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SUBSONIC AERODYNAMIC HEAT TRANSFER TO A SURFACE RECESSED WITHIN A FORWARD STAGNATION REGION SLIT

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SUMMARY

A flat-faced cylindrical model was tested in a high-temperature, subsonic arc jet to investigate the heat transfer to a surface recessed within a slit in the forward face of the model. Heat-transfer measurements were made for various recession depths and varying amounts of air injected over the recessed surface. Injected air was allowed to exit through the surface slit into the test stream. Heat-transfer rates measured on the model face and the recessed surface were compared to indicate effects of recession depth and flow rate of injected air. Large reductions in heat-transfer rates to the recessed surface were indicated and are presented as functions of recessed depth and rate of airflow.

INTRODUCTION

Many theoretical and experimental investigations have been conducted to assess the radiative and convective heat transfer to bodies traveling at hypersonic speeds through an atmosphere. (For example, see refs. 1 to 4.) Actual flight measurements of the radiative heat transfer during hyperbolic reentry are desirable to substantiate theoretical estimates. Instrumentation for radiation measurements may require an optical "window" set in the forward face of the reentering body. However, available window materials transparent to radiation are unable to withstand the reentry heating environment unless convective heat transfer can be reduced locally at the window.

To explore the possibility of reducing heat transfer to a small portion of the leading surface of a vehicle, an experimental investigation was conducted in a 2500-kilowatt arc jet using a flat-faced cylindrical test model. The model was designed to allow recession of a portion of the leading surface and injection of air over the recessed surface. Heat-transfer rates were measured on the model face and the recessed surface and compared to indicate the effects of recession depth and flow rate of injected air on heat transfer to the recessed surface.

SYMBOLS

c_p	specific heat of wall material, Btu/lb-$^{\circ}$R
$\dot{q}$	heat-transfer rate, Btu/ft^2-sec
$\dot{Q}$	ratio of heat-transfer rates
r	corner radius of model face, in.
R	radius of model, in.
t	time, sec
T	temperature, $^{\circ}$R
dT/dt	temperature rise rate, $^{\circ}$R/sec
$\dot{w}$	rate of airflow through surface slit, lb/sec
x	distance along face of body from axis of symmetry, in.
y	recession depth, in.
ρ	density of wall material, lb/cu in.
τ	wall thickness at thermocouple location, in.

Subscripts:

o	recessed surface of model
s	leading surface of model

APPARATUS AND MODELS

The 2500-kilowatt arc jet facility of the Langley Research Center described in reference 5 is a three-phase a-c powered jet constructed of water-cooled copper. (See fig. 1.) The magnetic-field coils provide a 1500-gauss field at the concentric ring electrodes to rotate the arcs at approximately 360 revolutions per second. Air is supplied at the base of each small ring electrode and permitted to flow through the annular space in which the arc rotates. The air is heated by the arcs and exits to the atmosphere through a 4-inch-diameter nozzle. The model was inserted 2 inches downstream of the nozzle exit by rotating the support sting from a position outside the test stream to the axial stream position with hydraulic mechanisms. Stream conditions at the model location were: static temperature, approximately 7,000° R; atmospheric static pressure; dynamic pressure, 40 pounds per square foot; and a Mach number of 0.18.

