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RESEARCH MEMORANDUM

CORRELATION OF FORCED-CONVECTION HEAT-TRANSFER DATA FOR AIR FLOWING IN SMOOTH PLATINUM TUBE WITH LONG-APPROACH ENTRANCE AT HIGH SURFACE AND INLET-AIR TEMPERATURES

By Leland G. Desmon and Eldon W. Sams

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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CORRELATION OF FORCED-CONVECTION HEAT-TRANSFER DATA FOR AIR FLOWING IN SMOOTH PLATINUM TUBE WITH LONG-APPROACH ENTRANCE AT HIGH SURFACE AND INLET-AIR TEMPERATURES

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SUMMARY

An investigation of forced-convection heat transfer was conducted with air flowing through an electrically heated platinum tube with a long-approach entrance, an inside diameter of 0.525 inch, and a length of 24 inches over ranges of Reynolds number up to 320,000, average inside-tube-wall temperature up to 3053° R, and inlet-air temperature up to 1165° R.

Correlation of the heat-transfer data using the conventional Nusselt relation wherein the physical properties of the air were evaluated at the average bulk temperature resulted in separation of data with tube-wall-temperature level. Satisfactory correlation of the data was obtained, however, by use of modified correlation parameters wherein the mass velocity G (or product of average air density and velocity evaluated at bulk temperature $\rho_b V_b$) in the Reynolds number was replaced by the product of average air velocity evaluated at the bulk temperature and the density evaluated at either the average inside-tube-wall temperature or the average film temperature; in addition all the physical properties of air were correspondingly evaluated at either the average inside-tube-wall temperature or the average film temperature.

INTRODUCTION

Experimental data on forced-convection heat transfer to air flowing in smooth tubes at surface temperatures up to about 2100° R and an inlet-air temperature of about 540° R are presented in references 1 and 2. The low surface-temperature data in these references agree reasonably well with the average line obtained by McAdams from correlation of the results of various investigators (reference 3). As the surface temperature increases, however, the data separate and can no longer be correlated by use of the conventional Nusselt relation. It is further shown in references 1 and 2 that, when certain modifications are applied to the conventional method of correlation, the data for all surface temperatures fall together, resulting in good correlation over the entire range of conditions investigated. The data are extended in reference 4 to include the effect of various entrance configurations. 1402

In order to increase the range of surface temperature, heat-transfer data were obtained with air flowing through an electrically heated silicon carbide tube at surface temperatures up to 2500° R (reference 5). These data were thought to be somewhat unreliable, however, because the silicon carbide tube was rough, porous, and of uncertain effective heat-transfer length. Accordingly, the range of high surface temperatures was reinvestigated with a platinum tube and the results are reported herein. The data cover ranges of surface temperature up to 3053° R and inlet-air temperature from 540° to 1165° R.

APPARATUS

A schematic diagram of the heater tube and associated components of the air and electrical systems used in this investigation is shown in figure 1. A photograph of the heater-tube installation is shown in figure 2. The setup, in general, was similar to those of references 1, 2, 4, and 5.

Heater Tube

The heater tube, details of which are shown in figure 3, consisted of a platinum tube having an inside diameter of 0.525 inch, a wall thickness of 0.080 inch, and an effective heat-transfer length of 24 inches. Both ends of the platinum tube were silver-soldered into specially fabricated copper bushings, which in turn were silver-soldered to Inconel flanges. Although the electrical leads were attached to the Inconel flanges, the resistance of the flanges and copper bushings was negligible compared to that of the platinum tube and therefore the effective heat-transfer length was considered to be the 24-inch length of platinum only. An approach section with a length of 24 inches and an inside diameter of 0.525 inch was attached to the inlet end of the heater tube. Measurements of the approach-section-wall temperature indicated that warming of this section by conduction losses from the heater-tube flange resulted in a maximum increase in inlet-air temperature of less than 1 percent.

