installation errors greater than 0.0005 in. seem unlikely, and the average error in measured force noted for this misalignment was less than 2%. The accuracy of the test equipment is thought to be of secondary importance, since the linear approximation of the results is dependent upon relative changes rather than absolute measurements. Since the test data are referenced to the flush position and the corresponding balance output, a minor error in either of these reference values would result only in a shifting of the linear relation, without modifying the slope appreciably. The good repeatability of the data is indicative of the quality of the relative measurements and thus of the over-all conclusions.

A comparison of the data obtained in this investigation with previous misalignment studies indicates general agreement. The tests of Shutts, Hartwig, and Weiler[4] were conducted in a continuous-flow supersonic tunnel with flow conditions similar to those of the present investigation. They found that lowering the floating element 0.001 in. reduced the balance output by 3.1%, a result that compares favorably with data obtained herein. They were not, however, able to make measurements with a projecting disk. Smith and Walker[3] made studies under subsonic flow conditions using a null-type balance. They found that: "the surface of the floating element could be depressed as much as 0.005 in. without any change in the surface shear. However, when the element protruded above the surface of the wall, there were noticeable deviations in the measured shear force." They also stated that the accuracy of the skin-friction balance used was believed to be ±2%. Since the present study indicates that the average error for a depression of 0.0005 in. is 2%, it is reasonable to suppose that Smith and Walker would not attempt to distinguish between measurements that fell within the expected accuracy of their instrumentation.

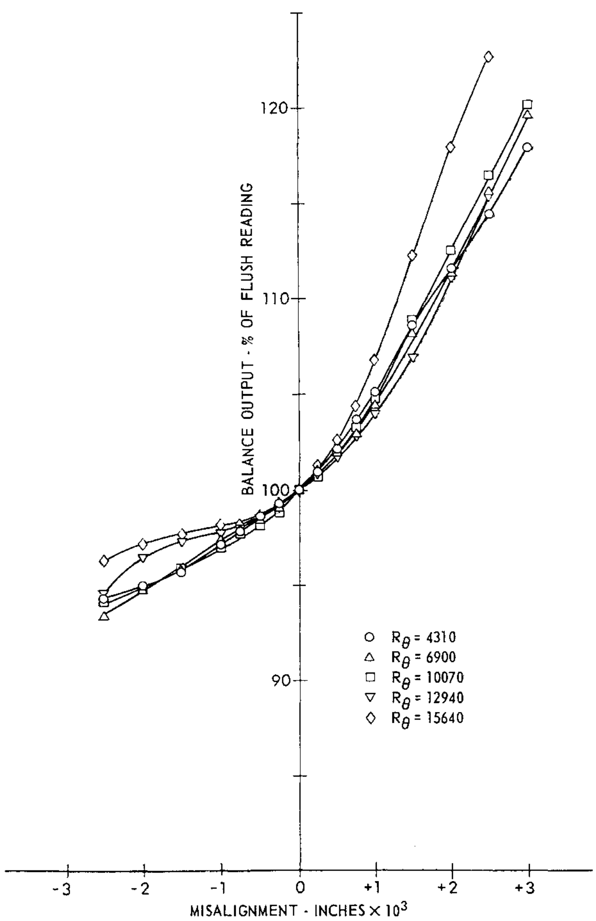

Fig. 4 Effect of misalignment for several Reynolds numbers at $M = 2.67$.

It should also be noted that both of the previous investigations discussed in this study were of the nature of minor digressions from other studies. Neither one utilized a traversing mechanism for the skin-friction balance, and it would seem likely that the data suffered from the scatter expected when an attempt is made to exactly repeat operating conditions from run to run.

References

[1] Coles, D., "Measurements in the boundary layer on a smooth flat plate in supersonic flow. II. Instrumentation and experimental techniques at the Jet Propulsion Laboratory," Jet Propulsion Lab. Rept. 20-70 (1953).

[2] Dhawan, S., "Direct measurements of skin friction," NASA TN 2567 (1952).

[3] Smith, D. W. and Walker, J. H. "Skin friction measurements in incompressible flow," NASA TR R-26 (1959).

[4] Shutts, W. E., Hartwig, W. H., and Weiler, J. E., "Turbulent boundary layer and skin friction measurements on a smooth, thermally insulated flat plate at supersonic speeds," Defense Research Lab. Rept. DRL-364, CM-823 (1952).

