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CORRELATION OF FREE-FLIGHT TURBULENT HEAT-TRANSFER DATA FROM AXISYMMETRIC BODIES WITH COMPRESSIBLE FLAT-PLATE RELATIONSHIPS

by Ernest V. Zoby and Edward M. Sullivan

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CORRELATION OF FREE-FLIGHT TURBULENT HEAT-TRANSFER DATA FROM AXISYMMETRIC BODIES WITH COMPRESSIBLE FLAT-PLATE RELATIONSHIPS

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SUMMARY

Published experimental turbulent heat-transfer data obtained over a range of free-flight conditions and body shapes were compared with calculated turbulent flat-plate values. The calculated values were evaluated by use of a modified Reynolds analogy and the skin-friction relationships of Blasius or Schultz-Grunow with compressibility effects accounted for by evaluating the flow properties on reference conditions. For reference Reynolds numbers less than 10^7, the calculated heating rates based on either of the two methods correlated well with the experimental data. For reference Reynolds numbers greater than 10^7 and less than 8×10^7, the calculated heating rates based on the Schultz-Grunow relation compare better with the available experimental data.

INTRODUCTION

One of the problems facing designers of hypersonic flight vehicles is that of accurately predicting turbulent heating rates. Reynolds analogy provides a correlation between the Stanton number and the skin-friction coefficient c_f. Expressions for the turbulent-boundary-layer skin-friction coefficient must be based on assumptions and empirical relations, and their validity can be established only by experimentation. One such expression which has been utilized and successfully correlated with supersonic flight-test data is that of Van Driest (ref. 1). His work is, however, limited in that it is based on perfect-gas considerations and hence is not applicable when the bow shock wave becomes strong enough to initiate dissociation. Therefore, other expressions for c_f which are applicable in the hypersonic flight regime must be developed and verified.

One obvious approach to the problem is to use existing expressions for c_f from incompressible flow and attempt to correct for compressibility effects and the state of the gas in the boundary layer. Extensive ground tests (e.g., refs. 2, 3, and 4) have shown that many of the incompressible skin-friction relationships, properly corrected through the use of reference temperature or reference enthalpy, are applicable over wide ranges of Mach number, Reynolds number, and wall temperature ratio. The application of these relationships to hypersonic flow problems is questionable since most of the experiments used to validate the expressions were performed in facilities limited to free-stream Mach numbers of 6 or less with flat-plate test models. Only a limited amount of turbulent heat-transfer data is available for blunt bodies (e.g., ref. 5).

In view of these considerations it is desirable to compare the heating rates computed from some of these c_f expressions with heating rates measured in flight on blunt and sharp noses and along conical and cylindrical surfaces. Representative flight-test heating-rate data are available for blunt bodies (refs. 6 to 11) and sharp cones (refs. 11 to 16); in most of these reports the data were compared with the method of Van Driest. In the present investigation, the heating rates calculated for comparison with experimental data are based on the turbulent skin-friction expressions of Blasius and Schultz-Grunow. These expressions were adopted because they are representative of the available incompressible c_f expressions and because they are recommended (refs. 17 and 18) for hypersonic reentry design problems.

An evaluation, using both ground- and flight-test data, was attempted in references 19 and 20 for blunt bodies and sharp cones. Since the authors of these references investigated the problem of predicting turbulent heating rates using the Blasius skin-friction coefficient, a comparison of their results with the results of the present investigation is included.

SYMBOLS

The units for the physical quantities in this paper are given in both U.S. Customary Units and the International System of Units (SI).

c_f	local skin-friction coefficient
c_p	specific heat at constant pressure, Btu/slug-degrees Rankine (joules/kilogram-degrees Kelvin)
H	enthalpy, Btu/slug (joules/kilogram)
l	reference length, 10 inches or 25.4 centimeters (fig. 2)
M	Mach number
N_{Nu}	Nusselt number

