# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

## TECHNICAL NOTE 3513

## HEAT TRANSFER AT THE FORWARD STAGNATION POINT OF BLUNT BODIES

By Eli Reshotko and Clarence B. Cohen

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Washington
July 1955

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3513

# HEAT TRANSFER AT THE FORWARD STAGNATION POINT OF BLUNT BODIES

By Eli Reshotko and Clarence B. Cohen

3657

## SUMMARY

Relations are presented for the calculation of heat transfer at the forward stagnation point of both two-dimensional and axially symmetric blunt bodies. The relations for the heat transfer, which were obtained from exact solutions to the equations of the laminar boundary layer, are presented in terms of the local velocity gradient at the stagnation point. These exact solutions include effects of variation of fluid properties, Prandtl number, and transpiration cooling. Examples illustrating the calculation procedure are also included.

CM-1

## INTRODUCTION

In the design of supersonic air vehicles, probably the most critical areas with regard to aerodynamic heating will be in the vicinity of the forward stagnation points of blunt bodies. This problem can be treated using laminar-boundary-layer theory. Stagnation-point heat-transfer relations are presented herein based on exact solutions to the laminar-boundary-layer equations with external flows of the Falkner-Skan type ($u_e = Ax^m$) and with constant surface temperature. The latter restriction is required because the existing exact solutions that include surface temperature variation apply to a temperature variation of the form $(t_w - t_{sp}) = Bx^n$. (All symbols are defined in appendix A.) Using this variation it can be shown that the available exact solutions for variable surface temperature are not valid at a stagnation point because the term $\frac{\partial}{\partial x}\left(k \frac{\partial t}{\partial x}\right)$ has been omitted from the energy equation.

The applicable solutions may be divided roughly according to their consideration of fluid properties.

Constant fluid properties. - For the case of constant fluid properties, Squire (ref. 1) and Sibulkin (ref. 2) have evaluated the parameter $Nu/\sqrt{Re_w}$ for two-dimensional and axially symmetric flow, respectively.

These calculations, for Prandtl numbers from 0.6 to 1.0, indicate that the following approximate relation closely represents the Prandtl number effect on $Nu/\sqrt{Re_w}$:

$$\left(\frac{Nu}{\sqrt{Re_w}}\right)_{Pr} = (Pr)^{0.4}\left(\frac{Nu}{\sqrt{Re_w}}\right)_{Pr=1} \tag{1}$$

Schuh (ref. 3) performed similar calculations with $Pr = 0.7$ for the flat plate, the two-dimensional stagnation point, and an intermediate pressure gradient. Levy (ref. 4) calculated many cases of constant-property flows for Prandtl numbers 0.7, 1.0, 5, and 10. Solutions for porous surfaces were obtained in reference 5 to estimate the effects of transpiration cooling on heat transfer. A numerical comparison of some of the results of references 3 to 5 is given in appendix B of reference 5. 3657

Variable fluid properties. - References 6 and 7 present solutions for $Pr_w = 0.7$ with and without transpiration cooling. The fluid properties were assumed to vary as powers of the temperature so that the Prandtl number varied within the boundary layer. Solutions to the compressible laminar-boundary-layer equations for $Pr$ of 0.7 and 1.0 with no transpiration cooling are presented in reference 8. The viscosity was taken to vary linearly with temperature so that $\rho\mu$ = constant. Solutions are presented in reference 9 for $Pr = 1.0$ with no transpiration cooling. The viscosity law there assumed is similar to that of Chapman and Rubesin (ref. 10).

For the present paper, additional stagnation-point solutions (both two-dimensional and axially symmetric) have been obtained for $Pr = 0.7$ with and without transpiration cooling. The method by which these solutions were calculated is indicated in appendix B.

The heat-transfer relations are given in terms of (1) a heat-transfer parameter $Nu/\sqrt{Re_w}$ from the exact solutions and (2) the local velocity gradient at the stagnation point.

## HEAT-TRANSFER RELATIONS

The characteristic quantity representing heat transfer which is obtained from exact solutions of the laminar-boundary-layer equations is $Nu/\sqrt{Re_w}$, where the Nusselt number $Nu = \dfrac{x\left(\frac{\partial t}{\partial y}\right)_w}{t_{aw} - t_w} = \dfrac{hx}{k_w}$, and the Reynolds number $Re_w = \dfrac{u_e x}{\nu_w}$.

In describing the flow over blunt bodies, the first term of the Taylor series for surface velocity is the linear relation

$$u_e = Cx \tag{2}$$

where $C$ is a constant representing the local velocity gradient external to the boundary layer at the stagnation point. Because of this linear velocity relation (eq. (2)), the ratio $Nu/\sqrt{Re_w}$ at the stagnation point ($x = 0$) is finite, although the Nusselt and Reynolds numbers individually become zero at $x = 0$. Furthermore, for a stagnation point, the external Mach number is zero, so that in the definition of Nu the adiabatic wall temperature is the free-stream stagnation temperature $t_0$.

