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RESEARCH MEMORANDUM

FOR REFERENCE

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AERODYNAMIC HEATING OF BLUNT NOSE SHAPES

AT MACH NUMBERS UP TO 14

By William E. Stoney, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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August 11, 1958

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AERODYNAMIC HEATING OF BLUNT NOSE SHAPES

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AT MACH NUMBERS UP TO 14*

By William E. Stone, authority of

CSTAR Date *3/31/71*
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SUMMARY

Results are presented from recent investigations of the aerodynamic heating rates of blunt nose shapes at Mach numbers up to 14. Data obtained in flight and wind-tunnel tests have shown that the flat-faced cylinder has about 50 percent the stagnation-point heating rates of the hemisphere over nearly the entire Mach number range. Tests made at a Mach number of 2 on a series of bodies made up of hemispherical segments of varying radius of curvature showed that slight amounts of curvature can decrease the local rates at the edge of the flat-faced cylinders with only a slight increase in the stagnation rate. The total heat transfer to such slightly curved bodies is also somewhat smaller than the total heat transfer to flat-faced cylinders.

Comparison of several tests with theoretical heating-rate distributions showed that both laminar and turbulent local rates can be predicted by available theories (given the pressure distribution about the body) reasonably well, although the scatter of the available data still leaves open the choice between the theories at the edge of the bodies, where they usually differ.

Tests on a flat-faced cylinder at a Mach number of 2.49 and at angles of attack up to 15° showed the movement of the apparent stagnation point from the center of the body to the 50 percent windward station at 15° angle of attack. The heat transfer near the windward edge increased about 30 percent while that near the leeward edge decreased about 20 percent at 15° angle of attack.

Preliminary results on a concave nose have indicated the possibility that this type of design may be developed to give heating rates significantly lower than even the flat-faced cylinder rates. The test results have also shown, however, the existence of an unsteady flow phenomenon which can increase the heating rates to extremely high values.

*Title, Unclassified.

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INTRODUCTION

The importance of blunt noses as a means of reducing the heat transfer to high velocity missiles has recently received much publicity. The question of just what blunt shape is best is still moot, and it is the purpose of this paper to present and examine some recent experimental results which may throw some light on this problem.

SYMBOLS

h	heat-transfer coefficient
M	Mach number
p	pressure
Q	total heat input
R	Reynolds number
r	radius
s,x	distance along surface measured from center line
s ^{TOTAL}	total distance along surface measured from center line to edge of body
T	temperature
u	velocity
α	angle of attack
Subscripts:	
d	based on diameter
F	flat face
HEMIS	hemisphere
LAM	laminar flow
l	local

TH theoretical
TURB turbulent flow
t stagnation
w wall
 ∞ free stream

Superscript:

'(prime) hemispherical segment

DISCUSSION

A motion-picture film supplement has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract and index page.

Stagnation-Point Heating on Hemispherical and Flat-Faced Cylinders

Heat is apparently an elusive thing, and the prediction and measurement of its transfer rates is still not the most exact of sciences. This fact is illustrated in figure 1, which presents the heat-transfer coefficients measured at the stagnation points of hemispheres and flat-faced cylinders as a function of free-stream Mach number. All the measured rates are divided by theoretical rates for the hemisphere determined either by the theory of Sibilkin for low Mach numbers (ref. 1) or by the theory of Fay and Riddell for higher Mach numbers (ref. 2). The latter theory includes the real gas effects due to the very high stagnation temperatures obtained at these flight conditions. The measured results (refs. 3 to 11 and unpublished data) were obtained on rocket models and in wind tunnels.

It is apparent from the scatter shown that both methods of measurement have their troubles. There is the possibility that a variable not accounted for by the theories is responsible for some of the scatter. It seems probable, however, that the scatter in the data is principally the result of heat losses of various types, errors in the measurement of the very thin skins usually used, and, in the case of the flight data, errors in the measurement of the flight conditions of the models. This last type of error is responsible for the fact that heating-rate distributions measured on flight models often show considerably less scatter if they are nondimensionalized by division by the measured stagnation rates rather than by theoretical rates. The agreement of the data taken in this way is due to the invariance of laminar heating-rate distributions with Mach number and Reynolds number.

