into the required spray.[2] Secondly, if breakup did occur, subsequent analyses of the flight data require knowledge of which of the basic breakup mechanisms (aerodynamic, vapor pressure, or capillary instability) was the dominant cause. The present investigation originated because of this need to define the boundaries of aerodynamic breakup.

An unbroken liquid stream exiting an orifice into a gaseous cross flow will be atomized if the cross-flow dynamic pressure is greater than a certain critical value[3,4] (assuming that the ambient pressure is such that vapor pressure or "flashing" breakup effects can be ignored). At dynamic pressures below this critical value, capillary instabilities[5] cause the jet to separate into drops which are then swept downstream with no further shatter. For purely aerodynamic breakup, there is ample theoretical and experimental evidence, mostly for drops, to indicate that the Weber number, which is the ratio of the dynamic pressure of the gas to the surface tension of the liquid, is useful as a correlating parameter.[6] However, before applying the available critical Weber number information to high altitude flight conditions, it is necessary to assess the applicability of data obtained at low speed, low Knudsen

Received March 6, 1970; revision received May 7, 1970.
*Aerospace Engineer, Aero-Physics Division. Member AIAA.
† Head, Flow Analysis Section, Aero-Physics Division.