3657

From the preceding relations, the heat-transfer coefficient $h$ can be expressed

$$h = \frac{k_w}{\sqrt{\nu_w}} \left(\frac{Nu}{\sqrt{Re_w}}\right) \sqrt{C} \tag{3}$$

CM-1 back

Similarly, the local rate of heat transfer $q$ to the wall per unit wall area, defined by the relation $q = h(t_0 - t_w)$, is

$$q = \frac{k_w(t_0 - t_w)}{\sqrt{\nu_w}} \left(\frac{Nu}{\sqrt{Re_w}}\right) \sqrt{C} \tag{4}$$

To solve a given problem, it is necessary to determine the velocity gradient $C$ from potential flow relations, and the parameter $Nu/\sqrt{Re_w}$ from the pertinent boundary-layer solutions.

## Local Velocity Gradient

The local velocity gradient in the vicinity of the stagnation point should wherever possible be evaluated from experimental velocity or pressure distributions for the configuration being considered. However, in the absence of such experimental information, a reasonable estimate may be made from potential flow relations.

The velocity on the surface of spheres and cylinders in subsonic potential flow is determined in references 11 and 12, respectively. The method used therein is the Rayleigh-Janzen expansion in powers of Mach number. The resulting velocity gradients at the stagnation point for $\gamma = 1.4$ are:

Sphere:

$$C = \frac{3u_1}{2r} \left(1 - 0.252\ M_1^2 - 0.0175\ M_1^4\right) \tag{5}$$

Cylinder:

$$C = \frac{2u_1}{r} (1 - 0.416\ M_1^2 - 0.164\ M_1^4) \tag{6}$$

where $u_1$ and $M_1$ are the subsonic velocity and Mach number ahead of the body, and $r$ is the radius of the body. Relations (5) and (6) were derived for uniform subsonic flow approaching the bodies. For the case of supersonic flight speeds, the body is preceded by a curved bow wave behind which the flow is nonuniform. Nevertheless, for a sphere the experimental pressure distribution near the stagnation point has been found from reference 13 to be well represented without consideration of shock curvature. In this case, $u_1$ and $M_1$ are taken to be the values of velocity and Mach number just behind the normal portion of the shock. However, for a cylinder in supersonic flight with axis normal to the flow, equation (6) does not appear adequate. The experimentally observed velocity gradients (refs. 14 and 15) more closely resemble that predicted for Newtonian flow, which is $C = \frac{\sqrt{2}\ u_1}{r}$.

3657

## Charts of Heat-Transfer Parameter

Values of the heat-transfer parameter $Nu/\sqrt{Re_w}$ for forced-convection heat transfer are presented in figure 1. The solid lines are for $Pr$ of 1.0 and 0.7 and represent the solutions of reference 9 and the present report. The dashed lines are for constant Prandtl number determined using equation (1). The small difference between the solutions of reference 7 and those of the present report for $Pr = 0.7$ arises from the different assumption of fluid-property variation. These solutions show that, for $t_w/t_0$ between 0 and 2, the variation in $Nu/\sqrt{Re_w}$ is less than about 10 percent from the values for $t_w/t_0 = 1$ for both the two-dimensional and the axially symmetric stagnation points. The values for $t_w/t_0 = 1$ are also those obtained for constant fluid properties.

The effect of transpiration through a porous wall on the heat-transfer parameter is shown in figure 2. The abscissa is the dimensionless normal velocity parameter $v_w/\sqrt{\nu_w C}$, which stems from the exact solutions. In general, as the normal velocity into the boundary layer is increased, the heat-transfer parameter decreases significantly. This decrease becomes more pronounced as the surface temperature is lowered. The broken lines represent values obtained by interpolation from the solutions of reference 7. The differences between the solutions of reference 7 and those of the present report, as evidenced by the lack of uniformity in the spacing of the curves of figure 2, are due to the different assumptions of fluid-property variation. For constant fluid properties $\left(\frac{t_w}{t_0} = 1\right)$, the two calculations should agree. An estimate of the spacing between the curves of $t_w/t_0 = 0$ and 0.25 for the axially symmetric case may be obtained by examination of the presently calculated points for $v_w/\sqrt{\nu_w C} = 0.707$.



## APPLICATION

To calculate either the heat-transfer coefficient $h$ from equation (3) or the local heat-transfer rate $q$ at a stagnation point from equation (4), it is necessary to know the local velocity gradient $C$ at the stagnation point and the dimensionless heat-transfer parameter $Nu/\sqrt{Re_w}$. The local velocity gradient may be obtained from established experimental data, and $Nu/\sqrt{Re_w}$ chosen from figures 1 or 2 according to the conditions at the stagnation point. In the absence of experimental data, the local velocity gradient may be estimated from equation (5) or (6), whichever is appropriate.