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The heater tube was thermally insulated from the atmosphere by three concentric stainless-steel radiation shields with insulating sand filling the spaces between the shields. The total thickness of insulation and shielding was $1\frac{1}{8}$ inches.

Inasmuch as local outside-tube-wall temperatures of 3000° F were contemplated (and actually measured), occasional thermocouple failures were anticipated. Accordingly, ring contact-type thermocouples were used to facilitate replacement and to avoid marring the surface of the platinum. The platinum - platinum-rhodium thermocouples used were located at 2-inch intervals along the length of the heater tube with one additional thermocouple, located 3/16 inch outside each end of the heater tube, peened into the copper bushings (fig. 3). The thermocouples were fabricated by butt-welding the two dissimilar wires, holding the junction on the tube surface, and wrapping each wire halfway around the tube. The two wires were then drawn through a two-hole ceramic tube from the test section at a point diametrically opposite the junction as may be seen in figure 2. The wires were spring-loaded to maintain several ounces of force to hold the junction against the tube wall. The temperature indicated by this thermocouple arrangement was found to be in good agreement with that indicated by a conventional peened-type thermocouple when checked in an induction furnace over a range of temperatures up to 2500° R.

Air and Electrical Systems

Air system. - As shown in figure 1, compressed air was supplied through a pressure-regulating valve, filter, heater, and two A.S.M.E. type flat-plate orifices in series to the inlet tank. From the inlet tank, the air passed through the approach section, the heater tube, and then into the mixing tank from which it was discharged to the atmosphere. The inlet tank, mixing tank, and entrance and exit piping adjoining the heater tube were thermally insulated.

The temperature of the air entering the heater tube was measured by a silver-shielded radiation-type thermocouple located in the inlet tank. The temperature of the air leaving the heater tube was measured by two chromel-alumel thermocouples located immediately downstream of a set of mixing baffles in the mixing tank.

Electrical system. - The electrical system was similar to that described in reference 5. Power was supplied to the heater tube from a 208-volt, 60-cycle supply line stepped down to the desired value through a transformer and two saturable reactors. The capacity of the electrical equipment was 25 kilovolt-amperes at a maximum of 10 volts. The power was measured by a watt meter connected to the tube, as shown in figure 1.

SYMBOLS

The following symbols are used in this report:

c_p	specific heat of air at constant pressure, (Btu/(lb)($^{\circ}$F))
D	inside diameter of heater tube, (ft)
G	mass velocity (mass flow per unit cross-sectional area), (lb/(hr)(sq ft))
h	average heat-transfer coefficient, (Btu/(hr)(sq ft)($^{\circ}$F))
k	thermal conductivity of air, (Btu/(hr)(sq ft)($^{\circ}$F/ft))
k_p	thermal conductivity of platinum, (Btu/(hr)(sq ft)($^{\circ}$F/ft))
Q	rate of heat transfer to air, (Btu/hr)
S	effective heat-transfer area of heater tube, 0.275 (sq ft)
T	total temperature, ($^{\circ}$R)
T_b	average bulk temperature equal to average of entrance and exit total temperatures, ($^{\circ}$R)
T_f	average film temperature equal to half the sum of average bulk and average inside-tube-wall temperatures, ($^{\circ}$R)
T_s	average inside-tube-wall temperature, ($^{\circ}$R)
V	velocity, (ft/hr)
W	air flow, (lb/hr)
μ	absolute viscosity of air, (lb/(hr)(ft))

ρ	density of air, (lb/cu ft)
hD/k	Nusselt number
$c_p\mu/k$	Prandtl number
DG/μ	Reynolds number
$\rho_f V_b D/\mu_f$	modified film Reynolds number
$\rho_s V_b D/\mu_s$	modified surface Reynolds number

Subscripts:

1	heater-tube entrance
2	heater-tube exit
o	outside surface of heater tube
b	bulk (when applied to properties, indicates evaluation at average bulk temperature)
f	film (when applied to properties, indicates evaluation at average film temperature)
s	surface (when applied to properties, indicates evaluation at average inside-tube-wall temperature)

PROCEDURE AND METHOD OF CALCULATION

Experimental Procedure

The experimental procedure, which is similar to that used in references 1, 2, 4, and 5, is briefly reviewed as follows: The air flow through the heater tube was adjusted to the desired value of Reynolds number at certain values of inlet-air and average surface temperatures. When conditions reached equilibrium, the data were recorded. This procedure was then repeated, maintaining the inlet-air and surface temperatures constant until the desired range of Reynolds number was covered for a series of values of inlet-air and surface temperatures.

