

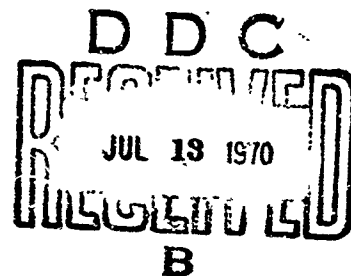
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Effect of Roughness on Heating at the Forward Surface of a Sphere at Mach 5

Prepared by R. L. VARWIG
Aerodynamics and Propulsion Research Laboratory

70 APR 15

Laboratory Operations
THE AEROSPACE CORPORATION



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AIR FORCE SYSTEMS COMMAND
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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-69-C-0066.

This report, which documents research carried out from January 1969 through September 1969, was submitted on 20 May 1970 to 1st Lt Edward M. Williams, Jr., SMTAE, for review and approval.

Approved



W. R. Warren, Jr., Director
Aerodynamics and Propulsion
Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



EDWARD M. WILLIAMS, Jr., 1st Lt, USAF
Project Officer

ABSTRACT

Heat transfer rates to the forward surface of a 4-in. diameter sphere were measured at a flow of Mach 5 at Re_D from 1.3 to 2.9×10^6 . The sphere surface varied in roughness in terms of stagnation-point boundary-layer thicknesses from smooth to $12.5 \delta_s$ with the roughness dimension characterized by Nikuradse's equivalent sand roughness dimension. For the smooth wall, the boundary layer remained laminar over the Re_D range. Transition was obtained by the addition of roughness equal to δ_s , however, the resulting turbulent heating was lower than that predicted by an exact solution of the smooth-wall boundary-layer equations. When the roughness was changed to 2 to $3 \delta_s$, the peak heating reflected the predictions more closely.

In comparison with essentially steady wind-tunnel measurements at equivalent flow conditions, the present work yielded generally lower heat-transfer rates for similar roughness dimensions. It is proposed that the different character of the roughness as well as its magnitude could influence the measured heat-transfer rates.

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NOMENCLATURE

D	model diameter
d	roughness bead dimension
H	total enthalpy
K	Nikuradse's equivalent sand roughness
k	thermal conductivity
Nu	Nusselt number = $\left[9/(H_e - H_w) \right] c_p x / \mu$
Pr	Prandtl number = $c_p \mu / \alpha$
q	heat-transfer rate to the model wall
Re _D	$\rho_\infty u_\infty D / \mu_\infty$
Re _w	$\rho_w u_e x / \mu_w$
x	distance along model from stagnation point
δ	boundary-layer thickness
ρ	density
μ	viscosity
θ	angular distance from stagnation point

Subscripts

∞	free-stream conditions
e	edge condition
w	wall conditions
s	stagnation-point conditions
ls	calculated laminar stagnation-point conditions

I. INTRODUCTION

Surface roughness effects have been shown to be important in predicting heat transfer rates to bodies in high-Reynolds-number flows (Ref. 1). This roughness at high Reynolds numbers produces large increases in surface heat flux compared with smooth surfaces (Refs. 1 through 3). This increase in surface heat flux has recently become of interest in the prediction of ablation rates and shape changes of high-speed reentry vehicle nose tips (Ref. 3).

Much work has been done in this area for laminar boundary-layer flow, where it is well known that maximum heat flux occurs at the stagnation point of a sphere. Less information is available for the case of turbulent boundary layers, where at sufficiently high Reynolds numbers, the heat flux is expected to be maximum near the sonic point (Ref. 4). This report presents heat-transfer measurements made on the forward surface of a 4-in. diameter sphere with the wall roughness size ranging from zero to one order of magnitude greater than the stagnation-point boundary-layer thickness. It was expected that these measurements would provide a guide for predicting the heating effects of roughness on blunt-nose reentry shapes.

The measurements were made in a shock-tunnel facility at Mach 5 with the unit Reynolds number varying from 2.7 to $9 \times 10^6 \text{ ft}^{-1}$. The results are compared with the existing predictions of King¹ and Beckwith and Gallegher (Ref. 4) and also with some recently available measurements from Avco (Ref. 5). Differences in the results are discussed.

¹ W. S. King, The Aerospace Corporation, private communication (1970).

II. MODEL AND INSTRUMENTATION

Because of the short test time and relatively low heat rates expected in the test facility, thin platinum-film resistance thermometers were chosen as the heat sensing gages. These are mounted on insulating surfaces and sense the change in temperature with essentially no lag because their thermal capacity is small compared to the surface on which they are mounted. By use of analog networks (Ref. 6), temperature change is converted to heat-transfer rate at the model surface.

The most satisfactory measurements were obtained on models made from the bottom half of 4-in. diameter boiling flasks. The thin platinum films were mounted directly on the surface of these hemispheres at 5-deg intervals from the stagnation point to 60 deg. Hanovia liquid bright platinum paint was used to make the film as detailed by Vidal (Ref. 7). Holes were drilled through the wall of the glass hemisphere to provide passage for electrical leads. After the gages were installed and the leads connected, an aluminum adapter ring was cemented to the inside rim of the glass model and the interior of the model was filled with epoxy. Thus, a strong, solid sphere was formed (Fig. 1) that was capable of withstanding more than 10 atm stagnation pressure that was applied during the tests.

Walls were roughened by the application of tiny, smooth glass spheres cemented to the surface in a close-packed arrangement. Spheres were used making it possible to characterize the surface roughness according to Nikuradse's equivalent sand roughness criterion K (Ref. 8). A smooth wall and three degrees of roughness that were 1, 3, and 12 times the stagnation-point boundary-layer thickness δ_s were used. The roughness bead dimension d with K are shown in Table I along with the stagnation-point boundary-layer thickness ratio K/δ_s .