The problem at hand may often, however, be that of finding the surface temperature under the action of various types of cooling or else that of finding the transpiration mass flow required to maintain a specified surface temperature. For such problems it is necessary to consider the usual heat balance

$$\frac{k_w}{\sqrt{\nu_w}}(t_0 - t_w)\left(\frac{Nu}{\sqrt{Re_w}}\right)\sqrt{C} = q_{ic} + \rho_w v_w (\Delta H)_{tc} + q_r \qquad (7)$$

The left side of equation (7) represents the rate of heat transfer by convection to the surface (eq. (4)). The first term on the right side $q_{ic}$, which represents the rate of heat removal from the surface by an internal coolant, is the product of the internal coolant mass flow per unit cooled surface area and the enthalpy rise of this internal coolant per unit mass. The second term on the right side of equation (7) accounts for the heat removed by transpiration cooling, where $(\Delta H)_{tc}$ is the enthalpy rise of the transpiration coolant per unit mass. The last term of equation (7) represents the heat transferred from the surface by radiation. This may be quite important when high surface temperatures are being considered.

The solutions shown in figure 2 are exact only if the coolant and the external fluid at the stagnation point have the same physical properties. In some applications it may be desirable to use a coolant which is a different fluid from that flowing over the body (e.g., water as a coolant, with air flowing over the body). Although it is not possible from the present calculation to predict the additional effects if different fluids are involved, it is expected that the present results would be reasonable so long as either the rate of injection is small, or the properties of the coolant are similar to those of the external flow.

3657

For the general case of a liquid coolant being evaporated,

$$(\Delta H)_{tc} = c_{p,v}(t_w - t_v) + L_v + c_{p,l}(t_v - t_{res})$$

The subscripts $v$ and $l$ refer to the vapor and liquid states, respectively, $L_v$ is the latent heat of vaporization of the coolant, $t_v$ is the vaporization temperature of the coolant, and $t_{res}$ is the temperature of the coolant reservoir.

For a specified problem, the pertinent terms of equation (7) are retained and the calculation performed to effect a heat balance. The following form of equation (7) is convenient:

$$\frac{Nu}{\sqrt{Re_w}} = \frac{Pr_w}{c_{p,w}(t_0 - t_w)}\left[\frac{q_{ic}}{\sqrt{\rho_w \mu_w C}} + \frac{v_w}{\nu_w C}(\Delta H)_{tc} + \frac{q_r}{\sqrt{\rho_w \mu_w C}}\right] \qquad (8)$$

EXAMPLES

Several examples are presented to illustrate the use of the heat-transfer relations and the heat balance. The calculations are for a hemispherical-nosed body having a 1-foot radius and moving at $M = 5$ at an altitude of 175,000 feet where the ambient temperature is 170° F. The Mach number and velocity behind the shock are $M_1 = 0.415$ and $u_1 = 1231$ feet per second. Equation (5) indicates a velocity gradient at the stagnation point of magnitude 1767 per second.

I. Rate of internal cooling required to maintain a given wall temperature. - Since only the heat-transfer rate is required, the calculation for example I can be performed using equation (4) and the values of the heat-transfer parameter $Nu/\sqrt{Re_w}$ from figure 1. A value of $q$ is obtained for each assumed wall temperature. The result is shown on the left in figure 3.

<u>II. Rate of transpiration cooling required to maintain a given wall temperature</u>. - For example II, the heat balance from equation (8) is

$$\frac{Nu}{\sqrt{Re_w}} = \left[\frac{Pr_w(\Delta H)_{tc}}{c_{p,w}(t_0 - t_w)}\right]\frac{v_w}{\sqrt{\nu_w C}}$$

For given values of free-stream stagnation temperature and coolant reservoir conditions, the bracketed term is a function of wall temperature
3657 only. This equation thus provides a relation between the heat-transfer parameter $Nu/\sqrt{Re_w}$ and the normal velocity parameter $v_w/\sqrt{\nu_w C}$. Another relation between these two quantities is that of figure 2. The results of simultaneously satisfying both relations are shown in figure 3. The coolant assumed was water at a reservoir temperature of 40° F.

<u>III. Surface equilibrium temperature considering only the heat transfer by radiation</u>. - For example III, the heat balance, from equation (7), is

$$\frac{k_w}{\sqrt{\nu_w}}(t_0 - t_w)\left(\frac{Nu}{\sqrt{Re_w}}\right)\sqrt{C} = q_r = \sigma \varepsilon t_w^4$$

where $\sigma$ is the Stefan-Boltzmann coefficient and $\varepsilon$ is the emissivity of the wall material. The radiation receiver temperature to the fourth power was neglected here, as it would be small compared with $t_w^4$. The result of the indicated calculation is that, for an assumed emissivity of 0.6, radiation lowers the wall temperature from a stagnation temperature of 3780° R to a temperature of 1740° R.