N_{Pr}	Prandtl number
N_{St}	Stanton number
$\dot{q}$	heating rate, Btu/foot^2-second (joules/meter^2-second)
R	Reynolds number
r_n	nose radius, feet (meters)
s	wetted distance from stagnation point, feet (meters)
T	temperature, degrees Rankine (degrees Kelvin)
U	velocity, feet/second (meter/second)
x	flat-plate wetted length, feet (meters)
Z	ratio of molecular weight of mixture at reference state to molecular weight of mixture at a temperature and pressure
θ_c	cone half-angle, degrees
μ	viscosity, slugs/foot-second (newton-seconds/meter^2)
ρ	density, slugs/foot^3 (kilograms/meter^3)

Subscripts:

aw	adiabatic wall
e	local conditions
i	incompressible
s	stagnation conditions
w	wall condition

x flat-plate wetted length

∞ free stream

An asterisk with a symbol indicates a reference condition.

ANALYSIS

Correlation of the flight-test data with calculated heating rates was accomplished with the Blasius and Schultz-Grunow flat-plate skin-friction relations (ref. 21). It is stated in references 17 and 21 that the Blasius relation applies for $10^5 \leqq R_{e,x} \leqq 10^7$ whereas the Schultz-Grunow relation applies for $10^5 \leqq R_{e,x} \leqq 10^9$.

The correlations were made by relating the skin-friction coefficients to the heating rate by a modified Reynolds analogy (ref. 22) expressed as

$$N_{St} = \frac{\dot{q}_w}{\rho_e U_e \left(H_{aw} - H_w\right)} = \frac{c_f}{2}\left(N_{Pr}\right)^{-2/3} \tag{1}$$

In order to evaluate equation (1), the skin-friction coefficient c_f must be properly calculated. As obtained from reference 21, the Blasius relation for the incompressible skin-friction coefficient is

$$\left(\frac{c_f}{2}\right)_i = 0.0296\left(R_{e,x}\right)^{-0.2} \tag{2}$$

and the Schultz-Grunow incompressible skin-friction relation is

$$\left(\frac{c_f}{2}\right)_i = 0.185\left(\log_{10} R_{e,x}\right)^{-2.584} \tag{3}$$

Compressibility effects are accounted for by evaluating the flow properties at reference conditions (refs. 17 and 18). The skin-friction coefficient is then written as

$$\frac{c_f}{2} = 0.0296\left(\frac{\rho^*}{\rho_e}\right)^{0.8}\left(\frac{\mu^*}{\mu_e}\right)^{0.2}\left(R_{e,x}\right)^{-0.2} \tag{4}$$

and

$$\frac{c_f}{2} = 0.185\left(\frac{\rho^*}{\rho_e}\right)\left(\log_{10} R_x^*\right)^{-2.584} \tag{5}$$

for the Blasius and Schultz-Grunow relations, respectively.

The skin-friction coefficients (eqs. (4) and (5)) were then related to the heating rate by equation (1) and the following expressions for the heating rate were obtained:

$$\dot{q}_w = 0.0296\rho_e U_e\left(H_{aw} - H_w\right)\left(N_{Pr}^*\right)^{-2/3}\left(R_{e,x}\right)^{-0.2}\left(\frac{\rho^*}{\rho_e}\right)^{0.8}\left(\frac{\mu^*}{\mu_e}\right)^{0.2} \tag{6}$$

and

$$\dot{q}_w = 0.185\rho_e U_e\left(H_{aw} - H_w\right)\left(N_{Pr}^*\right)^{-2/3}\left(\log_{10} R_x^*\right)^{-2.584}\left(\frac{\rho^*}{\rho_e}\right) \tag{7}$$

The reference conditions were evaluated by use of

$$\frac{T^*}{T_e} = 1 + 0.035{M_e}^2 + 0.45\left(\frac{T_w}{T_e} - 1\right) \tag{8}$$

from reference 3, in which T^*/T_e is given as T'/T_1, or

$$H^* = H_e + \frac{1}{2}\left(H_w - H_e\right) + 0.22\left(N_{Pr}\right)^{1/3}\left(H_s - H_e\right) \tag{9}$$

from reference 18. The T^* method was used for the perfect-gas cases, where $Z = 1$ and c_p is constant; whereas the reference-enthalpy (H^*) method was used where $Z \neq 1$ (ref. 23) and/or c_p is not constant. It should be noted that the reference-enthalpy method could be used over the entire gas regime.