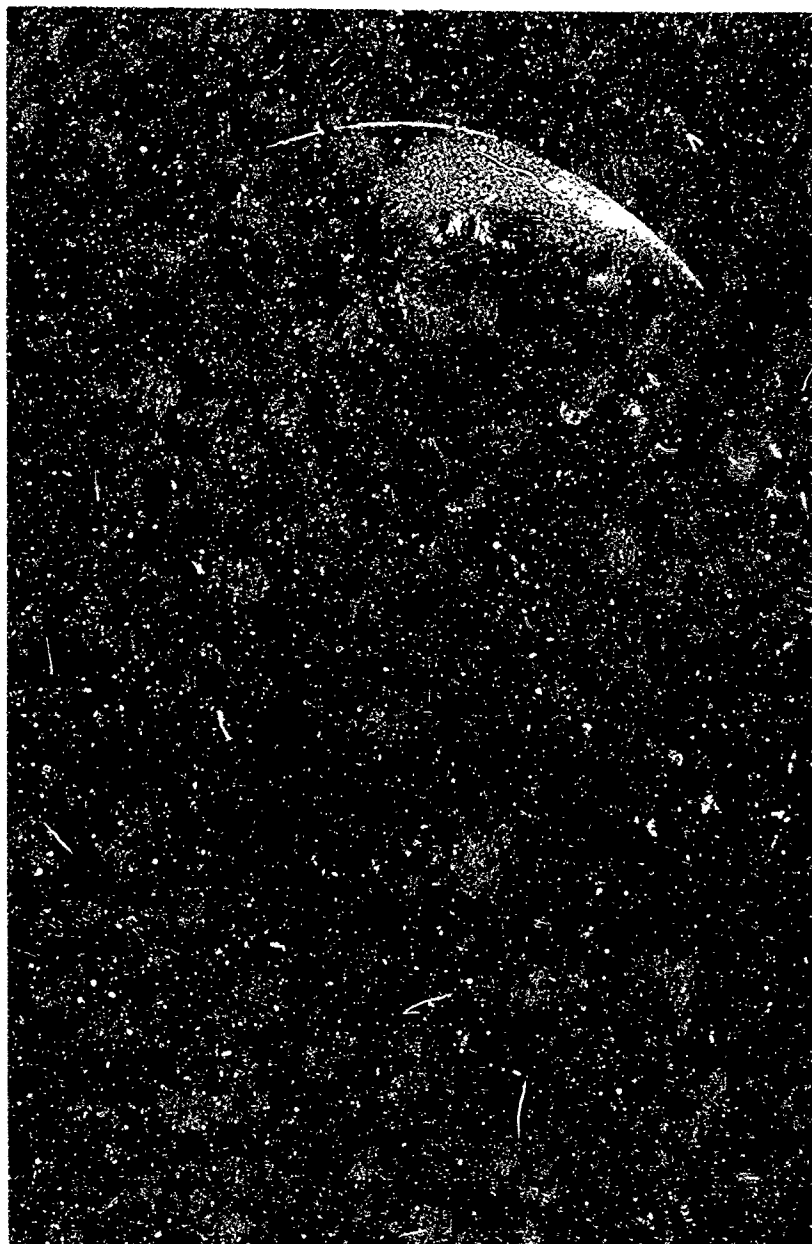


Fig. 1. Glass sphere model with 0.004-in. diameter beads covering surface

Table I. Wall Roughness Used in Tests

Wall	d, in.	K, in.	K/δ_s , in.
Smooth	0.0005	0.0003	0.1
Rough	0.004	0.0025	0.9 - 1.25
	0.010	0.0063	2.3 - 3.1
	0.040	0.025	9.0 - 12.5

The beads were most successfully applied with thinned glyptol enamel. When the enamel became tacky, the model was thrust into a container of the beads. Careful checking was required to make sure that only a single layer of beads covered the model and that no large gaps existed. In Fig. 2, a close-up of the roughness model surface for 0.004-in. diameter beads is shown.