Data were obtained over ranges of Reynolds number from about 20,000 to 320,000, average inside-tube-wall temperature up to 3053° R, inlet-air temperature up to 1165° R, and heat-flux density up to 145,000 Btu per hour per square foot.

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Method of Calculation

In the method of calculation, the physical properties of the air used in correlating the data are the same as those presented in reference 5; the pertinent relations are, however, given for convenience.

Heat-transfer coefficients. - The average heat-transfer coefficient h is computed from the experimental data by the relation

$$h = \frac{Wc_{p,b}(T_2 - T_1)}{S(T_s - T_b)} \tag{1}$$

The bulk temperature T_b is defined as the average of the heater-tube-entrance and -exit total temperature T_1 and T_2, respectively.

The average inside-tube-wall temperature T_s is computed from the relation

$$T_s = T_o - 0.012 \frac{Q}{k_p} \tag{2}$$

Equation (2) was obtained by substituting the physical dimensions of the platinum tube in an equation derived (reference 6) with the assumptions that heat is uniformly generated across the tube wall and that heat flow is directed radially inward. The outside-tube-wall temperature T_o is obtained from integration of axial-temperature-distribution curves and the thermal conductivity of platinum k_p may be closely approximated between the temperatures of 700° to 3100° R by the relation

$$k_p = 0.0062T_s + 37.7 \tag{3}$$

The straight-line equation (equation 3) best fits the data of reference 7 between the stated temperature limits.

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Correlation of heat-transfer data. - The data are first correlated in the conventional manner by the Nusselt relation

$$\frac{hD}{k} = C\left(\frac{DG}{\mu}\right)^m \left(\frac{c_p\mu}{k}\right)^n \tag{4}$$

where $(hD/k)/(c_p\mu/k)^{0.4}$ is plotted against DG/μ to determine experimentally the constant C and the exponent m; the exponent n is taken as 0.4; and the physical properties of the air are evaluated at the bulk temperature.

Correlation of the data is greatly improved, however, by use of modified correlation parameters wherein the mass velocity G (or $\rho_b V_b$) in the Reynolds number is replaced by the product of average air velocity evaluated at the bulk temperature and the density evaluated at either the average inside-tube-wall temperature or the average film temperature; in addition all the physical properties of air are correspondingly evaluated at either the average inside-tube-wall temperature or the average film temperature. The average film temperature is defined as half the sum of the average bulk and average surface temperatures. The modified surface Reynolds number is

$$\frac{\rho_s V_b D}{\mu_s} = \left(\frac{DG}{\mu_b}\right)\left(\frac{\mu_b}{\mu_s}\right)\left(\frac{\rho_s}{\rho_b}\right) = \left(\frac{DG}{\mu_b}\right)\left(\frac{\mu_b}{\mu_s}\right)\left(\frac{T_b}{T_s}\right) \tag{5}$$

and the modified surface Nusselt relation is

$$\frac{hD}{k_s} = C_s\left(\frac{\rho_s V_b D}{\mu_s}\right)^{m_s} \left(\frac{c_{p,s}\mu_s}{k_s}\right)^{n_s} \tag{6}$$

Similarly, the modified film Nusselt relation is

$$\frac{hD}{k_f} = C_f\left(\frac{\rho_f V_b D}{\mu_f}\right)^{m_f} \left(\frac{c_{p,f}\mu_f}{k_f}\right)^{n_f} \tag{7}$$

In equations (6) and (7), the constants C_s and C_f and the exponents m_s and m_f are experimentally determined and the exponents n_s and n_f are taken as 0.4.