Some Recent Data on Stagnation-Point Convective Heat Transfer in Partially Ionized Air

DALE L. COMPTON* AND DAVID M. COOPER†
NASA Ames Research Center, Moffett Field, Calif.

Nomenclature

$\dot{q}$ = stagnation-point heating rate, Btu/ft²-sec
r = nose radius, ft
p_{st} = stagnation pressure, atm
h_{st} = stagnation enthalpy, Btu/lb
h_w = wall enthalpy, Btu/lb
V_∞ = freestream velocity, fps

SEVERAL investigators[1–4] have presented data on convective heating in partially ionized air, and it is now generally agreed that, for conditions studied experimentally to date, ionization does not have a gross effect on convective heating. However, at least one experimental discrepancy still exists. Shock-tube measurements of heat transfer to nickel gages have been reported to be as much as a factor of 2 greater than similar measurements to platinum gages, both for air and for N_2-CO_2-A mixtures.[5] Other measurements (in N_2-CO_2-A) do not show this difference.[5] It is the purpose of the present work to use an independent experimental technique[6] to investigate the heat transfer from air to nickel-surfaced gages.

The experimental technique uses the time of onset of melting on small 7075-T6 aluminum models as a measure of the stagnation-point heating rate. A sabot-held $\frac{1}{4}$-in.-diam. aluminum hemisphere is gun-launched at high velocity into either still air or an oncoming airstream in the Ames Prototype Hypervelocity Free-Flight Facility. In this facility there are 11 spark shadowgraph stations, 4 ft apart on center, beginning 15 ft from the gun muzzle. Aerodynamic heating raises the temperature of the model, and, if heating is sustained, the surface of the model will at some time begin to melt. Melting occurs first in the model's stagnation region, where the heating rate is highest. Since the viscosity of molten aluminum is low, aluminum flows off the model surface and

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* Research Scientist, Vehicle Environment Division. Member AIAA.
† Research Scientist, Vehicle Environment Division.

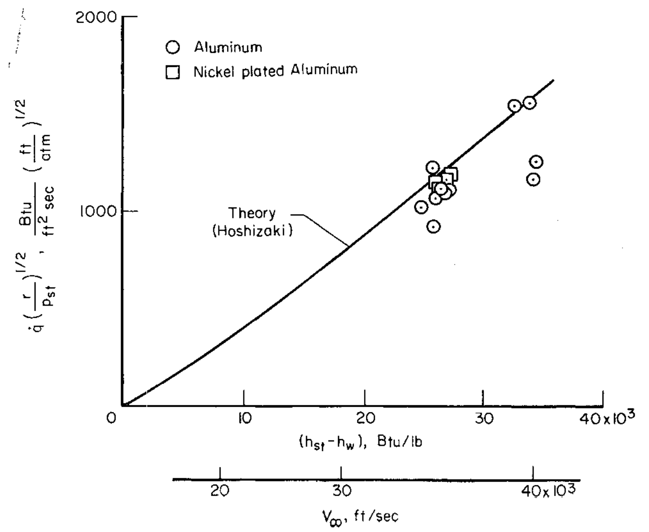

Fig. 1 Convective heating data.

into the wake where it produces a partially opaque screen visible on spark shadowgraphs. If the freestream density is adjusted correctly, melting can be made to begin during the portion of the model flight through the instrumented test section, and the time at which melting first occurs can be determined by studying successive shadowgraphs. From the melting-onset time the stagnation-point heating rate can be computed by solving the heat-conduction equation for the model interior. Although this technique is substantially different from the shock-tube technique, the stagnation conditions are nearly the same as those on stationary models in shock tubes at comparable enthalpy levels.

In order to study the effect of gage material, the surfaces of the aluminum models were nickel-electroplated. The thickness of the nickel coating was 0.0005 in., thick enough to assure a coherent nickel surface and thin enough so that, for purposes of solving the heat-conduction equation for the model interior, the nickel coat could be neglected. This was established from a solution of the heat-conduction equation for the composite model (assuming zero contact resistance between the nickel and aluminum), which showed that, over the flight trajectory, 97% of the heat transferred to the nickel surface reached the aluminum substrate. Thus, with respect to convective heat transfer, the model had the surface properties of nickel, and, with respect to conduction within the model, it had primarily the bulk properties of aluminum. Therefore, the convective heating-rate data from the present tests do not depend on the exact numerical values of density, specific heat, or temperature coefficient of resistivity for nickel.