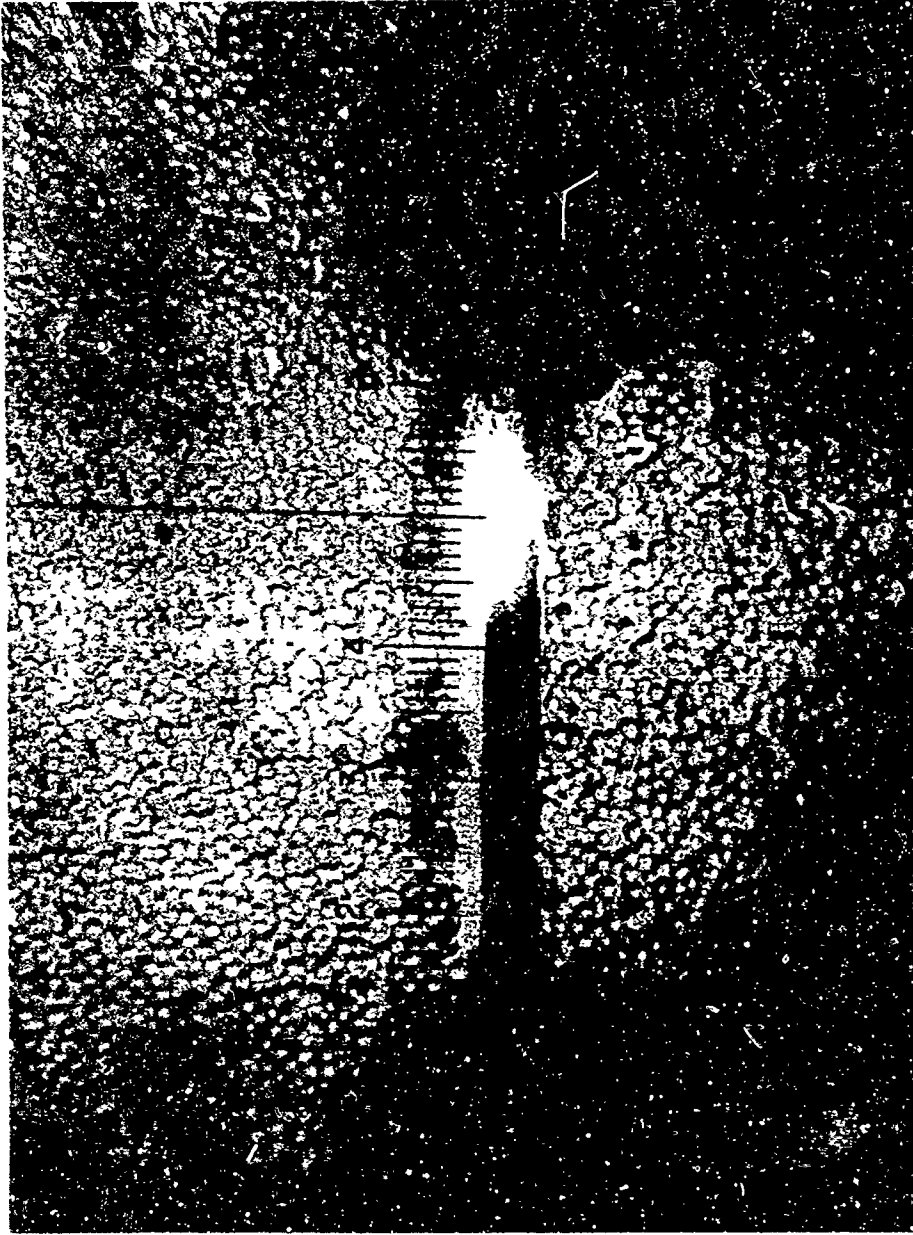


Fig. 2. Close-up of 0.004-in. diameter beads covering model surface

III. FACILITY

The tests were conducted in The Aerospace Corporation high-Reynolds-number shock tunnel. This facility has a 6 3/8-in. diameter driven section and is 25 ft long. The driver is 3 in. in diameter and 10 ft long. A 2-in. diameter throat at the end of the shock tube and a 12-in. diameter test section provided flow at Mach 5 at the exit of the conical nozzle.

With a maximum driver pressure of about 4500 psig available, the highest practical unit Reynolds number was $9 \times 10^6 \text{ ft}^{-1}$. A driver gas of 90% helium and 10% Argon (to provide tailored interface conditions and long constant reservoir conditions) driving air at an initial pressure of 3.04 atm was used to obtain this value. The shock Mach number was 2.16, and the reflected shock pressure that served as the reservoir pressure was about 54 atm at a temperature of 900°K. Testing time was 4 msec.

IV. RESULTS

Before the results are presented, a comment about what the heat gages measure for this type of mounting is required. The thin-film resistance thermometers are mounted on the model before the glass beads are applied. Hence, after the beads are applied, the thermometer was sitting on the bottom of a notch equal in depth to the diameter of the beads and about 0.04 in. wide. Therefore, the heat measured should be characteristic of that on the bottom in the center of an open cavity of depth d and length L . The thermometer was about 0.010-in. wide and hence occupied a region of the bottom of from $X/L = 0.38$ to 0.62 . According to measurements by Emery, et al. (Ref. 9), in a turbulent boundary layer flow, for $L/d = 2$, the smallest notch width they studied, the heat transfer in the middle of the notch was 0.53 times that forward of the notch. For $L/d = 4$, the ratio is 0.65. Hence, the heat rates measured for the 0.04-in. bead model should be multiplied by $1/0.53$ and for the 0.01 in. bead model by $1/0.65$. For the 0.004-in. bead model, the boundary layer off the stagnation point was thick in comparison to the notch depth, and the correction factor was neglected. With data treated in this way, the heat-transfer rate normalized with respect to the calculated laminar stagnation point heat transfer was plotted as a function of angular position from the stagnation point. These data are shown in Figs. 3, 4, 5, and 6 for smooth walls and three roughnesses and for Reynolds numbers based on free-stream conditions and the sphere diameter Re_D from 1.3 to 2.9×10^6 . The data were normalized with respect to the laminar stagnation point heat transfer calculated from

$$\delta_{ls} = \frac{H_e c}{Pr} \left[\rho_e \mu_e \frac{3.42 \times 10^3}{\frac{D}{2}} \right]^{1/2} (0.2267)$$

where $c = \rho_w \mu_w / \rho_e \mu_e$ and D is in feet. Also included in the figures are the predictions for laminar and turbulent heat-transfer obtained by King¹ from an exact numerical integration of the time-dependent boundary-layer equations. For the turbulent prediction, a mixing viscosity model with the eddy in the