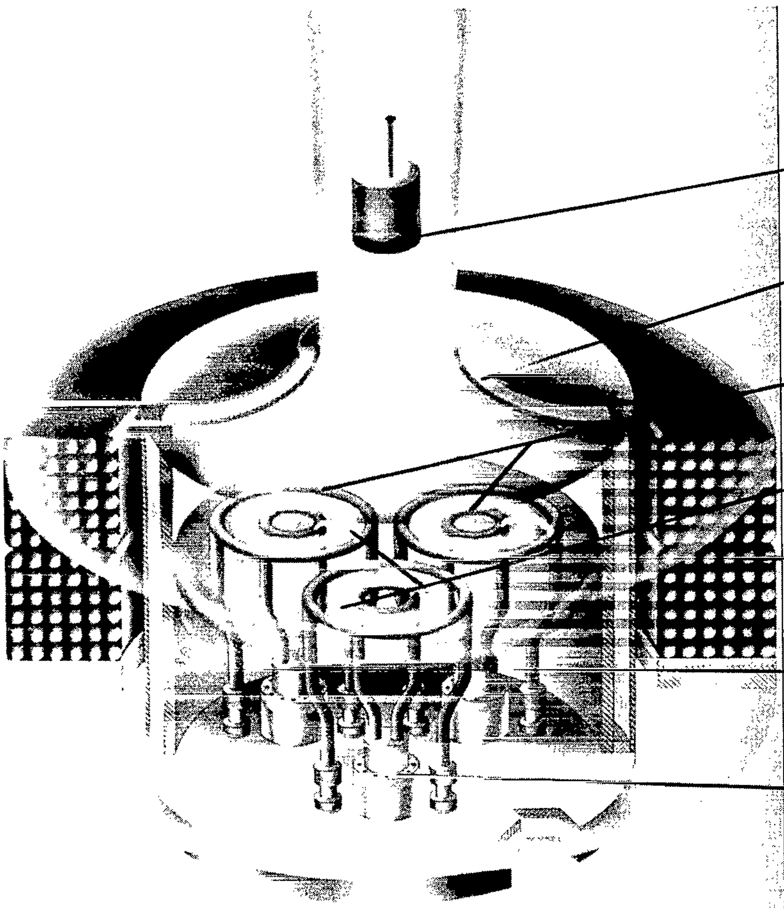

Figure 1.- 2500-kilowatt arc jet. L-62-99.1

A 3-inch-diameter cylindrical flat-faced model constructed of 0.030-inch-thick Inconel with a ratio of corner radius to body radius r/R of 0.100 was used for tests. A photograph of the test model and components is shown in figure 2. Figure 3 presents an assembly and detail schematic of the test configuration. A slit, 0.010 inch by 0.500 inch, was cut across the stagnation region of the leading face. A surface 0.030 inch thick, 0.020 inch wide, and 0.500 inch long was instrumented with one thermocouple on the rear surface, alined with the slit, and recessed at various depths behind the model face. Four thermocouples were spot welded to the inside face of the model as illustrated in figure 3. Stainless-steel tubing, 0.010-inch inside diameter, was fitted in a groove cut in the ceramic insulating block and Inconel support block and permitted injection of air normal to the recessed surface length. (See figs. 2 and 3.) The Inconel support block, the ceramic insulating block, and the recessible surface were designed to provide a press fit with each other.

The amount of airflow through the steel tubing was controlled and measured by a flowmeter. A Bourdon-tube gage was used to measure the line pressure at the exit point of the flowmeter. Thermocouple outputs and calibration deflections were recorded by an oscillograph.