The data used in the comparison were selected by inspecting plots of N_{St} or $\dot{q}$ given in the individual references for times when the angle of attack was 0° or near 0°. Only data which indicated fully developed turbulent flow were used, that is, points were not accepted if the trend of the data indicated any possibility that the flow at that location may have been in transition. Also, no obviously "wild" points were accepted.

For the calculated heating rates the following procedure was used to determine the flow properties:

(1) With the assumptions of equilibrium air and isentropic flow, the flow conditions (local or reference) on the blunt bodies were determined with the aid of calculated or measured (where available) pressure distributions and the measured wall temperatures.

(2) The conditions on the sharp cones were determined with the aid of reference 24 and the measured wall temperatures.

In addition, the following basic ground rules were adopted:

(1) Pressure-gradient effects on the blunt bodies were neglected.

(2) Reynolds numbers on the blunt bodies were based on s, the wetted distance from the stagnation point.

(3) Reynolds numbers on the sharp cones were calculated based on the wetted distance from the sharp tip by using the Van Driest relationship (ref. 25) between the Reynolds number on a sharp cone and that on a flat plate; that is, the equivalent flat-plate $R_{e,x}$ is equal to one-half of the sharp-cone $R_{e,x}$.

The authors recognize that use of a virtual origin other than the sharp tip of the cone may give better results if one is attempting to correlate heat-transfer data. However, the distance from the sharp tip has been employed in this paper because of problems associated with locating the virtual origin and the desire to utilize a simple method applicable for design purposes.

CORRELATION OF EXPERIMENTAL AND CALCULATED VALUES

Blunt Bodies

Experimental free-flight turbulent heat-transfer data on blunt bodies were obtained from references 6 to 11. The data cover ranges of free-stream Mach number from 2.9 to 13.4, free-stream Reynolds number per foot (per 0.3048 meter) from 0.64×10^6 to 30.7×10^6, body shapes from a hemisphere-cylinder to a sphere-cone with a half-angle of 25^o, wall temperature ratio T_w/T_e from 0.183 to 1.09, and Z values from 1.0 to 1.09. The blunt-body data are given in table 1. Figures 1(a) and 1(b) present the ratio of calculated (eqs. (6) and (7)) to experimentally measured heating rates at various nondimensional body stations s/r_n. Figure 1(a) presents the ratios on the hemispherical segments and figure 1(b) presents the ratios on the conical skirts of the sphere-cones. The calculated heating rates based on equation (6) were compared with the measured heating rates for all the body stations since the local Reynolds numbers did not exceed 10^7. For purposes of comparison, the calculated heating rates based on equation (7) were evaluated at several body stations as shown in figures 1(a) and 1(b). The predictions based on equation (7) gave approximately the same comparison with the experimental data as did the values calculated with equation (6). Figure 1 indicates reasonable agreement between these prediction procedures and experimental data. The largest deviations noted were +22 percent and -10 percent of the measured values.

The deviations just noted are apparently in contradiction with results shown in figure 5 of reference 19. The data shown in the figure in reference 19 spread out to ±50 percent of the correlation line. An investigation of this figure reveals that only five data points are from flight tests and that they were obtained near the tangency point of the blunt bodies, which is a region of relatively low pressure gradient. Of these five data points, one lies on the correlation line, three are approximately 20 percent off the line, and one is approximately 40 percent off the line. This last point (from ref. 26) has been investigated and there is serious doubt that it was in a fully developed turbulent flow. The other four data points show approximately the same scatter as shown in figure 1(a) of the present report. Therefore, figure 1(a) tends to substantiate what the limited data of reference 19 indicated, namely, the turbulent heating can be predicted on blunt noses to within 20 percent if fully developed turbulent flow exists. The reader should note that the data in the present paper extend this correlation into high-pressure-gradient regions of blunt noses, that is, within 30° from the stagnation point. Data corresponding to data presented in figure 1(b) are shown in figure 22 of reference 19. The data shown in reference 19 at an s/r_n of approximately 2.5 indicate the same scatter as that shown in figure 1(b).