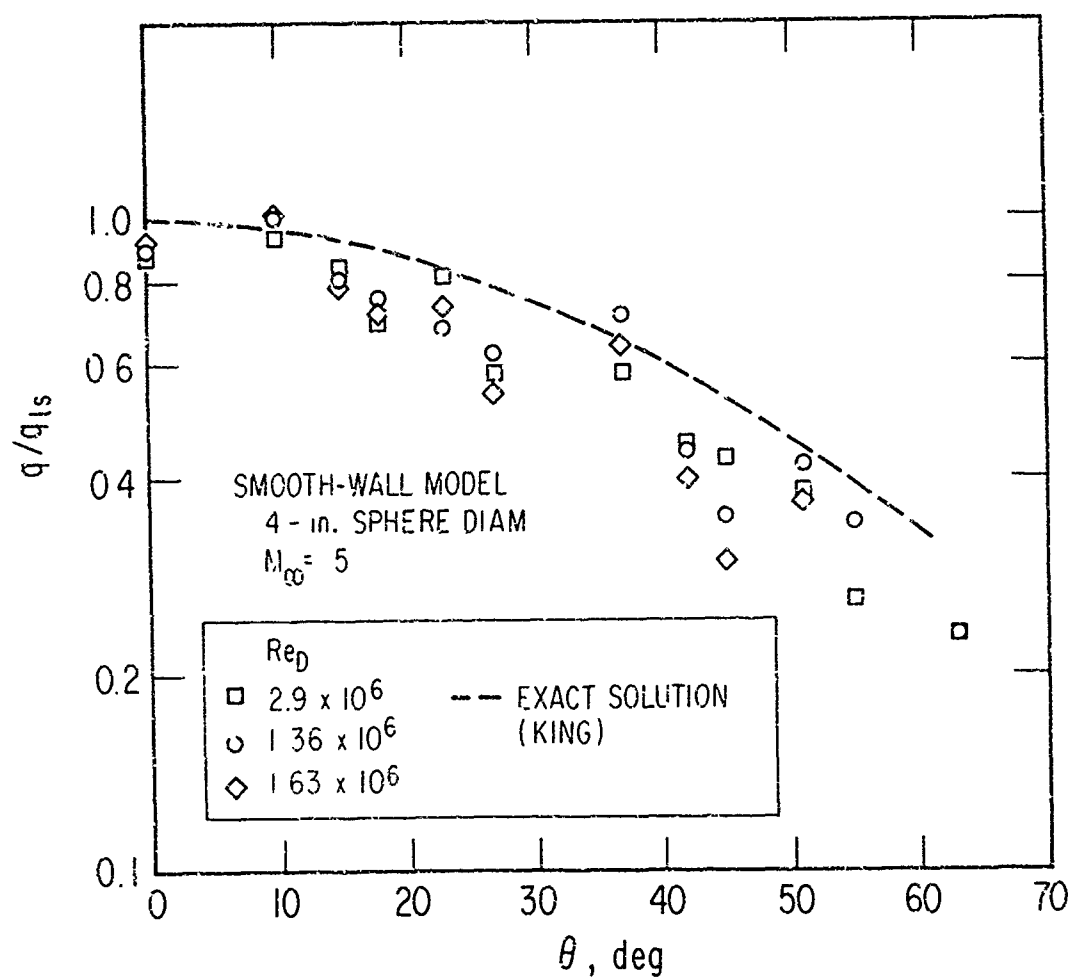


Fig. 3. Heat transfer to smooth glass sphere normalized by stagnation heat transfer as a function of angular position

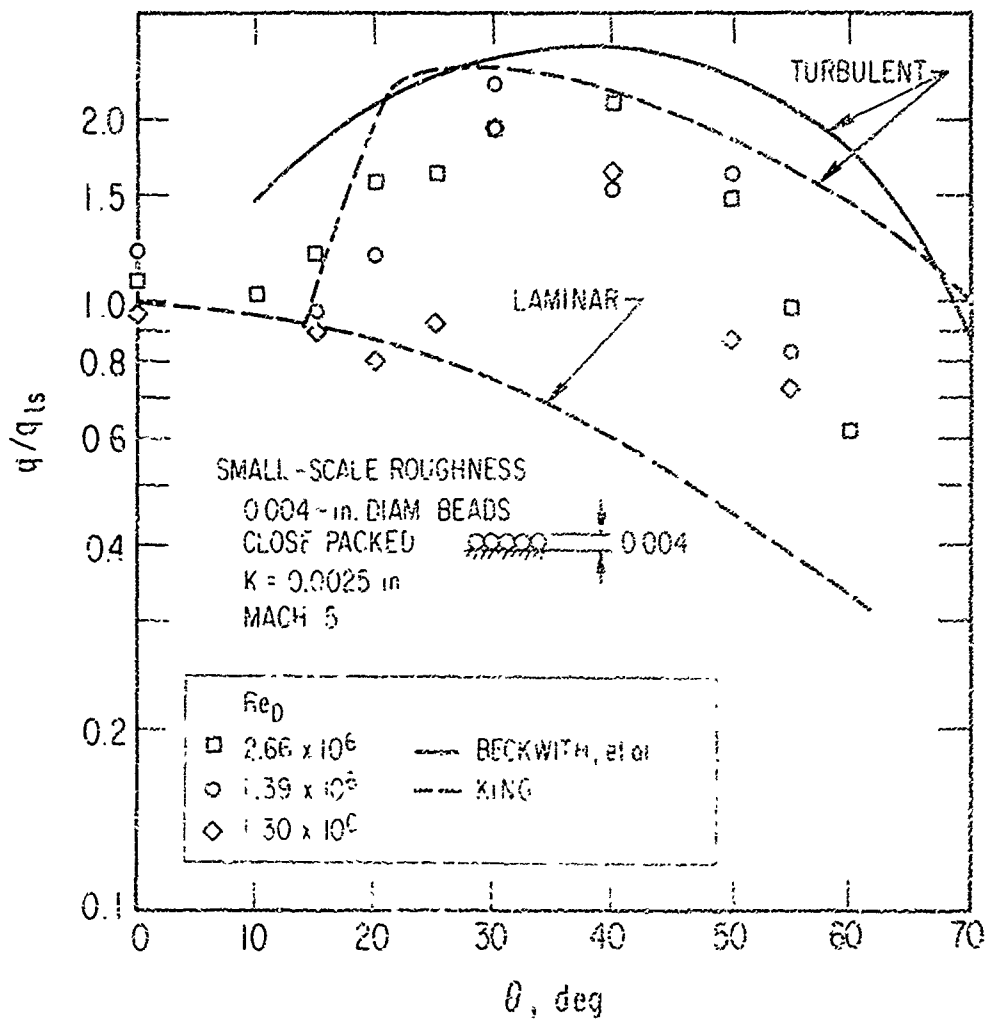


Fig. 4. Heat transfer to sphere with equivalent sand roughness of 0.0025 in.