With these qualifications, it then appears reasonable to say that the measured values support the theoretical values of the stagnation heating rates on the hemispheres throughout the Mach number range and that the stagnation heating rates on the flat-faced cylinder are roughly one-half those on the hemisphere. The markedly lower rates shown for the flat face indicate its possible value as a low-heating-rate shape, but a final evaluation requires the examination of the heating rates over the entire surface.

Local Heating Rates on a Flat-Faced Cylinder

Local heating rates on a flat-faced cylinder are presented in figure 2. The local heating rates measured in flight (refs. 11 and 12) and in wind tunnels (ref. 10 and unpublished data) are divided by their measured stagnation rates and presented as functions of local distance from the center line divided by the radius of the body. The scatter of some of the data is indicated by the spread of the rails through the symbols. The data are compared with the predictions of two laminar theories, the solid line representing the theory of Lees (ref. 13) and the dashed line, the theory of Stine and Wanlass (ref. 14). For both these theoretical distributions a pressure distribution measured at $M_\infty = 2$ in a wind tunnel (ref. 10) was used. This use is justified by the experimentally obtained fact that the local flow over blunt shapes "freezes" at Mach numbers above about 2, which means that the local Mach numbers do not change significantly with free-stream Mach number above that Mach number. Lees' theory is derived for the condition $\frac{T_w}{T_t} \ll 1$, which is the condition of all high Mach number flight tests. For this condition Lees argues that the direct influence of a local pressure gradient is small and can be neglected. The Stine and Wanlass calculations include a local-pressure-gradient effect, and this is the principal source of the difference shown between the two theories.

In figure 2 the data scatter is again large enough that it is impossible to decide which of the two theories better fits the data. A comparison of the two parts of the figure shows the invariance of the distribution with Mach number and Reynolds number mentioned previously. In spite of the data scatter it is also obvious that the flat-faced cylinder loses some of its advantages over the hemisphere by the increased heating rates at the edge of the face.

Stagnation-Point Heating Rates on Hemispherical Segments

In an attempt to decrease the edge heating rates while keeping low stagnation rates, a series of bodies were tested which were shaped by

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hemispherical segments of different radii. Figure 3 presents the ratio of stagnation-point heating rates measured on these hemispherical segments to the stagnation-point heating rate for the hemisphere of equal body radius plotted (open symbols) as a function of the ratio of body radius to the radius of curvature of the hemispherical segment. The results of two systematic investigations are shown and the agreement between them is fair in spite of the large Mach number and stagnation difference between them. All the results of figure 1 could, of course, be plotted in figure 3 at $\frac{r}{r'} = 0$ to give a band of data from about 0.4 to 0.8. The results of the two investigations shown have the advantage of being parts of a systematic series of tests, and they agree with the general results of figure 1, namely, that the stagnation-point heating rates for the flat face are about 50 percent of those for the hemisphere.

Plotting the solid points which were obtained from pressure measurements (ref. 15) as heating-rate ratios is not strictly honest since these points are actually the square root of the velocity gradient ratios; that is,

$$\frac{\sqrt{(du/dx)^2}}{\sqrt{(du/dx)_{HEMIS}}}$$

However, stagnation-point heating-rate theory shows that the heating rate is a direct function of the square root of the velocity gradient and, thus, the two types of data can be plotted in the same figure with the purpose of allowing the data to reinforce each other. The scatter in the pressure data is smaller, and the data show a small Mach number influence. The combination of pressure and heating-rate data allows a fairly decent line to be drawn through the data to show the effect of changing the nose radius of curvature. The use of theory allows a calculation of heating-rate ratios to be made from the Newtonian pressure principle also and this result is shown by the solid line. The comparison of this solid line with the data is interesting because it shows that the data depart from this line for that body for which Newtonian theory predicts a Mach number of 1 at the shoulder (i.e., slope at the shoulder = 45°).