Sharp Cones

Representative experimental turbulent heat-transfer data on sharp cones were obtained from references 11 to 16. The data cover ranges of M_∞ from 1.99 to 4.2, R_∞ per foot (per 0.3048 meter) from 0.789×10^7 to 2.0×10^7, cone half-angles from 5° to 25°, and wall temperature ratios T_w/T_e from 0.928 to 2.28. The data utilized are shown in table 2.

Figure 2 presents the ratio of calculated (eqs. (6) and (7)) to experimentally measured heating rates on sharp cones at various body stations x/l where l was arbitrarily selected as 10 in. (25.4 cm). The heating rates calculated by use of equation (6) agree with the measured heating rates to within +21 percent and -18 percent at all stations, with most of the data agreeing within ±10 percent. Figure 2 also shows that the use of equation (7) improves this agreement between the experimental and calculated heating rates.

The results of figure 2 are in general agreement with the results of reference 20. If the Schultz-Grunow skin-friction correlation had been used in reference 20, most of the data for reference Reynolds numbers greater than 10^7 would have been within ±15 percent of the calculated line.

Composite Correlation

A composite correlation for all the data in tables 1 and 2 is shown in figure 3 in the form of $N_{Nu,x}^*$ as a function of R_x^*. The solid line is computed from the expression

$$N_{Nu,x}^* = 0.0296\left(N_{Pr}^*\right)^{1/3}\left(R_x^*\right)^{4/5} \tag{10}$$

and the dashed line is computed from

$$N_{Nu,x}^* = 0.185\left(N_{Pr}^*\right)^{1/3}\left(R_x^*\right)\left(\log_{10} R_x^*\right)^{-2.584} \tag{11}$$

The data points were evaluated by using the experimentally measured heating rates and the flow properties based on reference conditions in the expression

$$N_{Nu,x}^* = N_{St}^* \, N_{Pr}^* \, R_x^* \tag{12}$$

The experimental Nusselt numbers calculated with equation (12) show excellent agreement with the Nusselt number relation of equation (10) for $10^5 \leqq R_x^* \leqq 10^7$ and with the Nusselt number relation of equation (11) for $10^7 \leqq R_x^* \leqq 4 \times 10^7$. (In view of the fact that there is only one set of flight-test data in this Reynolds number range, it cannot be established that the Schultz-Grunow relation is definitely the better of the two methods.) It should again be noted that for the blunt-body data R_x^* is based on the wetted length from the stagnation point whereas for the sharp-cone data R_x^* is based on one-half of the wetted length from the tip. It should also be noted that, if the Nusselt number relation of equation (11) is extended through the lower Reynolds number values, the experimental Nusselt numbers are in good agreement with the relation over the entire Reynolds number range.

The results presented in figure 3 show that the sharp-cone and blunt-body data can be correlated by using the previously outlined procedure.

CONCLUDING REMARKS

Experimental turbulent heat-transfer data obtained for a range of free-flight environments and body shapes were compared with values calculated by use of turbulent flat-plate theory. The calculated values were evaluated by using a modified Reynolds analogy and the skin-friction coefficients of Blasius and Schultz-Grunow with compressibility effects accounted for by evaluating the flow properties on reference conditions.

The results of this investigation show that the selected incompressible flat-plate turbulent heating equations used in the appropriate manner produce good correlation with available flight-test data over large ranges of Mach number, Reynolds number, and wall temperature ratio for bodies with various cone half-angles and bluntness ratios. For reference Reynolds numbers less than 10^7, the calculated heating rates based on either the Blasius or Schultz-Grunow skin-friction coefficient were within +22 percent and -10 percent of the measured heating rates. For reference Reynolds numbers greater than 10^7 and less than 8×10^7, the calculated heating rates based on the Schultz-Grunow skin-friction coefficient gave a better correlation with the experimental data from the single available flight in the reference Reynolds number range than did the rates based on the Blasius skin-friction coefficient.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 12, 1966,
711-02-04-01-23.