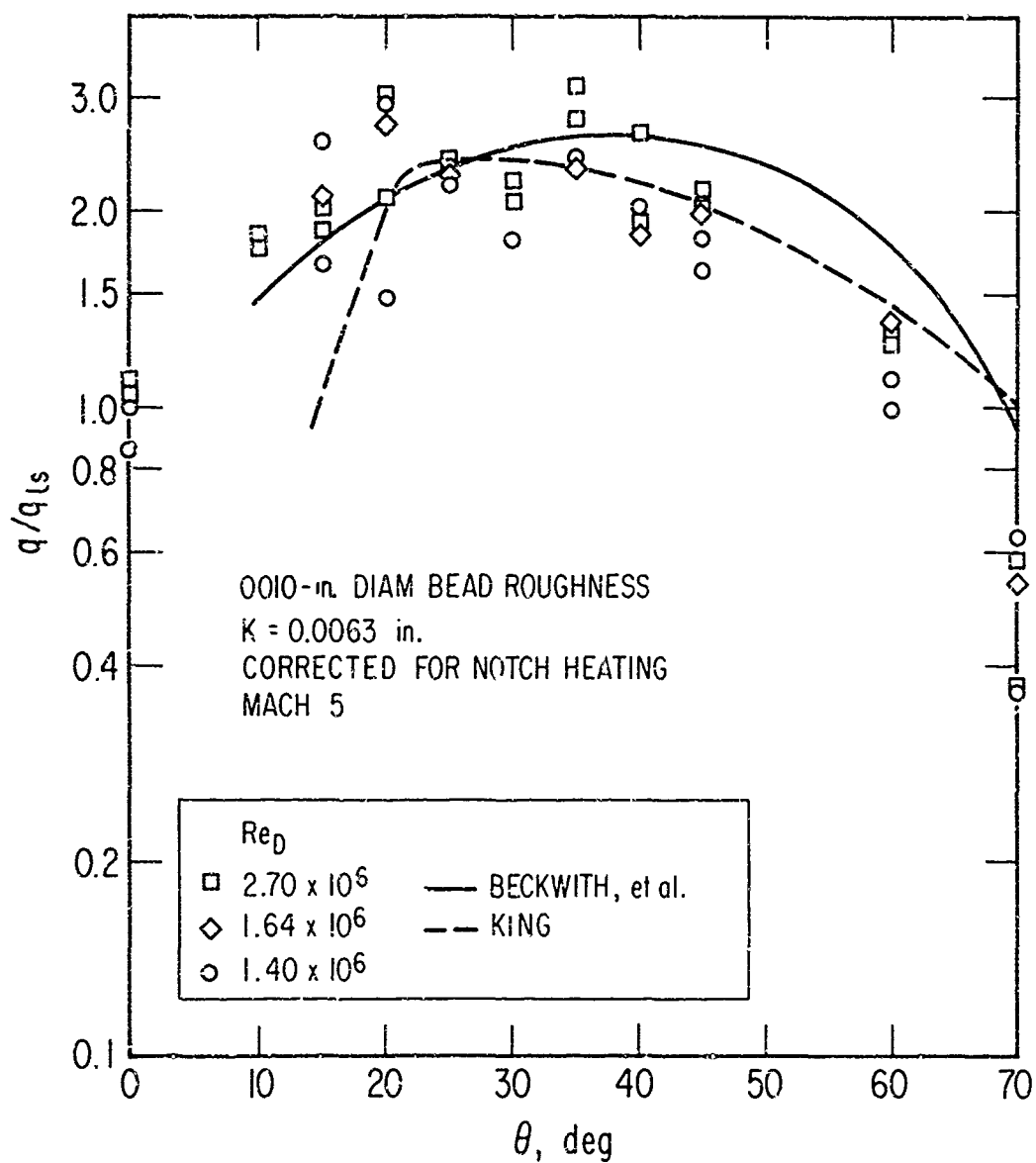


Fig. 5. Heat transfer to sphere with equivalent sand roughness of 0.0063 in.