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RESULTS AND DISCUSSION

Correlation of Data at Inlet-Air Temperature of 540° R

The data obtained at an inlet-air temperature of 540° R are comparable with the data presented in references 1, 2, 4, and 5.

Conventional correlation based on bulk temperature. - The heat-transfer data obtained at a nominal inlet-air temperature of 540° R and at surface temperatures from 981° to 3053° R are presented in the conventional manner in figure 4 where Nusselt number divided by Prandtl number to the 0.4 power $(hD/k_b)/(c_{p,b}\mu_b/k_b)^{0.4}$ is plotted against Reynolds number DG/μ_b. Included for comparison is the average curve obtained by McAdams (reference 3).

As has been shown previously (references 1, 2, 4, and 5), the data form a family of parallel curves with a common slope of about 0.8 above a Reynolds number of about 25,000. Each curve represents an individual surface temperature. The low temperature data approach McAdams' curve; but as surface temperature is increased, the data fall progressively below the reference curve until at a surface temperature of 3053° R and a Reynolds number of 100,000 the conventional method predicts a value of Nusselt number that is almost 100 percent too high.

Modified correlation based on surface temperature. - When Reynolds number is modified in the manner previously described and all the physical properties of the air are evaluated at the average surface temperature, the results shown in figure 5 are obtained. The data are the same as in figure 4 and agree with the results of reference 4. The curve through the data is that which best fits the data of reference 4. The equation of the curve for Reynolds numbers above 10,000 is

$$\left(\frac{hD}{k_s}\right)\Bigg/\left(\frac{c_{p,s}\mu_s}{k_s}\right)^{0.4} = 0.023\left(\frac{\rho_s V_b D}{\mu_s}\right)^{0.8} \qquad (8)$$

Although the curve was established from data obtained at surface temperatures up to about 2100° R, it is valid for predicting heat-transfer coefficients at higher surface temperatures as indicated by the agreement between it and the present data for which the average surface temperatures were as high as 3053° R.

Modified correlation based on film temperature. - The data are replotted in figure 6 where Reynolds number is modified as previously described, but all the physical properties of the air including density are evaluated at the average film temperature instead of the average surface temperature. The equation of the curve drawn through the data above a Reynolds number of 13,000 is

$$\left(\frac{hD}{k_f}\right) \bigg/ \left(\frac{c_{p,f}\mu_f}{k_f}\right)^{0.4} = 0.0196 \left(\frac{\rho_f V_b D}{\mu_f}\right)^{0.8} \qquad (9)$$

This method of correlation results in a maximum scatter of ± 12 percent above a Reynolds number of 13,000 compared to ± 4 percent in figure 5.

Comparison of methods of evaluating the heat-transfer data. - The relation between the methods of correlation used in figures 4, to 6 is illustrated in figure 7 where two data points at average surface temperatures of 1511° and 3053° R are plotted as determined by all three methods. The ordinate is Nusselt number divided by Prandtl number to the 0.4 power and the abscissa is Reynolds number. The equation of the reference curve is

$$\frac{\text{Nusselt number}}{\text{Prandtl number}^{0.4}} = 0.023(\text{Reynolds number})^{0.8} \qquad (10)$$

If Prandtl number is considered a constant in order to facilitate explanation, the vertical height of either data point on any temperature basis is inversely proportional to the thermal conductivity at the temperature of evaluation. In other words, as the temperature at which the thermal conductivity is evaluated is increased from bulk to surface, the value of the ordinate decreases. Similiarly, the horizontal distance to the right of an abscissa value of unity is inversely proportional to the product of absolute viscosity and temperature of evaluation as may be seen from equation (5).

The final result of increasing the temperature of evaluation is to move the given data point to the left at a faster rate than in the downward direction, thus reducing the separation with surface temperature. The magnitude of the effect of modifying the data is proportional to the average surface temperature at which the data were obtained, as indicated by the fact that the 3053° R point moves farther than the 1511° R point when undergoing the same modification. The effect of the modifications is that of bringing the data at various average surface temperatures to a common line having a slope of 0.8.