The bodies tested had sharp or nearly sharp corners, and thus a Mach number of 1 occurred at or very close to the corner. It has been suggested (ref. 15) that for bodies of varying radii of curvature (for example, a body with a flat meridian near the stagnation point faired into the cylinder with a radius of curvature of 25 percent of the cylinder radius), the value of r on a plot such as shown in figure 2(b) should be taken at that point at which the local flow is

sonic, this point to be determined as best as possible, usually by means of pressure distributions. Although the present data can throw no light on the value of this procedure the reader should be aware that the corner can influence the results discussed for this figure and the following local-heating-rate-distribution figures, and that it does this through the mechanism of the sonic-point location. A more general discussion of a closely similar point is given in reference 16, where it is pointed out that the corner shape effects can be felt even if the position of the sonic line is known and is ahead of the corner, at least for Mach numbers less than 3 for bodies of revolution.

Local Heating Rates on Hemispherical Segments

Again the local heating rates must be examined to permit an evaluation of the various noses tested. In figure 4 the local rates measured on the series of $M = 2$ tunnel models for which the stagnation rates were presented in figure 3 are presented as a function of the ratio of local surface distance from the center line to the total surface distance from the center line. The local rates have been nondimensionalized by division by the stagnation rate of the flat face. The resulting ratios have been adjusted so that the stagnation-point ratios fit the dashed curve shown in figure 3. This has been done in an effort to remove some of the scatter shown in this figure and means that it has been assumed that the difference shown in the stagnation rates was shared by all the measuring stations. This assumption is partially justified at least by the consistency of the measured values of the first two or three stations away from the center line. This consistency appears on the figure as the flatness in the faired curves near the center line. For comparison the laminar-theory distributions of Stine and Wanlass (ref. 14) for the flat-faced cylinder and the hemisphere are also shown (solid lines). (The theory of Stine and Wanlass was used for the flat face since the condition predicted by Lees, namely $\frac{T_w}{T_t} \ll 1$, is not true for the tunnel conditions being compared herein.)

The effect of changing the radius of curvature of the nose is about as might be expected; that is, as the radius of curvature of the nose is increased above that of the hemisphere, the stagnation-point heating rates are reduced but the edge rates are increased. Similarly, as the radius is decreased from the infinite radius of the flat face, the stagnation rate increases and the edge rate decreases. Thus it is possible to reduce the peak local heating rates somewhat by slight amounts of curvature. Although the edge data are not too accurate because of high conduction losses near the corner and because of unknown effects on the local conditions caused by small and varying amounts of radius at the edge, integration of the local rates over the entire surface shows that

small reductions in the total heat-transfer rates are obtainable for bodies with small values of $\frac{r}{r'}$. Note that the hemisphere has about 50 percent more total heat transfer than the flat face, principally because of its 100 percent greater area.

Comparison of Turbulent and Laminar Rates

With Theoretical Calculations

Up to this point only laminar flow has been discussed. For hemispheres it has been shown (ref. 7) that turbulent rates as high as three times the laminar stagnation rates can occur. A similar situation exists for the blunter shapes. Figure 5 presents heat-transfer rates measured on a blunt nose of radius ratio $\frac{r}{r'} = 0.50$ for two conditions of the model surface. Again the measured rates have been divided by the measured stagnation rates. The circular and the square symbols give the distributions measured when the body was relatively smooth, while the diamond symbols represent the data obtained when the body was sand-blasted to a roughness of about 200 microinches. (The data shown by the square symbols were obtained on the body with a small 1/4-inch spot of 200-microinch roughness at the stagnation point only. The body was 4 inches in diameter.) As on the hemisphere, heating rates as high as three times the stagnation-point values were obtained.

The rough-surface data are compared with flat-plate turbulent theory derived from Van Driest (see ref. 17, and appendix of ref. 10). The agreement is fairly good and is similar to the agreement shown for flat-plate theory with data from hemispherical noses. (See ref. 7.)

The laminar data are compared with the laminar-distribution theories of Lees (ref. 13) and Stine and Wanlass (ref. 14) based on measured pressure distributions. Again the scatter of the data is just enough to preclude any choice between the theories near the edge where they indicate a marked difference. There is the possibility that the high point (square symbol) is the start of transition. The lateral heat flow around the corner has not been calculated because of the lack of temperature data right in the small-radius corner region, and thus it is possible that the results for the outer two stations are somewhat low. In general, these comparisons are representative of the local measurements made on the remaining bodies of the series shown in figure 3.