<u>IV. Rate of transpiration cooling required to maintain a given wall temperature with radiation</u>. - The heat balance for example IV can be written, from equation (8),

$$\frac{Nu}{\sqrt{Re_w}} = \frac{Pr_w}{c_{p,w}(t_0 - t_w)}\left[\frac{v_w}{\sqrt{\nu_w C}}(\Delta H)_{tc} + \frac{q_r}{\sqrt{\rho_w \mu_w C}}\right]$$

Here again the coolant was taken to be water at a reservoir temperature of 40° F, and the emissivity was taken to be 0.6. For each assumed value of surface temperature (necessarily below 1740° R because of the radiation calculation of example III), values of $Nu/\sqrt{Re_w}$ and $v_w/\sqrt{\nu_w C}$ are found by trial-and-error solution using figure 2. The results are shown in figure 3.

Discussion of examples. - An examination of figure 3 shows that, omitting radiation, for small reduction in surface temperature the mode of cooling does not significantly affect the heat-transfer rate. However, as the desired surface temperature is further lowered, transpiration cooling requires noticeably less heat removal than does internal cooling. This same trend has been noted for zero pressure gradient (ref. 16). On a weight-of-coolant basis, transpiration cooling using a liquid coolant which becomes vaporized has a significant advantage over internal cooling for which boiling may not be permitted.

Radiation alone is seen to cool the surface from 3780° to 1740° R. 3657
However, if surface temperatures below 1000° R are required, radiation reduces the required convection heat transfer only slightly.

## CONCLUDING REMARKS

Relations are presented for calculating the forced-convection heat-transfer coefficient and local rate of heat transfer at both two-dimensional and axially symmetric stagnation points. These relations involve the local velocity gradient at the stagnation point and the dimensionless heat-transfer parameter $Nu/\sqrt{Re_w}$.

An examination of various exact solutions shows that cooling a surface at constant temperature without transpiration cooling can reduce the parameter $Nu/\sqrt{Re_w}$ by less than 10 percent from that of the insulated surface.

On the other hand, flow into the boundary layer through a porous surface tends to cause a large decrease in heat transferred to the surface. This decrease is more pronounced as the surface temperature is reduced.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 20, 1955

3657

CM-2

## APPENDIX A

## SYMBOLS

The following symbols are used in this report:

| | |
|---|---|
| $A$ | constant from $u_e = Ax^m$ |
| $B$ | constant from $(t_w - t_{sp}) = Bx^n$ |
| $C$ | stagnation-point velocity gradient |
| $c_p$ | specific heat at constant pressure |
| $f$ | boundary-layer stream function |
| $(\Delta H)_{tc}$ | enthalpy rise of transpiration coolant |
| $h$ | heat-transfer coefficient $\equiv \dfrac{k_w\left(\dfrac{\partial t}{\partial y}\right)_w}{t_{aw} - t_w}$ |
| $k$ | thermal conductivity |
| $M$ | Mach number |
| $m$ | exponent from $u_e = Ax^m$ |
| $Nu$ | Nusselt number $\equiv \dfrac{hx}{k_w}$ |
| $n$ | exponent from $(t_w - t_{sp}) = Bx^n$ |
| $Pr$ | Prandtl number |
| $q$ | local heat-transfer rate per unit area |
| $q_{ic}$ | rate of heat transfer to an internal coolant |
| $q_r$ | radiation heat-transfer rate per unit area |
| $Re_w$ | Reynolds number $Re_w = \dfrac{u_e x}{\nu_w}$ |
| $r$ | radius of sphere or cylinder |

| | |
|---|---|
| S | enthalpy function $= \frac{t_s}{t_0} - 1$ |
| t | temperature |
| $t_v$ | vaporization temperature |
| u | velocity component in x-direction |
| v | velocity component in y-direction |
| x | coordinate from stagnation point along body surface |
| y | coordinate normal to body surface |
| $\beta$ | pressure-gradient parameter, $\beta = \frac{2m}{m + 1}$ |
| $\gamma$ | ratio of specific heats |
| $\eta$ | boundary-layer similarity parameter |
| $\mu$ | dynamic viscosity |
| $\nu$ | kinematic viscosity |
| $\rho$ | density |

Subscripts:

| | |
|---|---|
| aw | adiabatic wall |
| e | local flow outside boundary layer (external) |
| s | stagnation value |
| sp | stagnation-point value |
| w | wall or surface value |
| 0 | free-stream stagnation value |
| 1 | conditions in front of body (but behind shock wave in supersonic flow) |