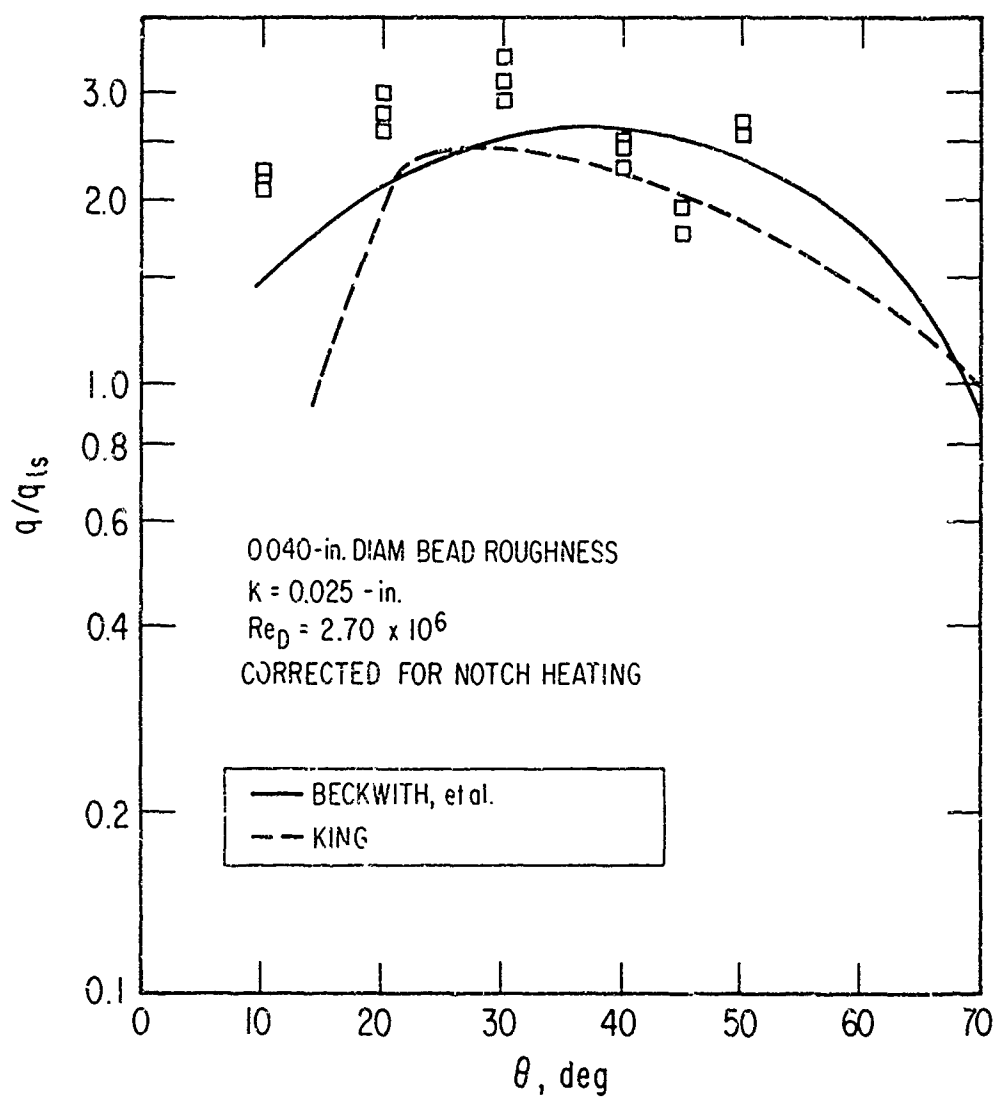


Fig. 6. Heat transfer to sphere with equivalent sand roughness of 0.025 in.

length direction was used. For comparison, the predictions from a local turbulent flat-plate method devised by Beckwith (Ref. 4) are also presented. The local turbulent flat-plate prediction is based on Falkner's skin-friction equation, the Reynolds' analogy, and the laminar heat-transfer coefficient at the stagnation point from Reshotko and Cohen (Ref. 10). If it is assumed that the wall temperature remains constant, this relation is

$$\frac{q}{q_s} = 0.157 \text{ Pr} \left(\frac{\text{Nu}}{\sqrt{\text{Re}_w}} \right)^{-1} \left(\frac{p}{u_\infty} \frac{du_e}{dx} \right)^{-1/2} \left(\frac{p_e}{p_s} \frac{u_e}{u_\infty} \right)^{6/7} \left(\frac{x}{D} \right)^{-1/7} \left(\frac{\rho_w u_e D}{\mu_w} \right)^{5/14}$$

$\text{Nu}/\sqrt{\text{Re}_w}$ is evaluated from Ref. 10 for $T_w/T_s = 0.33$. A Pr of 0.76 is used and the velocity gradient at the stagnation point is computed from

$$\frac{du_e}{dx} = \frac{1}{R} \left[\frac{2(p_s - p_\infty)}{\rho_s} \right]^{1/2}$$

No account of surface roughness is taken in either prediction.

From the smooth-wall measurements, it is seen that transition apparently does not occur at the Re_D obtainable.

For the small-scale roughness, transition occurs for all Re_D . Maximum heat transfer reaches nearly the same value for all Re_D at from 30 to 40 deg on the body. As Re_D is increased from 1.3 to 1.4 to 2.7×10^6 , transition begins at 20, 15, and then 10 deg on the body.

For roughness produced by 0.01-in. and 0.04-in. beads, transition occurs between 0 and 10 deg and peak heating at 35 and 30 deg, respectively. The stagnation-point heat transfer was not always available because the thermometer is at the most vulnerable position on the body and experienced a high casualty rate, probably from diaphragm particles.

From these measurements, it can be concluded that the Reynolds number is not high enough for natural transition for smooth walls, but as the wall becomes rough, transition occurs. For the small scale roughness, the measured heat transfer is lower than that predicted by both the local turbulent flat-plate method and the exact solution and falls increasingly below the predictions as θ increases beyond 40 deg. This decrease occurs because the transition did

not occur naturally but was triggered by the rough surface. As the boundary layer increases in thickness with θ , the surface roughness becomes less significant in determining the heating rate.

For the 0.01-diameter bead roughnesses, the stagnation-point heating with no notch correction was reasonably well predicted by laminar theory. This is in contrast to the measurements of Strass and Tynen (Ref. 11), who measured stagnation-point heating of a small, flat disk in a heated jet. Their measured heat transfer increased beyond laminar theory as the size of the roughness increased. Since the calorimeter they used measured the average heating of the rough stagnation point disk, they reasoned that some of the disk protruded beyond the boundary layer into the hot gas at the edge of the boundary layer and thus reflected higher heating rates. In the present tests the heating is measured at the surface at the base of the protuberances and should reflect the laminar prediction.

The peak heating measured for the 0.01- and 0.04-in. bead roughnesses is just slightly higher than both predictions. However, the data are best correlated by the exact solutions except at the maximum angular position.

Since these tests began, new heating data have been obtained by DiChristina (Ref. 5) on a 7-in. diameter sphere with roughness somewhat similar in scale but different in character from those used in this study. The measurements were made at the U. S. Naval Ordnance Laboratory Mach 5 bl down wind tunnel at an Re_D range that included and extended beyond the present work. Hence, natural transition could be obtained. The wall-temperature ratio T_w/T_s was 0.4.

These data (Figs. 7, 8, and 9) show that transition occurred at a lower Re_D for the smooth wall than that indicated by the results of the present study. For the small scale roughness, the peak heating obtained was nearly the same in size and shape as that obtained for the 0.01-in. diameter roughness at similar Re_D .

In the large-scale protuberance model, the heating was 30 percent greater at the peak than in the present work. This may be accounted for by the shape of the protuberances. They were rectangular projections as tall as