Effect of Angle of Attack

For hemispherical noses the effect of angle of attack on the local heating distributions is fairly small, as can be seen from geometric reasoning alone, but as the body is blunted, the possibility of larger changes due to angle of attack must be considered. Some recent data from the Langley Unitary Plan wind tunnel give an indication of these changes for a flat-faced cylinder for angles up to 15° .

In figure 6 both the pressure and the heating-rate distributions are plotted as a function of local surface distance from the center line. The local pressures have been divided by the total pressure behind the shock. The lines faired through the data (there were pressure measurements at all the stations indicated by the symbols in the heating-rate plot) indicate that the apparent stagnation point moved from the center to $s/s_{TOTAL} = 0.25$ at $\alpha = 7.5^\circ$ and to $s/s_{TOTAL} = 0.50$ at $\alpha = 15^\circ$ on the windward side.

The local heating rates have been divided by the stagnation rate for the zero-angle-of-attack case. As can be seen in the figure the rates are increased about 30 percent on the windward side and decreased about 20 percent on the leeward at 15° angle of attack. These results are also representative of tests at $M = 3.59$ and several other Reynolds numbers of the same order of magnitude.

Concave Nose

Some rocket-model tests of a series of small specimens indicated the possibility of extremely low heating rates on concave shapes and thus a large-scale flight test was initiated. The flight-test results were so startling that several wind-tunnel investigations were initiated and rushed to completion. The results of all these tests (refs. 18 and 19 and unpublished data) are presented in figures 7 and 8.

A sketch of the configuration, which is simply a concave hemisphere with slightly rounded corners, is presented in figure 7. The ratio of local heating rate to the stagnation-point heating rate of a hemisphere of the same size and flight conditions (calculated by the theory of Fay and Riddell (ref. 2)) is presented as a function of the ratio of local surface distance from the stagnation point to the total distance for both the flight tests (on the left) and the wind-tunnel tests (on the right). The rails indicate the spread of the data.

The low heating rates over most of the inside of the cup increase to only the order of the flat-face stagnation-point heating rates at the inside of the edge (see sketch in fig. 7). The agreement between

the flight and tunnel data in this case is fairly good; however, other wind-tunnel results do not compare so well.

Some of the wind-tunnel tests were made on a small model on which only the stagnation-point heating rates were measured. These tests which are presented in figure 8 indicated unstable flow phenomena in the cup. The schlieren photographs are typical of the two states noted, (1) where the shock was apparently steady, and (2) where the shock was asymmetrical and apparently unsteady in that the asymmetry changed erratically from lip to lip. An independent test at $M = 3.9$ and $R_{\infty,d} = 1.9 \times 10^6$ was made by Robert W. Dunning of the Langley High Mach Number Jet Group on a nose similar to that used in the heat-transfer tests except that the lip was sharp. Motion pictures of this test show one especially interesting feature in that at small angles of attack ($< 2^\circ$) the flow inside the cup appeared to be turbulent even when the shock was apparently symmetrical and steady. This turbulence would then explode for some unknown reason and the apparently unsteady condition would follow.

The stagnation-point heat-transfer data for all the tests are presented in figure 8, again as a ratio of the theoretical hemispherical stagnation-point results and as a function of free-stream Mach number. Note that the flight-test data extend from $M = 2.5$ to 6.5 and that the heating rates repeat themselves as the model decelerates to $M = 4.0$. As the Mach number increases, the free-stream Reynolds number (based on diameter) changes from 9×10^6 to 14×10^6 at the peak M down to 5×10^6 at $M = 4.0$, indicating little or no effect of Reynolds number on the data.