3657

## APPENDIX B

## EXACT SOLUTIONS FOR STAGNATION-POINT FLOW WITH PRANDTL NUMBER OF 0.7

In reference 9 Stewartson's transformation was applied to the compressible laminar-boundary-layer equations. The requirement of similarity was introduced and a viscosity law similar to that of Chapman and Rubesin (ref. 10) was assumed. The equations that resulted are

$$\left.\begin{aligned} f''' + ff'' &= \beta(f'^2 - 1 - S) \\ S'' + Pr\, fS' &= (1 - Pr)\left[\frac{(\gamma - 1)M_e^2}{1 + \frac{\gamma - 1}{2} M_e^2}\right](f'f''' + f''^2) \end{aligned}\right\} \tag{B1}$$

where $f$ is the boundary-layer stream function, $S$ is an enthalpy function, and primes denote differentiation with respect to the boundary-layer similarity variable $\eta$. For stagnation-point flow, $M_e = 0$. With $Pr = 0.7$, the equations to be solved are

$$\left.\begin{aligned} f''' + ff'' &= \beta(f'^2 - 1 - S) \\ S'' + 0.7\, fS' &= 0 \end{aligned}\right\} \tag{B2}$$

with the boundary conditions

$$\left.\begin{aligned} f(0) &= \begin{cases} 0 & \text{without transpiration cooling} \\ f_w = -\dfrac{v_w}{\sqrt{\nu_w C}}\sqrt{\beta} & \text{for transpiration cooling} \end{cases} \\ f'(0) &= 0 \\ S(0) &= S_w = \frac{t_w}{t_0} - 1 \end{aligned}\right\} \tag{B3}$$

For a two-dimensional stagnation point, $\beta = 1$; while for an axially symmetric stagnation point, $\beta = 1/2$ (ref. 17 from Mangler's transformation). Solutions to equations (B2) with boundary conditions (B3) were obtained on the IBM card-programmed calculator.

Values of the heat-transfer parameter $Nu/\sqrt{Re_w}$ are obtained from the solutions as follows. For two-dimensional flow,

$$\frac{Nu}{\sqrt{Re_w}} = -\left(\frac{S_w'}{S_w}\right)\sqrt{\frac{1}{2 - \beta}}$$

so that, at a two-dimensional stagnation point $(\beta = 1)$:

$$\frac{Nu}{\sqrt{Re_w}} = -\left(\frac{S_w'}{S_w}\right)_{\beta=1}$$

3657

For axially symmetric flow, the appropriate two-dimensional value of $Nu/\sqrt{Re_w}$ must be multiplied by $\sqrt{3}$ according to Mangler's transformation, so that at an axially symmetric stagnation point $(\beta = 1/2)$:

$$\frac{Nu}{\sqrt{Re_w}} = -\sqrt{2}\left(\frac{S_w'}{S_w}\right)_{\beta=1/2}$$

The solutions of reference 7 are, of course, also adapted to axially symmetric stagnation-point flow by obtaining the value of $Nu/\sqrt{Re_w}$ for $\beta = 1/2$ (Euler number $Eu = 1/3$) and multiplying by $\sqrt{3}$. Since in reference 7 solutions are not presented for $Eu = 1/3$, these must be obtained by interpolation. The normal velocity parameter defined in terms of the variables of reference 7 may be written $v_w/\sqrt{\nu_w C} = - f_w(Eu + 1)/2\sqrt{Eu}$, which for an axially symmetric stagnation point becomes $v_w/\sqrt{\nu_w C} = - 2f_w/\sqrt{3}$.

## REFERENCES


1. Goldstein, Sydney, ed.: Modern Developments in Fluid Dynamics. Vol. II. First ed., Clarendon Press (Oxford), 1938, p. 631.

2. Sibulkin, M.: Heat Transfer Near the Forward Stagnation Point of a Body of Revolution. Jour. Aero. Sci., vol. 19, no. 8, Aug. 1952, p. 570.

3. Schuh, H.: Laminar Heat Transfer in Boundary Layers at High Velocities. Rep. and Trans. 810, British M.A.P., Apr. 15, 1947.

3657

4. Levy, Solomon: Heat Transfer to Constant-Property Laminar Boundary-Layer Flows with Power-Function Free-Stream Velocity and Wall-Temperature Variations. Jour. Aero. Sci., vol. 19, no. 5, May 1952, pp. 341-348.

5. Donoughe, Patrick L., and Livingood, John N. B.: Exact Solutions of Laminar-Boundary-Layer Equations with Constant Property Values for Porous Wall with Variable Temperature. NACA TN 3151, 1954.

6. Brown, W. Byron, and Donoughe, Patrick L.: Tables of Exact Laminar-Boundary-Layer Solutions When the Wall is Porous and Fluid Properties are Variable. NACA TN 2479, 1951.