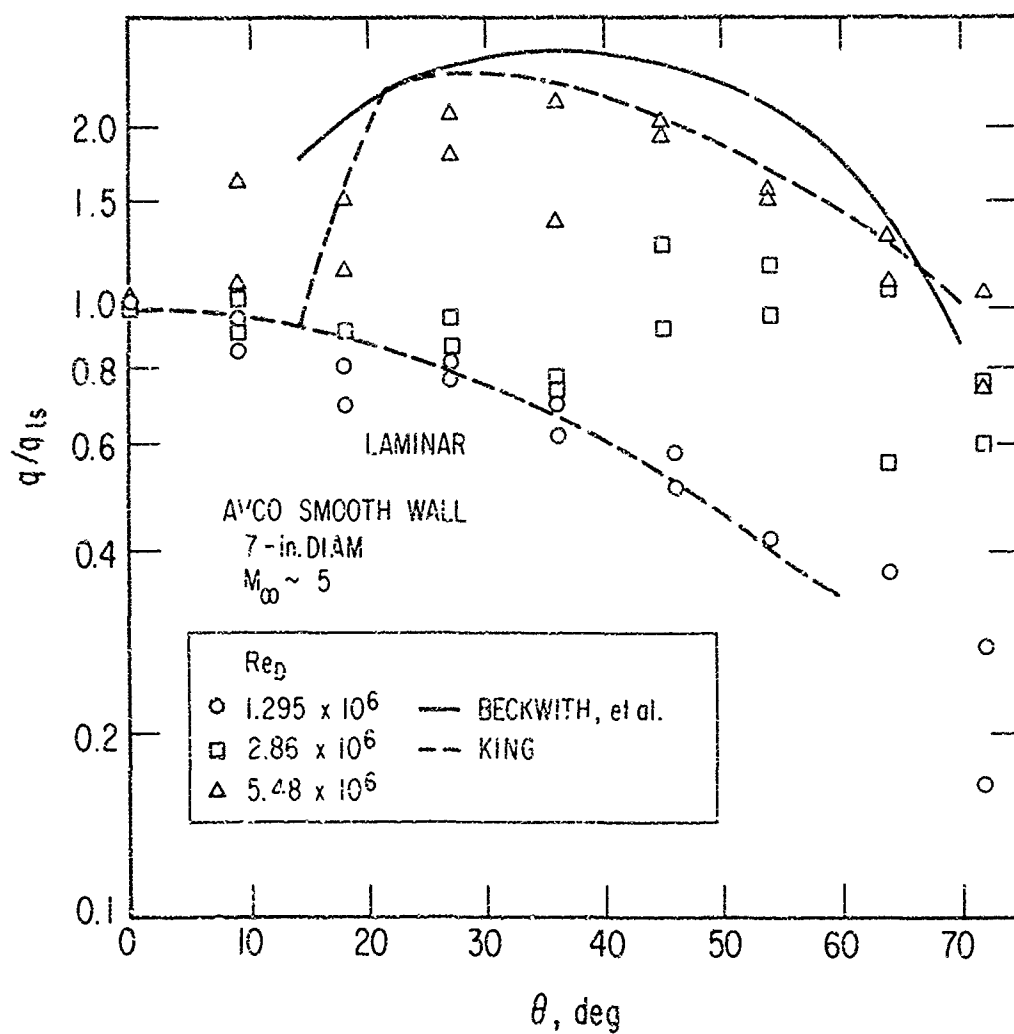


Fig. 7. Heat transfer to smooth wall in NOL Mach 5 tunnel (Ref. 11)

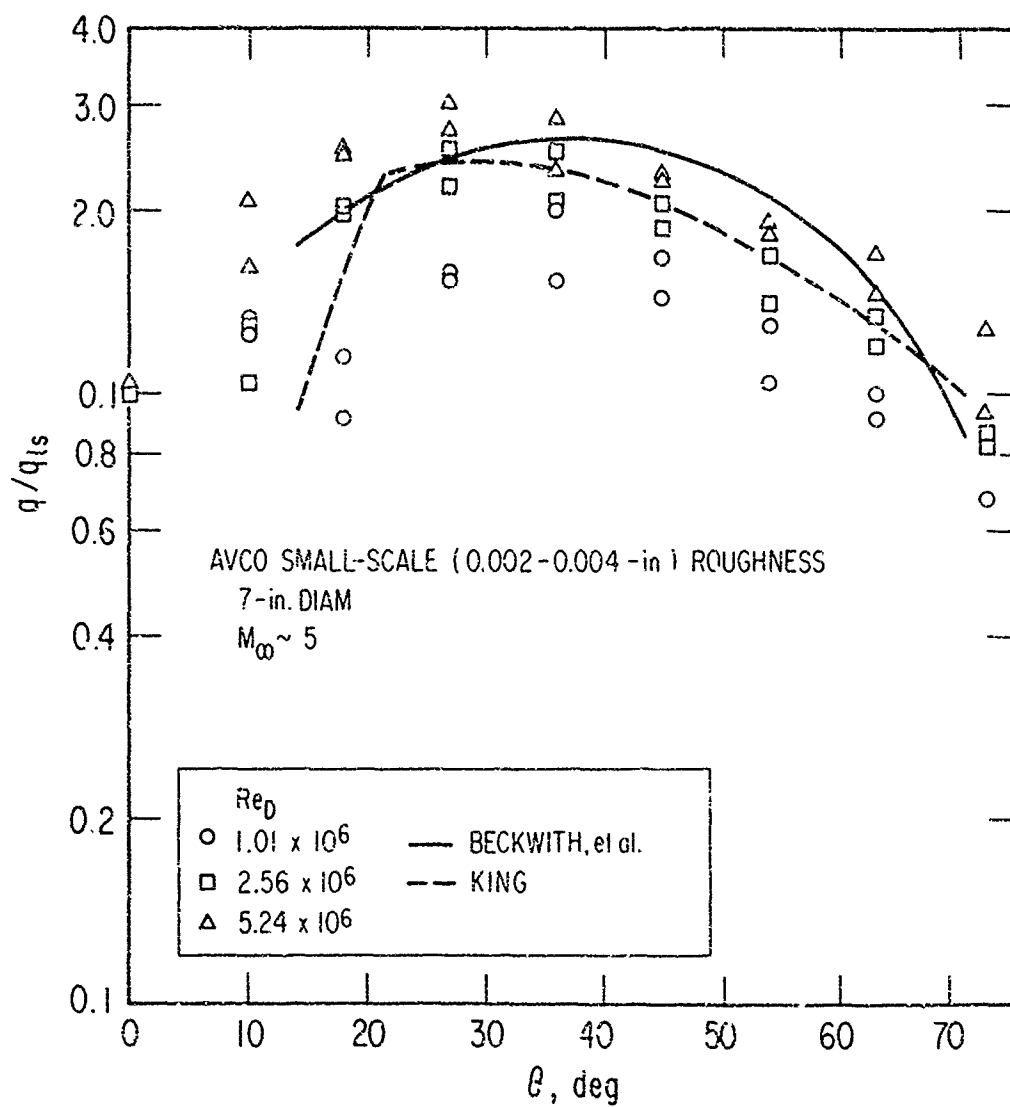


Fig. 8. Heat transfer to wall with roughness of 0.002 to 0.004 in. in NOL Mach 5 tunnel (Ref. 11)