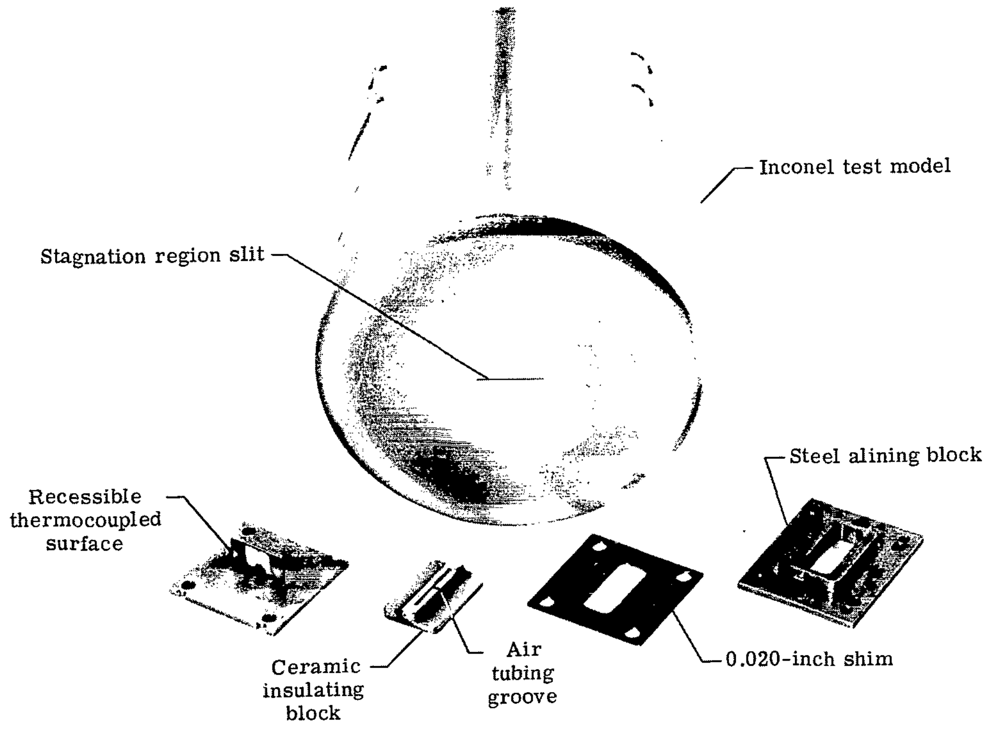

Figure 2.- Model and components. L-63-1658.1

TEST PROCEDURES

All experiments were conducted at stream conditions previously described with a test duration of 1 to 3 seconds. Steady flow properties were established in the stream before inserting the model to avoid the effects of transient starting conditions. Insertion was accomplished in less than 1/10 of a second. Prior to each test the depth of the recessed surface was set at a value of 0.020 inch, 0.040 inch, 0.060 inch, or 0.080 inch below the leading face of the model by inserting 0.020-inch shims between the steel alining block and the recessed surface support. The airflow rate was preset at values ranging from 0 to approximately 0.00035 pound per second and was found to remain constant when monitored throughout a test run. At least three tests for each combination of variables were made to determine repeatability. At the end of each test the model was allowed to cool to room temperature before further experiments were conducted.