Calibration tests of the nickel-plated aluminum models were performed in the same manner as for the uncoated aluminum models.[6] To wit, models were launched at a velocity at which ionization is negligible, 24,000 fps, and the time of melting onset was measured. Compared with the uncoated aluminum models, the nickel-plated models took a measurably longer time before melting was observed. This was partly because, as just described, the nickel shell absorbed a finite amount of heat, and partly because the shell had not reached melting temperature at the time when the aluminum substrate began to melt and apparently was not sluffed away immediately. The correction (applied to all data) for this effect, in terms of heating rate, was approximately 7% and should be nearly independent of test velocity since the heating rates at all test velocities were similar.

The results for the nickel-plated models at higher velocities are shown on Fig. 1 and are compared with similar data.[6] It is clear that, at a velocity of 36,000 fps, the heating rates are the same for both the aluminum and nickel-plated aluminum models. Furthermore, these heating rates are at the same general level as those measured with platinum gages[1-3] and platinum, nickel, and gold gages[5] and therefore, support the evidence that nickel gages do not lead to higher heating rates. Some additional data taken with aluminum models at a velocity of 41,000 fps are also shown on Fig. 1. All of these data agree reasonably well with the theory of Hoshizaki.[3]

References

[1] Gruszczynski, J. S. and Warren, W. R., Jr., "Experimental heat transfer studies of hypervelocity flight in planetary atmospheres," AIAA Paper 63-450 (1963).

[2] Rose, P. H. and Stankevics, J. O., "Stagnation point heat transfer measurements in partially ionized air," AIAA J. **1**, 2752–2763 (1963).

[3] Hoshizaki, H., "Heat transfer in planetary atmospheres at supersatellite speeds," ARS J. **32**, 1544–1551 (1962).

[4] Nerem, R. M., "Measurements of aerodynamic and radiative heating at super-orbital velocities," Ohio State Univ. Research Foundation Rept. 1598-1 (1964).

[5] Collins, D. J. and Spiegel, J. M., "Effect of gage material on convective heat transfer," AIAA J. **2**, 777–778 (1964).

[6] Compton, D. L. and Chapman, G. T., "Two new free-flight methods for obtaining convective-heat-transfer data," *AIAA Aerodynamic Testing Conference* (American Institute of Aeronautics and Astronautics, New York, 1964), pp. 115–128.

Aligned Magnetic Field Problem

S. Leibovich* and G. S. S. Ludford†
Cornell University, Ithaca, N. Y.

In a recent paper,[1] we considered the hydromagnetic flow engendered by a thin nonconducting airfoil set impulsively into motion in the direction of an applied magnetic field. The nonuniqueness in the steady problem was resolved by tracing the transient motion to its limit as time became infinite. The airfoil was assumed to be symmetric and the liquid perfectly conducting; only the slow-flow approximation was considered.

Figure 1 is a sketch of the magnetic field for Alfvén number $m = \frac{1}{3}$ according to this theory, which of course strictly applies for vanishingly small Alfvén numbers. Just enough magnetic lines are drawn into the airfoil from outside the current sheets to balance the flux across its surface. The main result is that finally the fluid between the two current sheets (thick lines) moves with the airfoil as if solid (slug flow), whereas outside the flow is undisturbed.

Since there are no magnetic sources inside the airfoil, there is no net magnetic force on it. On the other hand, continuity of total pressure requires a jump in dynamic pressure across the current sheets so that there is a pressure excess $\frac{1}{2}\mu[1 - (1 - m)^2]H_0{}^2$ at the front of the airfoil and a deficiency $\frac{1}{2}\mu[(1 + m)^2 - 1]H_0{}^2$ at the rear. These produce a drag

$$\tfrac{1}{2}\mu[(1 + m)^2 - (1 - m)^2]H_0{}^2\cdot 2t = 4m\mu\, H_0{}^2t$$

so that the drag coefficient, based on freestream dynamic pressure and chord, is $8\tau/m$, where τ is the thickness ratio.

Recently we were able to remove the restriction to slow flow and now have results for arbitrary sub-Alfvénic flow. The magnetic field is sketched in Fig. 2, which has two interesting aspects. First, the slow-flow figure is a remarkable approximation even for an Alfvén number as large as $\frac{1}{3}$. The influence of convection is to replace the singularities at the top and bottom of the profile by smooth current sheets;

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* Research Assistant, Department of Theoretical and Applied Mechanics. Student Member AIAA.

† Professor of Applied Mathematics, Department of Theoretical and Applied Mechanics. Member AIAA.