7. Brown, W. Byron, and Livingood, John N. B.: Solutions of Laminar-Boundary-Layer Equations Which Result in Specific-Weight-Flow Profiles Locally Exceeding Free-Stream Values. NACA TN 2800, 1952.

8. Levy, Solomon: Effect of Large Temperature Changes (Including Viscous Heating) upon Laminar Boundary Layers with Variable Free-Stream Velocity. Jour. Aero. Sci., vol. 21, no. 7, July 1954, pp. 459-474.

9. Cohen, Clarence B., and Reshotko, Eli: Similar Solutions for the Compressible Laminar Boundary Layer with Heat Transfer and Pressure Gradient. NACA TN 3325, 1955.

10. Chapman, Dean R., and Rubesin, Morris W.: Temperature and Velocity Profiles in the Compressible Laminar Boundary Layer with Arbitrary Distribution of Surface Temperature. Jour. Aero. Sci., vol. 16, no. 9, Sept. 1949, pp. 547-565.

11. Kaplan, Carl: The Flow of a Compressible Fluid Past a Sphere. NACA TN 762, 1940.

12. Kaplan, Carl: Two-Dimensional Subsonic Compressible Flow Past Elliptic Cylinders. NACA Rep. 624, 1938.

13. Stine, Howard A., and Wanlass, Kent: Theoretical and Experimental Investigation of Aerodynamic-Heating and Isothermal Heat-Transfer Parameters on a Hemispherical Nose with Laminar Boundary Layer at Supersonic Mach Numbers. NACA TN 3344, 1954.

14. Gowen, Forrest E., and Perkins, Edward W.: Drag of Circular Cylinders for a Wide Range of Reynolds Numbers and Mach Numbers. NACA TN 2960, 1953. (Supersedes NACA RM A52C20.)

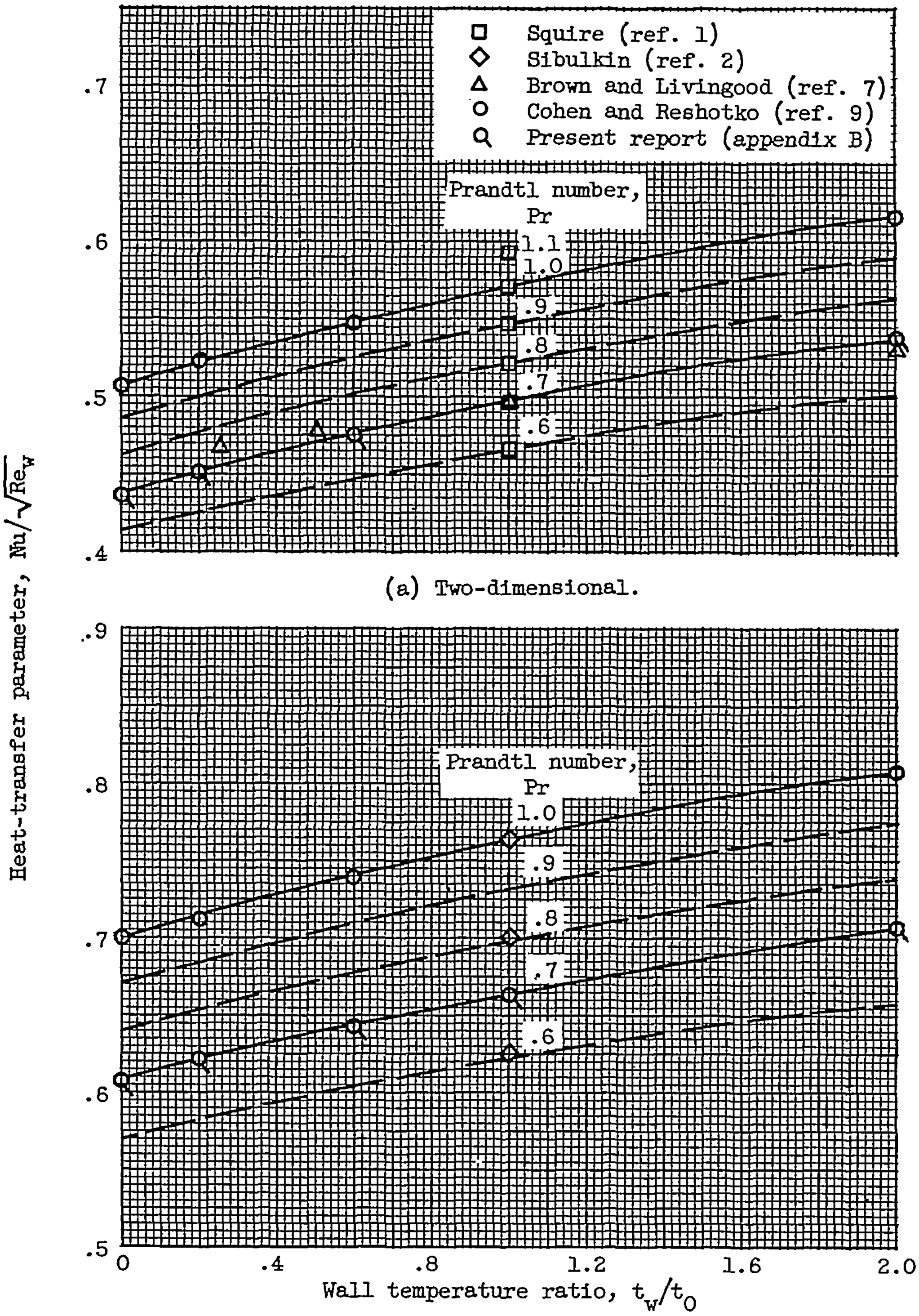
15. Moeckel, W. E.: Experimental Investigation of Supersonic Flow with Detached Shock Waves for Mach Numbers Between 1.8 and 2.9. NACA RM E50D05, 1950.