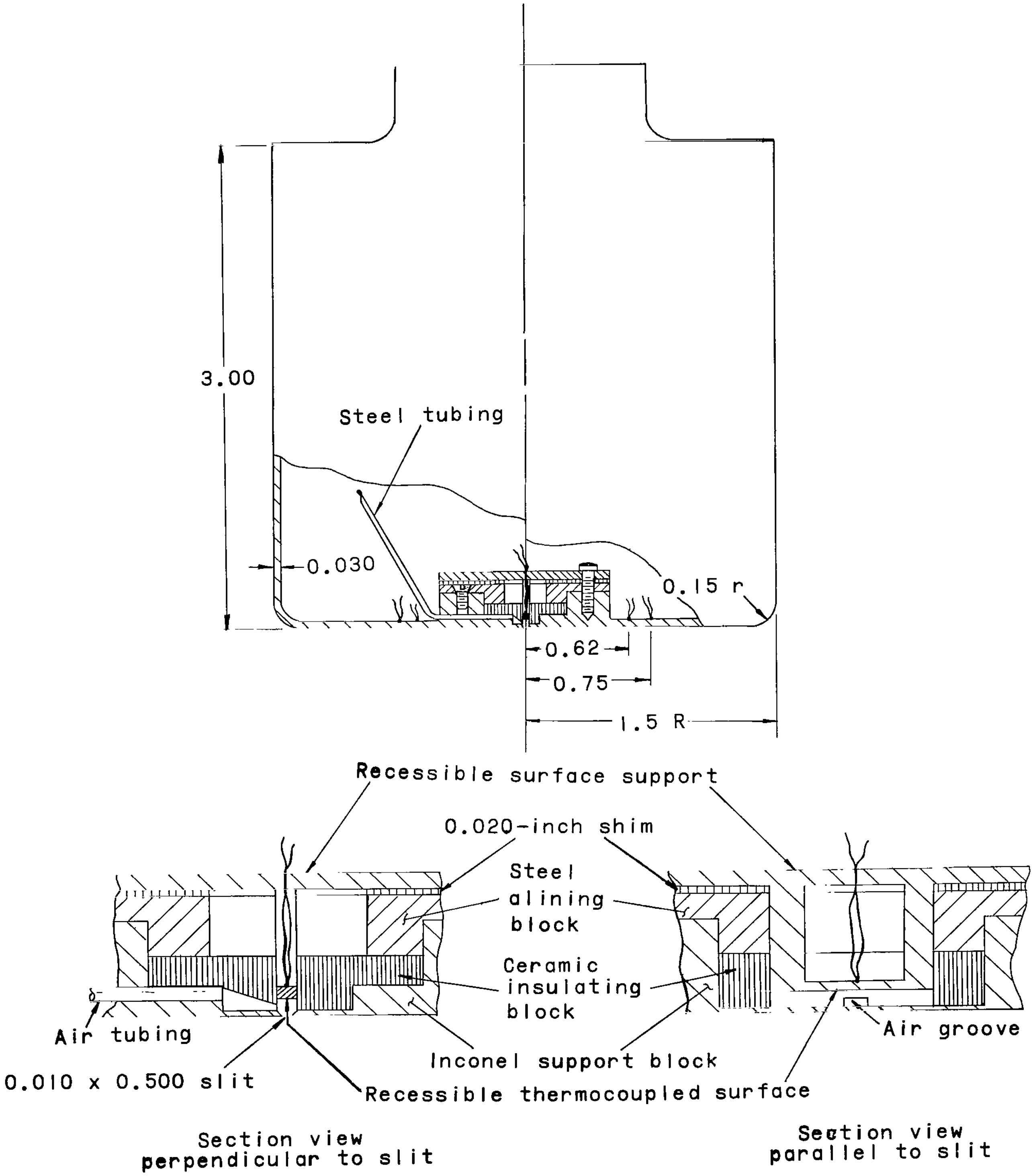

Figure 3.- Assembly and detail of test configuration. All dimensions are in inches.

DATA REDUCTION

The aerodynamic heat transfer to the model was calculated from the equation

$$\dot{q} = C_p \tau \rho \frac{dT}{dt}$$

where the specific heat is given as 0.11 Btu/lb/°F and the density is 0.300 lb/cu in. For the 0.030-inch-thick model surface and recessible surface, the equation reduces to

$$\dot{q} = 0.143 \frac{dT}{dt}$$

The slopes of the temperature-time traces dT/dt were measured for the initial-temperature-rise portion of the oscillogram for each run.

Heat-transfer rates calculated for the model face and the recessed surface were compared by means of the ratio

$$\frac{\dot{q}_o}{\dot{q}_s} = \dot{Q}$$

to indicate the effects of airflow rate and recession depth on recessed-surface heat-transfer rates.

For all tests the heat-transfer rates measured at the model face varied no more than 5 percent from a value of 85 Btu/sq ft/sec. Consequently, a mean constant value of 85 Btu/sq ft/sec for $\dot{q}_s$ was used in all calculations of the ratio $\dot{Q}$.

RESULTS AND DISCUSSION

The ratio of recessed-surface and leading-face heat-transfer rates $\dot{Q}$ is presented in figure 4 as a function of airflow rates for various recession depths. The data indicate reasonably good repeatability for approximately similar airflow rates and test-stream conditions. Some scatter can be noted at relatively low flow rates and small recession depths. A composite replot of the curves given in figure 4 is presented in figure 5 to facilitate comparison of data at the various recession depths. In general, heat transfer to the recessed surface decreased as the airflow was increased for each recession depth. With no airflow, the heat transfer to the recessed surface decreased with increased recession depth from 0.020 inch to 0.060 inch, and then increased with further recession to 0.080 inch. With airflow, recessed surface heat-transfer rates did not always decrease for larger recession depths. These apparent inconsistencies may be peculiar to this