The wind-tunnel data fall roughly into two groups - the heat-transfer rates when the unsteady shock condition exists (solid symbols) and the rates when the steady shock is formed (open symbols). These data, especially those for the unsteady flow, show a strong Reynolds number dependence which is not shown in the flight data. The triangles presented on the right part of figure 7 show the data obtained in the Unitary Plan wind tunnel for the one case in which the flow was apparently unsteady. This particular case occurred at $M = 2.49$ and $R_{\infty,d} = 1 \times 10^6$ and with the model at an angle of attack of $7\frac{1}{2}^\circ$. Results from some of the tests from the Langley Gas Dynamics Branch and especially the film supplement to the present paper indicated that the instability which in their tests was almost certain to exist at $\alpha = 0$, was gone at

$\alpha > 2^\circ$. (It should be noted here that the flight model showed no indication of lateral movement on its normal and transverse accelerometers.)

To date the data on the concave shapes have shown that extremely low heat-transfer rates can be obtained over most of the surface of a concave nose; however, the existence of an unsteady state with extremely high rates has also been found. A comparison of all the stagnation-point wind-tunnel and flight-test data for the apparently steady shock case indicates the possibility that other, and as yet unknown, parameters are important in this phenomenon.

Shape is certainly one of these important factors in this phenomenon. Unpublished results from tests made by John O. Reller, Jr., of the Ames Laboratory on a series of cups of different deepness on the front end of an ogive nose at $M = 4$ indicated that the depth of the cup is important in determining the stability of the flow. The depth of the cup was varied by changing the radius of the hemisphere in a manner similar to the method of obtaining the hemispherical segment noses of the present paper. From shadowgraphs of the shock wave it was found that the cup with $\frac{r_{\text{body}}}{r_{\text{cup}}} = 0.76$ remained steady during the tests while the next body in the series for which $\frac{r_{\text{body}}}{r_{\text{cup}}} = 0.95$ exhibited the asymmetrical shock associated with the unsteady flow phenomenon during nearly all the test time.

SUMMARY OF RESULTS

Recent investigations of the aerodynamic heating rates of blunt nose shapes at Mach numbers up to 14 have yielded the following results:

1. Data obtained in flight and wind-tunnel tests have shown that the flat-faced cylinder has about 50 percent the stagnation-point heating rates of the hemisphere over nearly the entire Mach number range.

2. Tests made at a Mach number of 2 on a series of bodies made up of hemispherical segments of varying radius of curvature showed that slight amounts of curvature can decrease the local rates at the edge of the flat-faced cylinders with only a slight increase in the stagnation rate. The total heat transfer to such slightly curved bodies is also somewhat smaller than the total heat transfer to flat-faced cylinders.

3. Comparison of several tests with theoretical heating-rate distributions showed that both laminar and turbulent local rates can be predicted by available theories (given the pressure distribution about the body) reasonably well, although the scatter of the available data

still leaves open the choice between the theories at the edge of the bodies, where they usually differ.

4. Tests on a flat-faced cylinder at a Mach number of 2.49 and at angles of attack up to 15° showed the movement of the apparent stagnation point from the center of the body to the 50-percent windward station at 15° angle of attack. The heat transfer near the windward edge increased about 30 percent while that near the leeward edge decreased about 20 percent at 15° angle of attack.

5. Preliminary results on a concave nose have indicated the possibility that this type of design may be developed to give heating rates significantly lower than even the flat-faced-cylinder rates. The test results have also shown, however, the existence of an unsteady flow phenomenon which can increase the heating rates to extremely high values.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 19, 1958.

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STAGNATION-POINT HEATING RATES MEASURED ON HEMISPHERES
AND FLAT-FACED CYLINDERS

HEMISPHERE DATA		FLAT-FACED-CYLINDER DATA	
○, □	GAS DYN. (REF. 7)	◇	PREFLIGHT JET (REF. 10)
△	11-IN. HYP. TUN. (REF. 8)	▲	UPWT (UNPUBLISHED)
▽	GAS DYN. (UNPUBLISHED)	▼	GAS DYN. (UNPUBLISHED)
—	LOCKHEED X-17 (5 FLIGHTS; REF. 3)	---	PARD (4 FLIGHTS; REFS. 4, 5, 6, 11)
- - -	PARD (REF. 9)		