16. Low, George M.: The Compressible Laminar Boundary Layer with Fluid Injection. NACA TN 3404, 1955.

17. Schlichting, Herman: Grenzschicht-Theorie. Verlag und Druck G. Braun, Karlsruhe, 1951, pp. 160-161.

3657

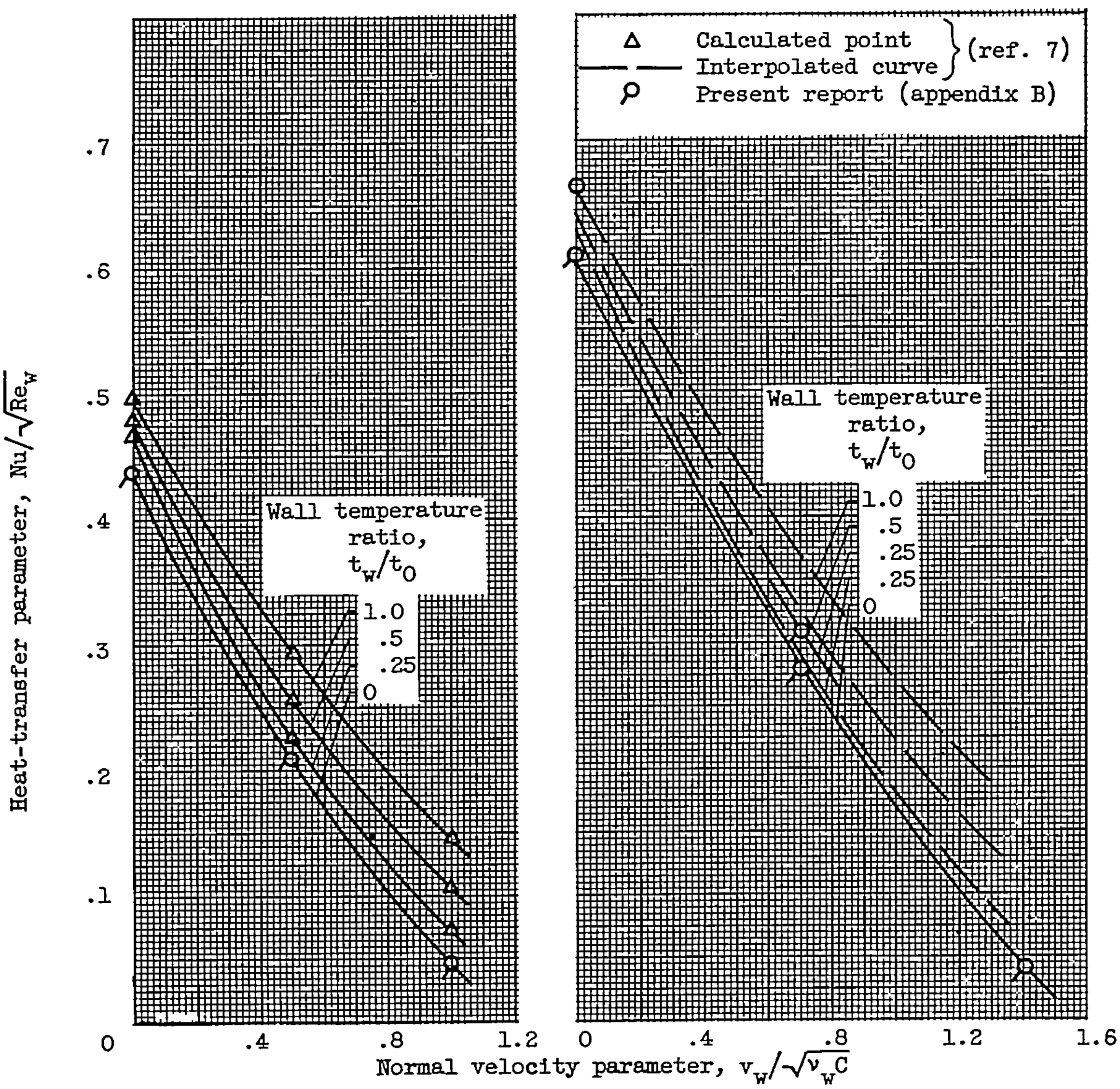
3657




(b) Axially symmetric.