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Correlation of Elevated Inlet-Air Temperature Data

Additional heat-transfer data were obtained over a range of elevated inlet-air temperatures from 760° to 1165° R. When plotted in the conventional manner wherein the physical properties of the air are evaluated at the average bulk temperature, the data exhibited a trend with surface temperature similar to that shown in figure 4. A slight inlet-air-temperature effect was also in evidence in figure 8.

Correlation based on surface temperature. - The elevated inlet-air-temperature data are plotted in figure 8 using modified surface Reynolds number and evaluating the physical properties of the air at the average surface temperature. The curve shown is the one used to correlate the data obtained at an inlet-air temperature of 540° R in figure 5.

Comparison of data obtained at one inlet-air temperature, such as 760° R, with three average surface temperatures shows that this method of correlation largely eliminates the trend with surface temperature. The scatter, which is in evidence, is primarily believed to be separation of data with inlet-air temperature, the maximum scatter being about ±16 percent. An average line through the data would be about 12 percent below the reference line. Although the reason for separation of data with inlet-air temperature is unknown, measurements of the approach-section-wall temperature indicate that this effect is not due to a change in inlet-air temperature between the point where measured in the inlet tank and the heater-tube entrance. The effect becomes more pronounced at the higher inlet-air temperatures.

Correlation based on film temperature. - The elevated inlet-air-temperature data are again shown in figure 9 using modified film Reynolds number and evaluating the physical properties of the air at the average film temperature. The curve shown is the one used to correlate data obtained at an inlet-air temperature of 540° R in figure 6. Examination of the data reveals that both the surface-temperature and inlet-air-temperature trends are small and the scatter is random. The maximum scatter is about ±11 percent, somewhat less than that evident in the previous correlation. An average line through the data would be about 6 percent below the reference line.

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Correlation of Data at Inlet-Air Temperatures from 540° to 1165° R

Determination of constant in modified Nusselt equation. - All the heat-transfer data obtained over ranges of average surface temperature from 981° to 3053° R and nominal inlet-air temperature from 540° to 1165° R are shown in figure 10 where the ordinate is $(hD/k_s)/0.023\left[(c_{p,s}\mu_s/k_s)^{0.4}(\rho_s V_b D/\mu_s)^{0.8}\right]$ and the abscissa is modified surface Reynolds number $\rho_s V_b D/\mu_s$. Values of the ordinate in figure 10 correspond to the ratio of the experimentally determined constant in the Nusselt equation divided by 0.023, the value given in references 2 to 4. A separation of data with inlet-air temperature is quite evident. The data obtained at an inlet-air temperature of 540° R agree very well with a constant value of 0.023. As the inlet-air temperature increases, however, the average value of the constant decreases until at an inlet-air temperature of 1165° R the constant should be 80 percent of 0.023 or 0.0184. The average value of the constant for all the data is 0.0215 with a scatter around this value of ±18 percent.

The data from figure 10 are replotted in figure 11 where the parameters are the same except that they are evaluated at the average film temperature instead of the average surface temperature. An inlet-air-temperature effect is also seen in figure 11, but its magnitude is smaller than that in figure 10 and not as well defined. The average constant for all the data is 0.823 × 0.023 or about 0.019 with a scatter around this value of ±15 percent. Comparing the scatter in figures 10 and 11 leads to the conclusion that the modified-film-temperature method of correlation is somewhat better than the modified-surface-temperature method when the elevated inlet-air-temperature data are considered.