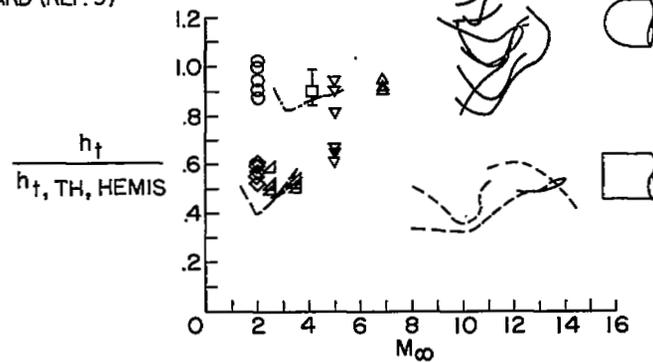


Figure 1

LOCAL HEAT-TRANSFER COEFFICIENTS ON A FLAT-FACED CYLINDER

$M_\infty < 5$

LAMINAR THEORY USING M=2 PRESS. DIST.
 - - - - STINE AND WANLASS (REF. 14)
 - - - - LEES (REF. 13)

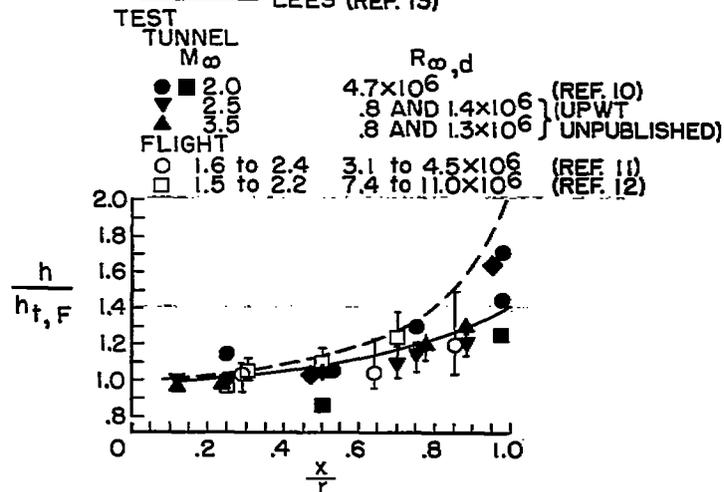


Figure 2(a)

LOCAL HEAT-TRANSFER COEFFICIENTS ON A FLAT-FACED CYLINDER

$M_\infty > 10$

LAMINAR THEORY USING M=2 PRESS. DIST.
 - - - - STINE AND WANLASS (REF. 14)
 - - - - LEES (REF. 13)

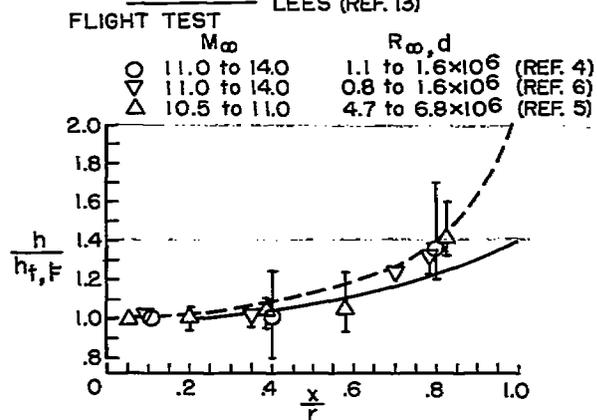


Figure 2(b)