Figure 1. - Effect of Prandtl number and wall temperature on heat-transfer parameter.

3657




(a) Two-dimensional.

(b) Axially symmetric.

Figure 2. - Effect of transpiration cooling on heat-transfer parameter for various wall temperatures. Prandtl number, 0.7.

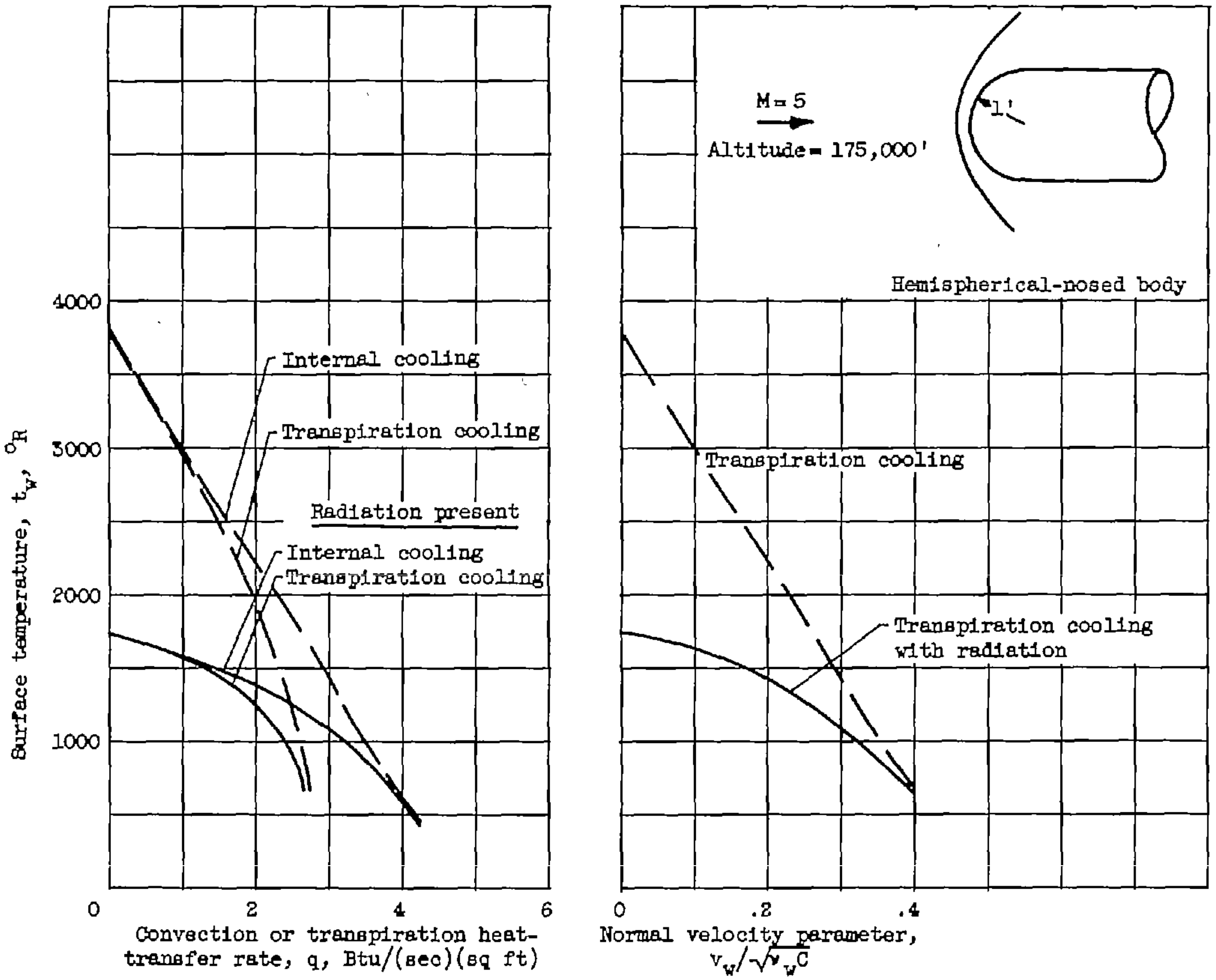



Figure 3. - Effects of internal cooling, transpiration cooling, and radiation on stagnation-point heat transfer and surface temperature of hemispherical-nosed body.

NACA-Langley - 7-8-55 - 1000