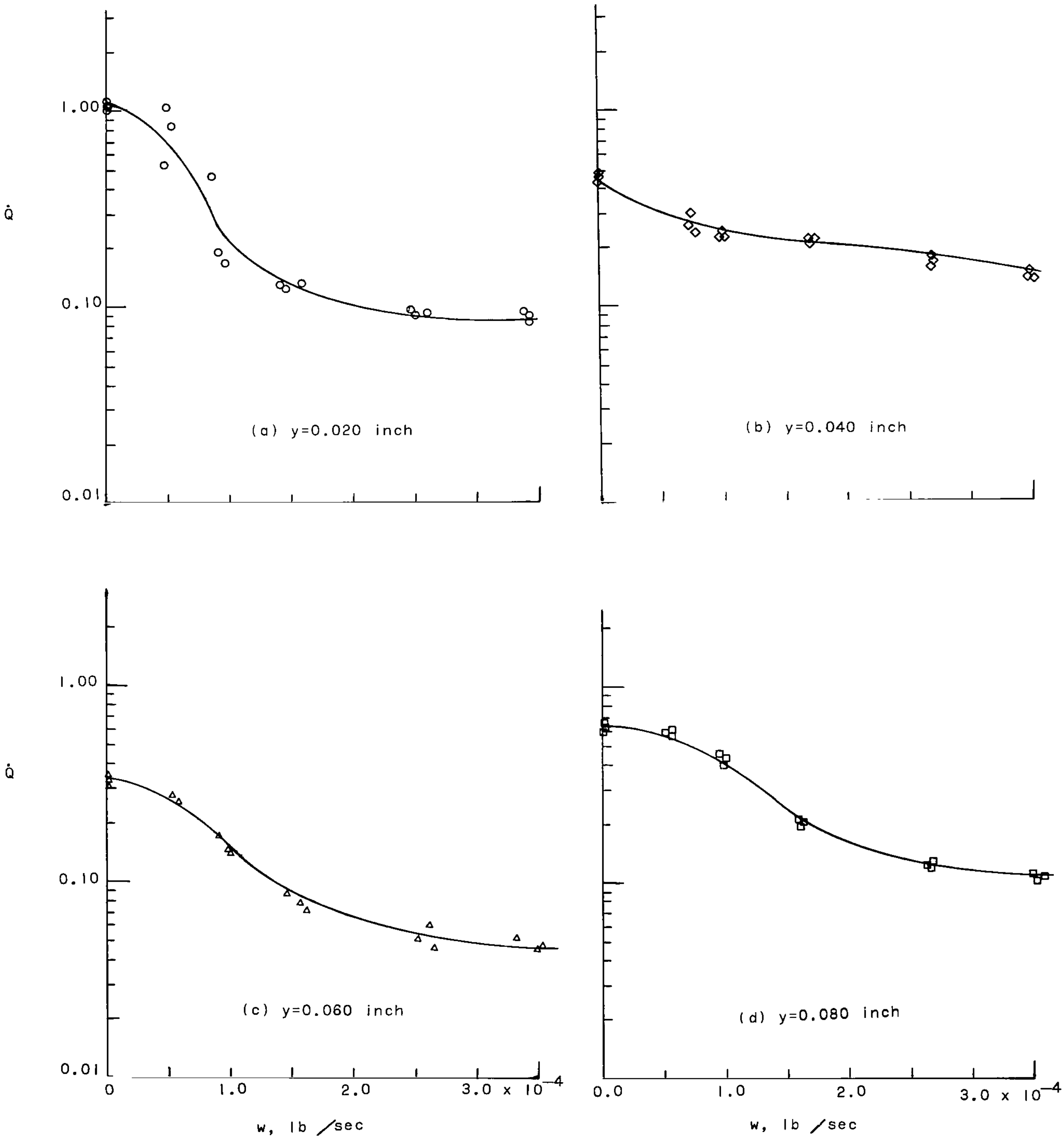

Figure 4.- Heat-transfer ratio plotted against airflow for various recession depths.