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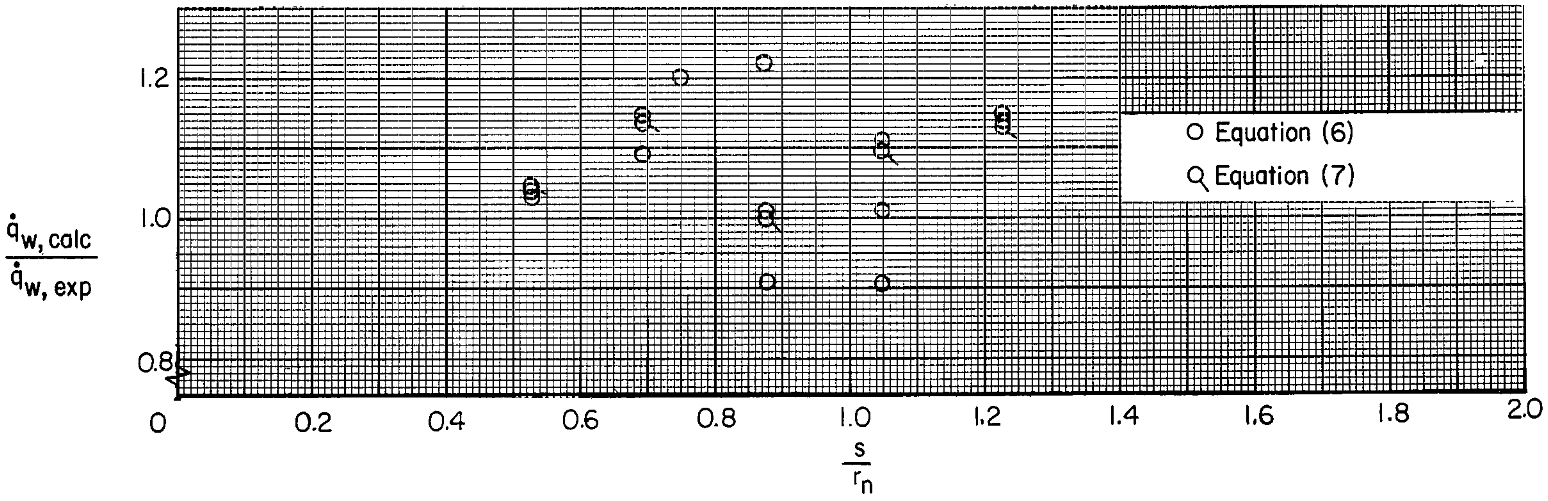
TABLE 1.- CONDITIONS FOR FIGURE 1 (BLUNT BODY)

s/r_n	Reference	M_∞	R_∞ per ft (per 0.3048 m)	θ_c, deg	T_w/T_e	$\dfrac{\dot{q}_{w,calc}}{\dot{q}_{w,exp}}$	
						Eq. (6)	Eq. (7)
2.00	6	3.9	9.5×10^6	9	0.894	1.11	1.06
3.15	6	3.9	9.5	9	.93	1.13	----
3.50	6	3.9	9.5	9	.965	1.05	----
4.00	6	3.9	9.5	9	.995	1.15	----
4.80	6	3.9	9.5	9	1.03	1.025	----
17.45	7	3.8	13.1	9	1.075	1.01	1.01
19.1	8	2.98	17.0	9	1.09	1.11	----
.524	9	11.61	29.9	0	.348	1.04	----
.524	9	11.35	30.4	0	.328	1.03	1.049
.698	9	12.05	28.5	0	.299	1.15	1.14
.698	9	11.0	30.7	0	.38	1.089	----
.873	9	11.6	21.6	0	.246	1.016	1.008
1.047	9	12.05	28.5	0	.285	1.113	1.105
1.047	9	11.41	20.1	0	.22	.906	----
1.047	9	11.6	21.6	0	.234	1.014	----
1.222	9	12.09	27.4	0	.225	1.152	1.135
1.222	9	12.0	25.6	0	.183	1.147	----
7.45	10	13.4	1.52	14.5	.246	.905	----
10.5	10	13.4	1.52	14.5	.24	.935	.915
12.5	10	5.3	.64	14.5	.46	1.025	----
.70	11	3.5	17.6	25	.75	1.21	----
.875	11	4.7	21.6	25	.90	.909	----
.875	11	4.0	19.4	25	.85	1.22	----
1.36	11	4.7	21.6	25	.90	1.12	----
1.76	11	4.0	19.4	25	.90	1.14	----
3.41	11	4.0	19.4	25	.90	1.14	----