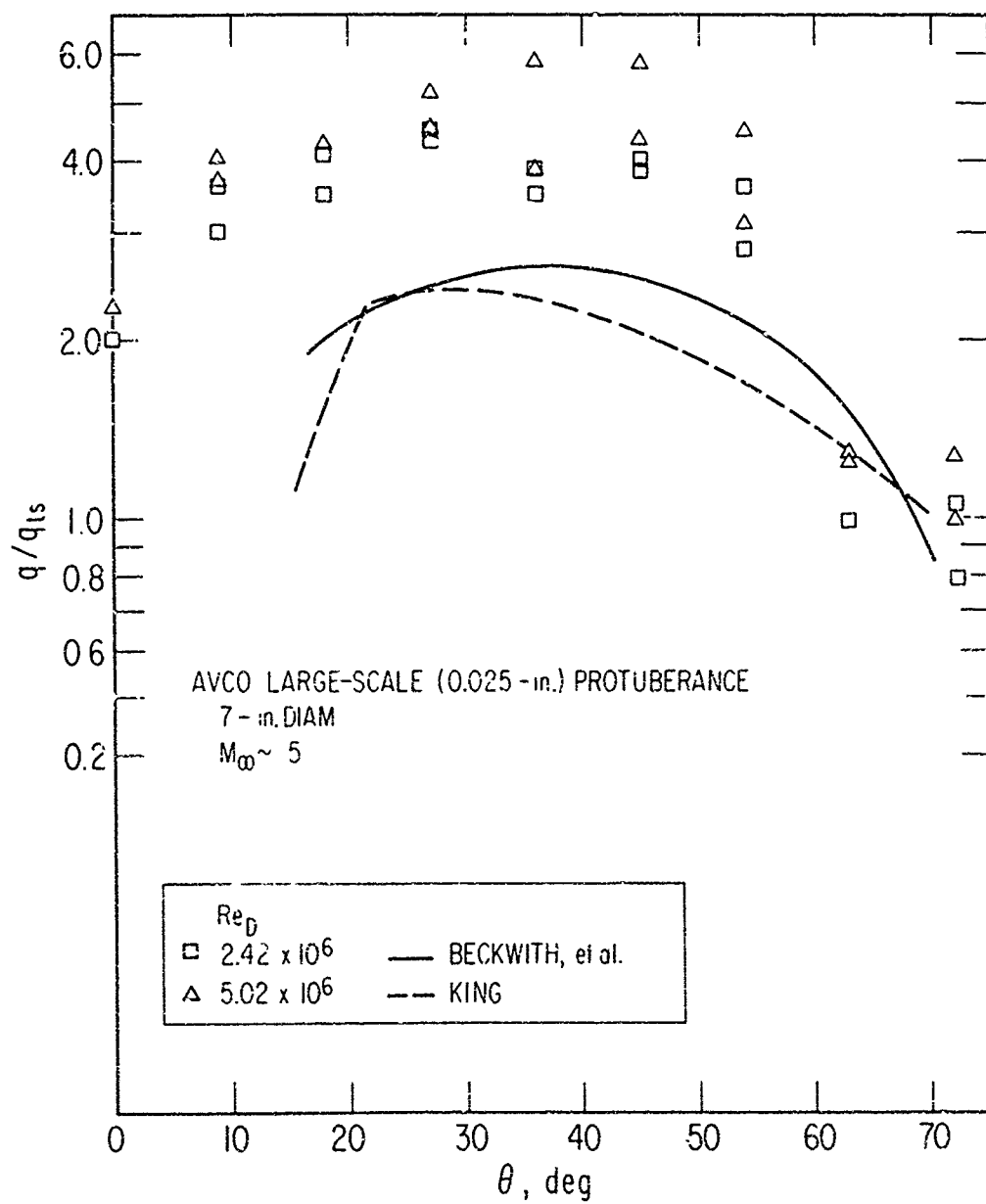


Fig. 9. Heat transfer to wall with rectangular roughness of 0.025 in. high in NOL Mach 5 tunnel (Ref. 11)

they were wide and separated by the same width. The equivalent sand roughness can be several times the maximum dimension (0.025 in.) of the protuberance for this shape.

At the stagnation point, the heating was greater than the laminar prediction for the large-scale protuberance. Since slug calorimeters were used to make this measurement as in Ref. 1, the same explanation of the difference may apply, i. e., the protuberances projected out into the free stream and reflect greater heating than would be predicted at the wall at the base of the boundary layer.

V. SUMMARY

Heat transfer rates to the forward surface of a 4-in. diameter sphere were measured at a flow of Mach 5 at Re_D from 1.3 to 2.9×10^6 . The sphere surface varied in roughness in terms of stagnation-point boundary-layer thickness δ_s from smooth to $12.5 \delta_s$ with the roughness dimension characterized by Nikuradse's equivalent sand roughness dimension. For the smooth wall, the boundary layer remained laminar over the Re_D range. Transition was obtained by the addition of roughness equal to δ_s ; however, the resulting turbulent heating was lower than that predicted by an exact solution of the boundary-layer equations. When the roughness was changed to 2 to $3 \delta_s$, the peak heating reflected the predictions more closely.

In comparison with the essentially steady wind-tunnel measurements of Ref. 11 at equivalent flow conditions, the present work yielded generally lower heat-transfer rates for similar roughness dimensions. It is proposed that the different character of the roughness as well as its magnitude could influence the measured heat-transfer rates.

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