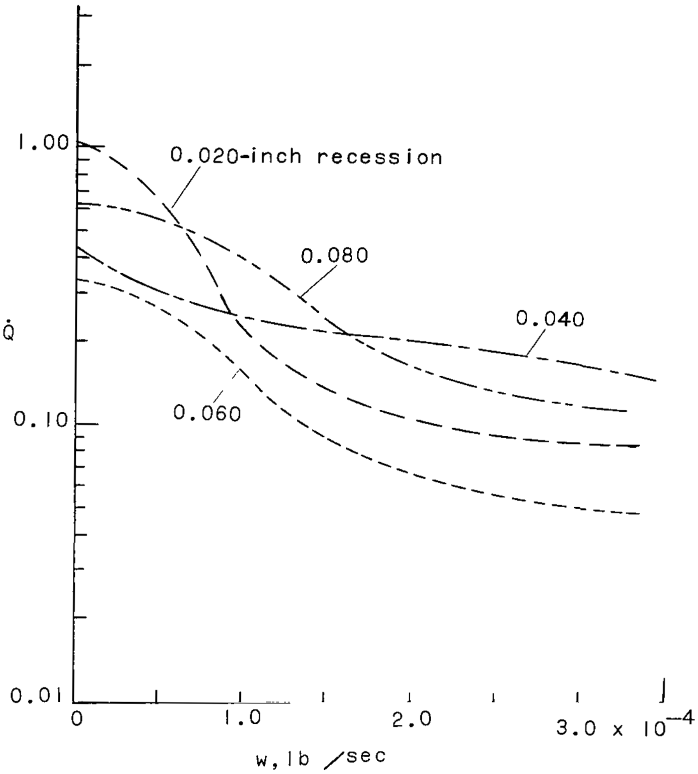

Figure 5.- Comparison of heat-transfer rate ratio for various recession depths.

particular configuration but were not investigated further since the only requisite for tests presented herein was reduction in heat-transfer rates. A recession depth of 0.060 inch gave comparatively lower recessed-surface heat-transfer rates at all airflow rates.

The three-dimensional conduction effects on the measured heat-transfer rates to the recessed surface were considered negligible. The small thickness-length ratio of the recessible surface in the slitwise direction and the low thermal conductivity of the ceramic insulating block minimized conduction errors and provided essentially one-dimensional heat conduction. Additionally, the press fit design of the recessible surface, ceramic insulator, and Inconel support block prevented convective air and heat losses from the recessed-surface cavity to the model cavity. No effects of the heat-sink characteristics of the Inconel support block were evident in the measured model-surface heat-transfer rates. Thermocouple measurements taken in an x/R range of 0.40 to 0.50 were considered representative of stagnation-point values in the absence of the slit and recessed surface. For 3-inch-diameter flat-faced cylindrical bodies in a subsonic stream, heat-transfer rates measured in this range of x/R indicate only slight deviations from stagnation-point heat-transfer rates. (See ref. 6.) Thus, the ratio $\dot{Q}$ is considered a conservative and reliable indication of reduction in heat-transfer rate due to recessed depth and airflow rates.

Heat transfer to the model and recessed surface due to radiation from the hot gases and arcs was evidently less than 5 percent of the total. Figure 4 indicates that the lowest recessed-surface heat-transfer rate measured was approximately 5 percent of the stagnation value. Thorough investigation of radiant heat transfer was neglected because of its apparently small contribution and the difficulties involved in assessing related factors such as surface emissivities of the model and recessed surface and the effects of electrode material contamination on the emissivity of the test stream. Hot test-stream gases attempting to enter the slit were partially blocked by the exiting airflow. This condition accounted for most of the heat-transfer-rate reduction as evidenced in the experimental data.

The combination of recession depth and airflow rate showed substantial reductions in heat-transfer rates. Heat-transfer rates to recessed surfaces were less than 10 percent of the stagnation value for particular combinations.

CONCLUDING REMARKS

Heat-transfer rates were measured on a surface recessed within a slit in the forward face of a 3-inch-diameter cylindrical flat-faced model exposed to a high-temperature subsonic test stream. Comparison with the model-face heat-transfer rates indicated reductions in heat-transfer rates to the recessed surface which were dependent on the recessed depth and amount of air injected over the surface. The variation with recession depth of heat-transfer rates to the recessed surface showed conflicting trends at different airflow rates. Heat transfer to the recessed surface generally decreased with increased airflow at all recession depths. In some instances, the heat transfer to the recessed surface was reduced to less than 10 percent of the model forward stagnation value.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 28, 1963.

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