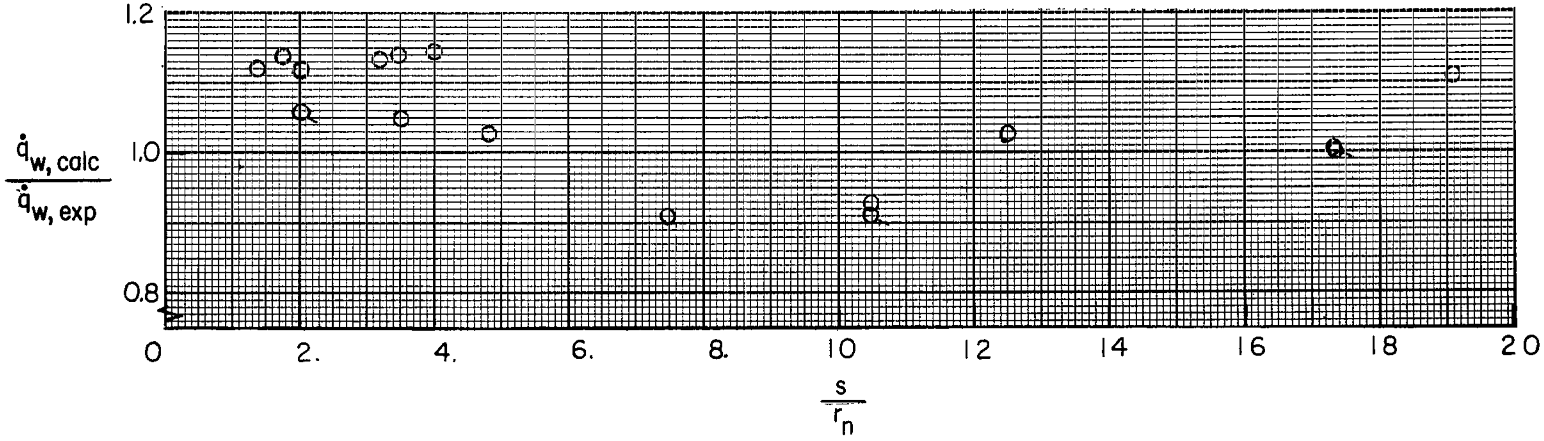
TABLE 2.- CONDITIONS FOR FIGURE 2 (SHARP CONE)

$\left[l = 10 \text{ in.} \quad (25.4 \text{ cm})\right]$

x/l	Reference	M_∞	R_∞ per ft (per 0.3048 m)	θ_c, deg	T_w/T_e	$\dfrac{\dot{q}_{w,calc}}{\dot{q}_{w,exp}}$	
						Eq. (6)	Eq. (7)
0.613	11	1.99	1.41×10^7	25	1.0	1.145	----
.613	11	3.5	1.92	25	1.325	1.21	----
1.0	11	1.99	1.41	25	.985	1.1	----
1.775	11	2.25	1.53	25	1.04	1.07	1.13
1.395	12	2.97	.789	12.5	.928	1.105	----
1.42	12	2.97	.789	12.5	.94	1.055	----
1.55	13	4.2	1.55	7.5	1.7	1.06	----
1.7	13	4.2	1.55	7.5	1.65	1.055	----
1.4	14	3.09	1.57	7.5	1.65	1.04	----
1.0	15	3.75	1.15	5	2.2	1.165	----
1.4	15	3.8	1.17	5	2.2	1.08	----
1.9	15	3.9	1.435	5	2.28	.96	----
2.4	15	3.9	1.435	5	2.18	1.02	----
3.0	15	3.9	1.435	5	2.16	1.095	----
1.2	16	2.1	1.41	5	1.045	1.03	1.009
2.2	16	2.1	1.41	5	1.045	1.06	1.06
2.7	16	2.1	1.41	5	1.05	.995	----
5.9	16	2.75	1.7	5	1.1	.91	.968
6.7	16	3.62	2.0	5	1.345	.85	.907
7.5	16	2.86	1.35	5	1.815	.85	.90
8.3	16	3.62	2.0	5	1.345	.818	.895
8.3	16	2.86	1.35	5	1.8	.877	.916
8.8	16	2.86	1.35	5	1.805	.9	.932