STAGNATION-POINT HEATING RATES ON HEMISPHERICAL SEGMENTS OF DIFFERENT CURVATURES

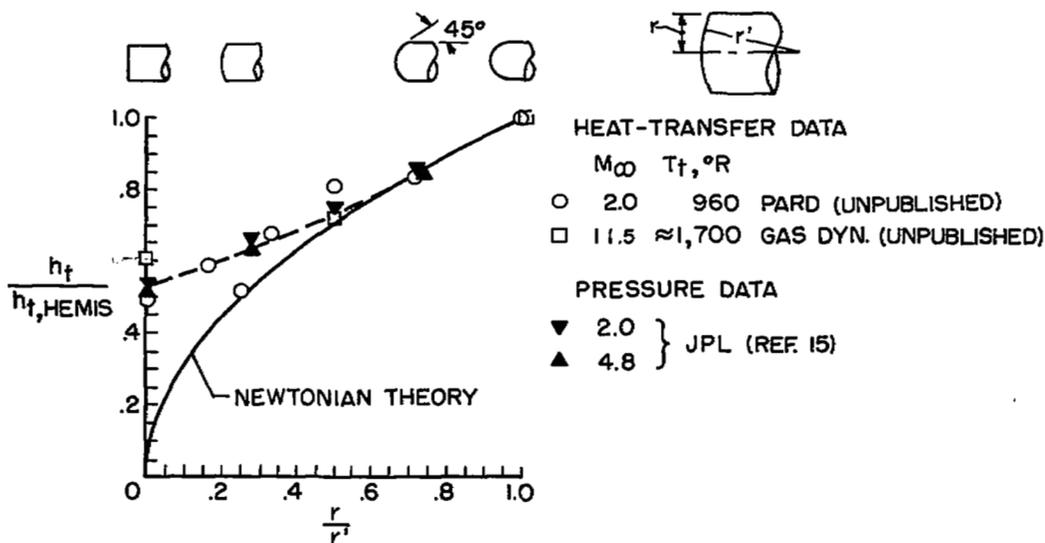


Figure 3

HEMISPHERICAL-SEGMENT LOCAL HEAT-TRANSFER COEFFICIENTS DIVIDED BY FLAT-FACED STAGNATION VALUES

$M_\infty=2; R_\infty, d \approx 4.7 \times 10^6$

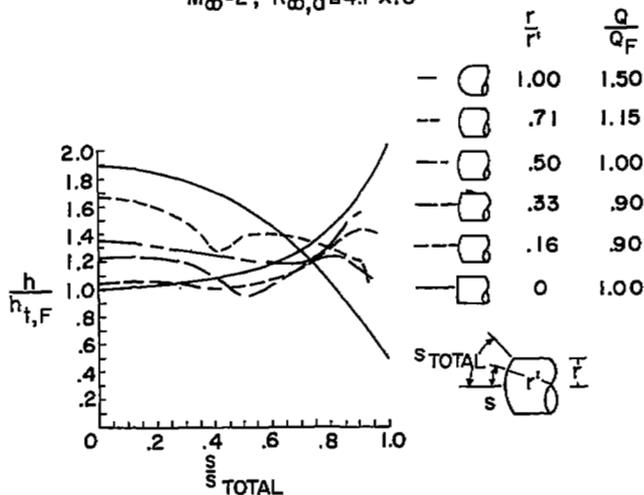


Figure 4

COMPARISON OF MEASURED AND THEORETICAL HEATING RATES ON A HEMISPHERICAL SEGMENT