(a) Hemispherical nose.



(b) Conical skirts of sphere-cones.

Figure 1.- Comparison of experimental and calculated turbulent heating rates on blunt bodies.

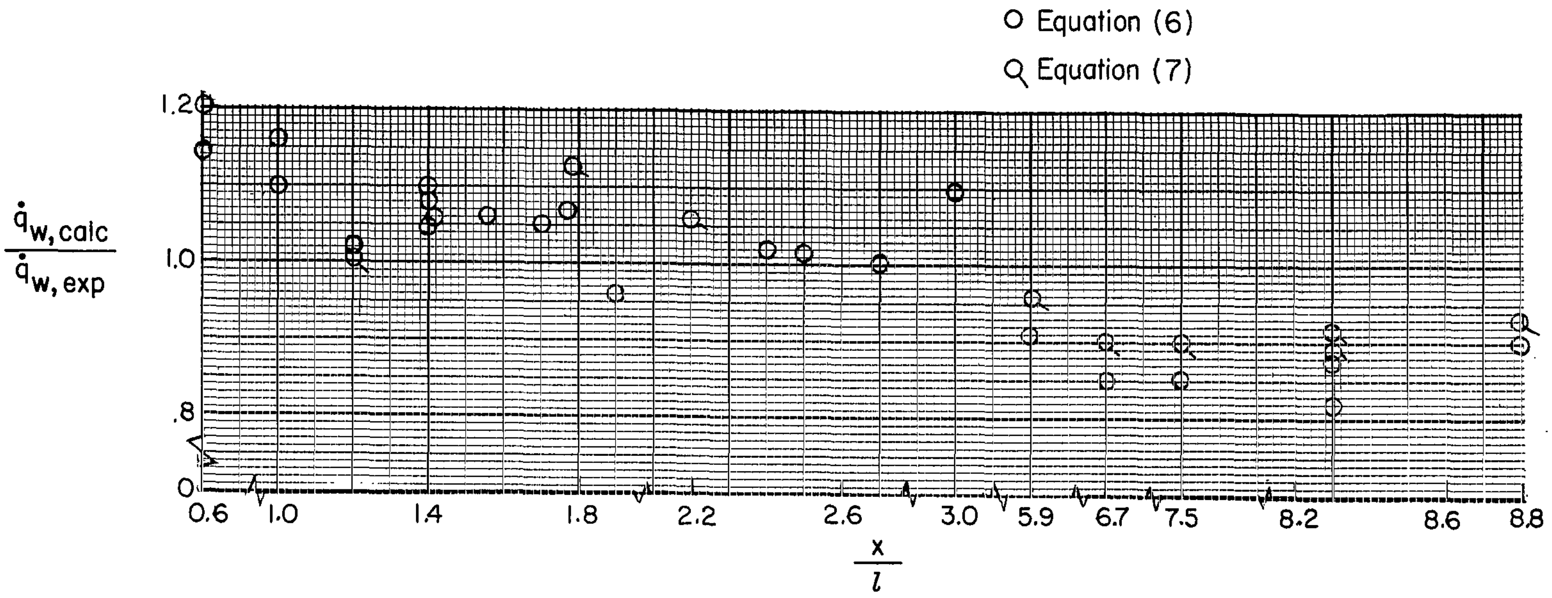


Figure 2.- Comparison of experimental and calculated turbulent heating rates on sharp cones. l = 10 in. (25.4 cm).

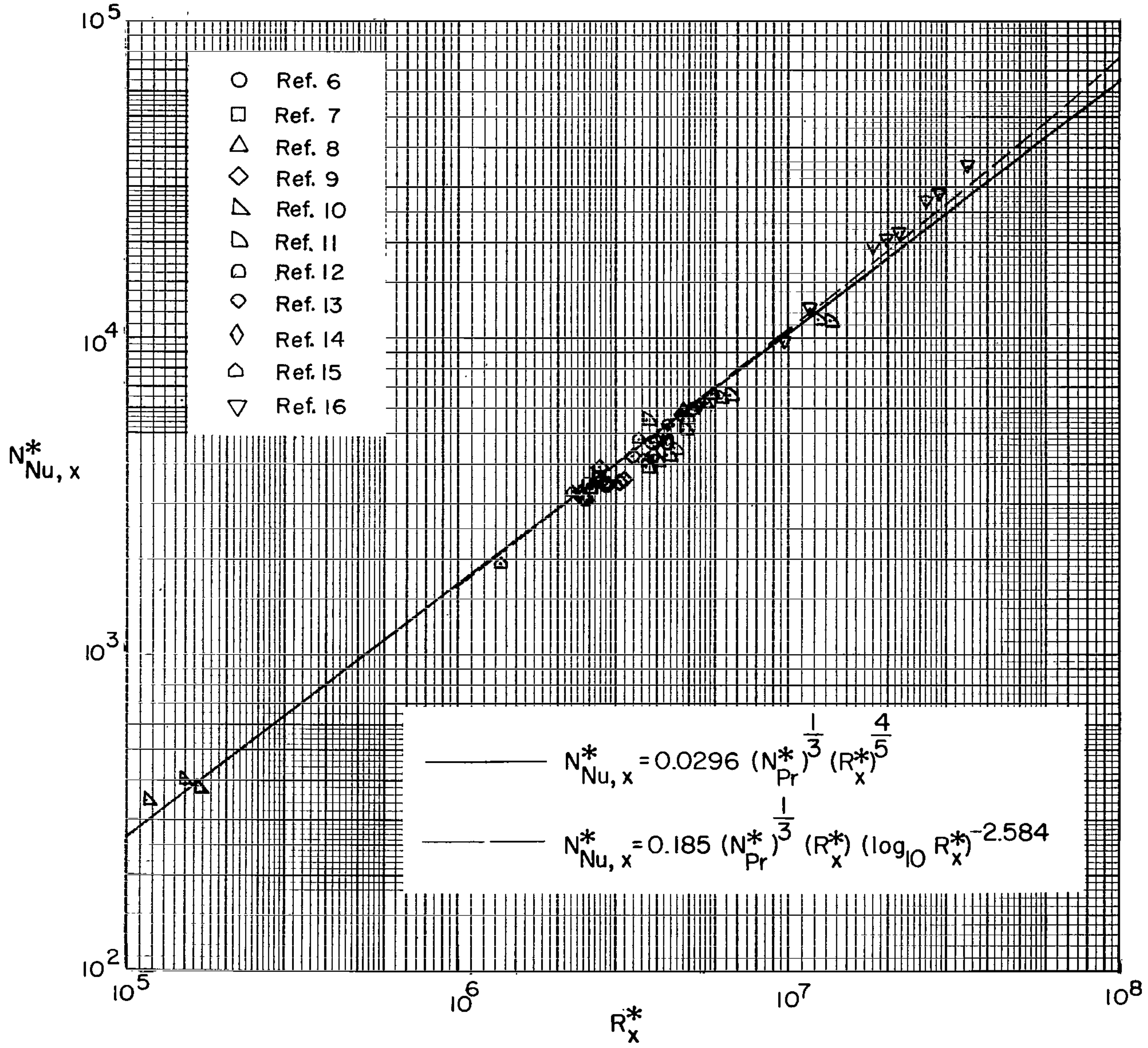


Figure 3.- Variation of Nusselt number with Reynolds number.

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