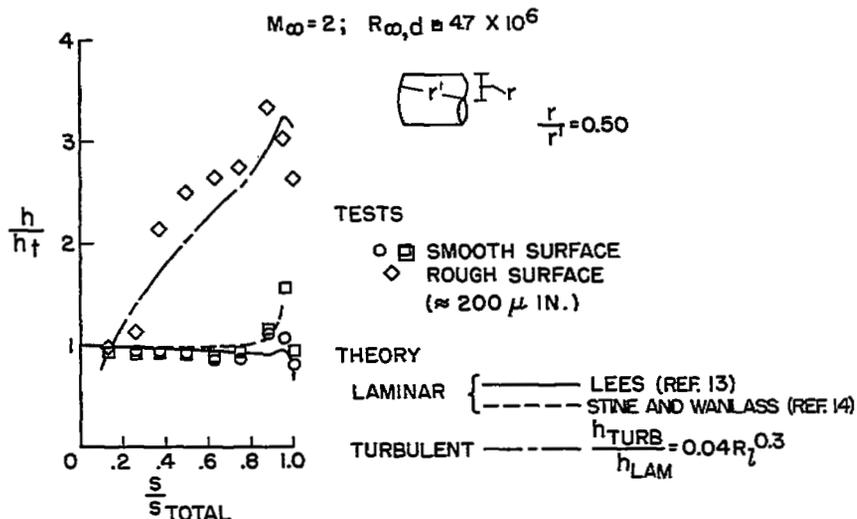


Figure 5

VARIATION OF PRESSURE AND HEAT-TRANSFER COEFFICIENTS ON A FLAT-FACED CYLINDER WITH α

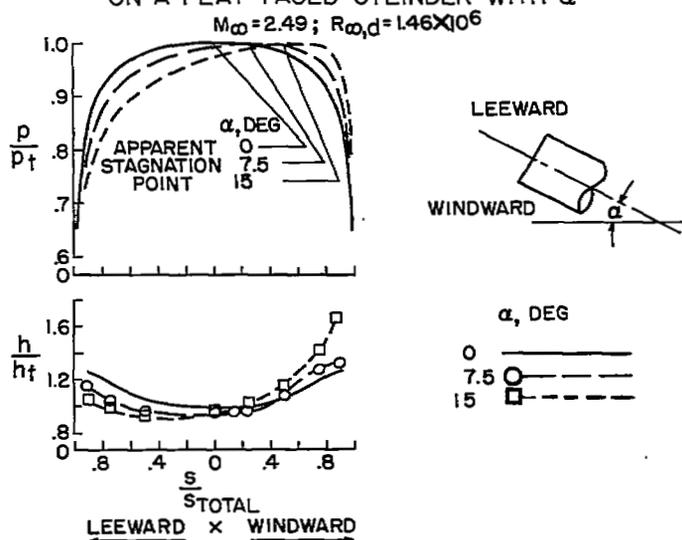


Figure 6

HEATING RATE AND PRESSURE DISTRIBUTIONS ON A CONCAVE NOSE

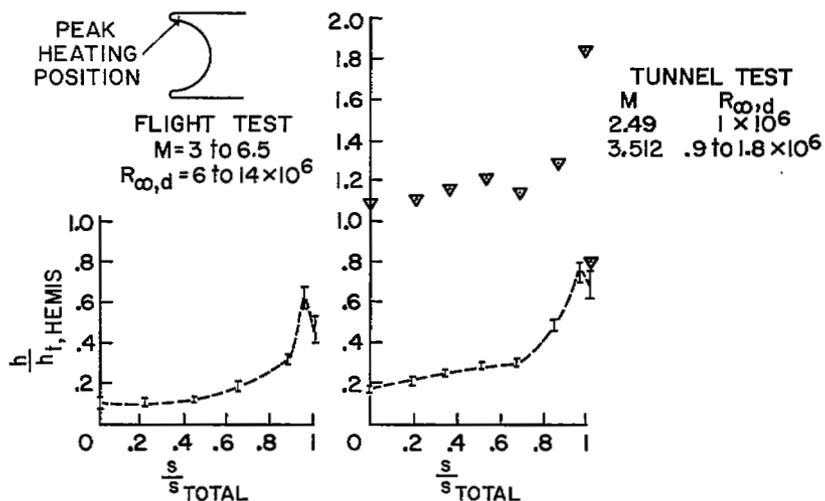


Figure 7

STAGNATION-POINT HEATING RATES MEASURED ON CONCAVE NOSE

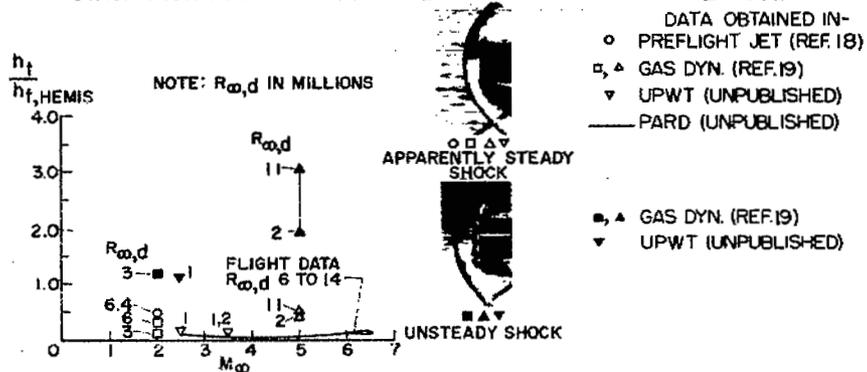


Figure 8