Correlation based on surface temperature. - All the data obtained in the present investigation are shown in figure 12 together with the long-approach-entrance data of reference 4, where the product of Nusselt number divided by Prandtl number to the 0.4 power is plotted against modified surface Reynolds number and the physical properties are based on the surface temperature. The equation of the line best fitting the data above a Reynolds number of 10,000 is

$$\left(\frac{hD}{k_s}\right)\bigg/\left(\frac{c_{p,s}\mu_s}{k_s}\right)^{0.4} = 0.022\left(\frac{\rho_s V_b D}{\mu_s}\right)^{0.8} \tag{11}$$

This value of the constant is only about 5 percent below the conventionally used value of 0.023 but is more representative of the data. The value 0.022 was arrived at by weighting all the data points (including those obtained from reference 4). As in figure 10, the maximum scatter in the correlation above a Reynolds number of 10,000 is about ±18 percent; the root mean square deviation from the line is, however, only $6\frac{1}{2}$ percent.

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Correlation based on film temperature. - Figure 13 is the same as figure 12 except that the physical properties of the air are evaluated at the average film temperature instead of the average surface temperature. The equation of the line best fitting the data above a Reynolds number of 13,000 is

$$\left(\frac{hD}{k_f}\right) \Bigg/ \left(\frac{c_{p,f}\mu_f}{k_f}\right)^{0.4} = 0.020\left(\frac{\rho_f V_b D}{\mu_f}\right)^{0.8} \tag{12}$$

In figure 11, the maximum scatter in the correlation is about ±15 percent and the root mean square deviation from the line is, as in figure 12, only $6\frac{1}{2}$ percent.

CONCLUDING REMARKS

The discussion of figures 12 and 13 indicates that the modified film correlation is somewhat better than the modified surface correlation from the standpoint of maximum scatter of experimental data. It appears, however, that the modified-surface and modified-film correlation methods, respectively, overcorrect and undercorrect the data; the undercorrection results in the smaller scatter. Future investigation may indicate that use of some temperature between surface and film will result in the best correlation.

Until the small uncertainties in the method of correlation have been explained, the equation of the line recommended for design purposes at Reynolds numbers above 10,000 is

$$\frac{hD}{k_s} = 0.022\left(\frac{\rho_s V_b D}{\mu_s}\right)^{0.8} \left(\frac{c_{p,s}\mu_s}{k_s}\right)^{0.4}$$

SUMMARY OF RESULTS

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The results of a heat-transfer investigation conducted with air flowing through an electrically heated platinum tube with a long-approach entrance, an inside diameter of 0.525 inch, and a length of 24 inches, over ranges of Reynolds number up to 320,000, average inside-tube-wall temperature up to 3053° R, inlet-air temperature up to 1165° R, and heat-flux density up to 145,000 Btu per hour per square foot showed that:

1. Correlation of the average heat-transfer coefficient according to the conventional Nusselt relation wherein the physical properties of the air are based on the average bulk temperature resulted in separation of data with surface temperature.

2. The heat-transfer data obtained at an inlet-air temperature of 540° R correlated best using modified correlation parameters wherein the mass velocity G (or product of average air density and velocity evaluated at bulk temperature $\rho_b V_b$) in the Reynolds number was replaced by the product of average air velocity evaluated at the bulk temperature and the density evaluated at either the average inside-tube-wall temperature or the average film temperature; in addition, all the physical properties of air were correspondingly evaluated at either the average inside-tube-wall temperature or the average film temperature.

3. Although the modified film correlation was slightly better than the modified surface correlation when the heat-transfer data obtained at all inlet-air temperatures from 540° to 1165° R were included, it is believed that modified surface and modified film correlations overcorrect and undercorrect the data, respectively.

4. Until the small uncertainties in the method of correlation have been explained, the equation of the line recommended for design purposes at Reynolds numbers above 10,000 is

$$\frac{hD}{k_s} = 0.022\left(\frac{\rho_s V_b D}{\mu_s}\right)^{0.8}\left(\frac{c_{p,s}\mu_s}{k_s}\right)^{0.4}$$

where

$\frac{hD}{k_s}$ Nusselt number evaluated at surface temperature

$\frac{\rho_s V_b D}{\mu_s}$ modified surface Reynolds number

$\frac{c_{p,s}\mu_s}{k_s}$ Prandtl number evaluated at surface temperature

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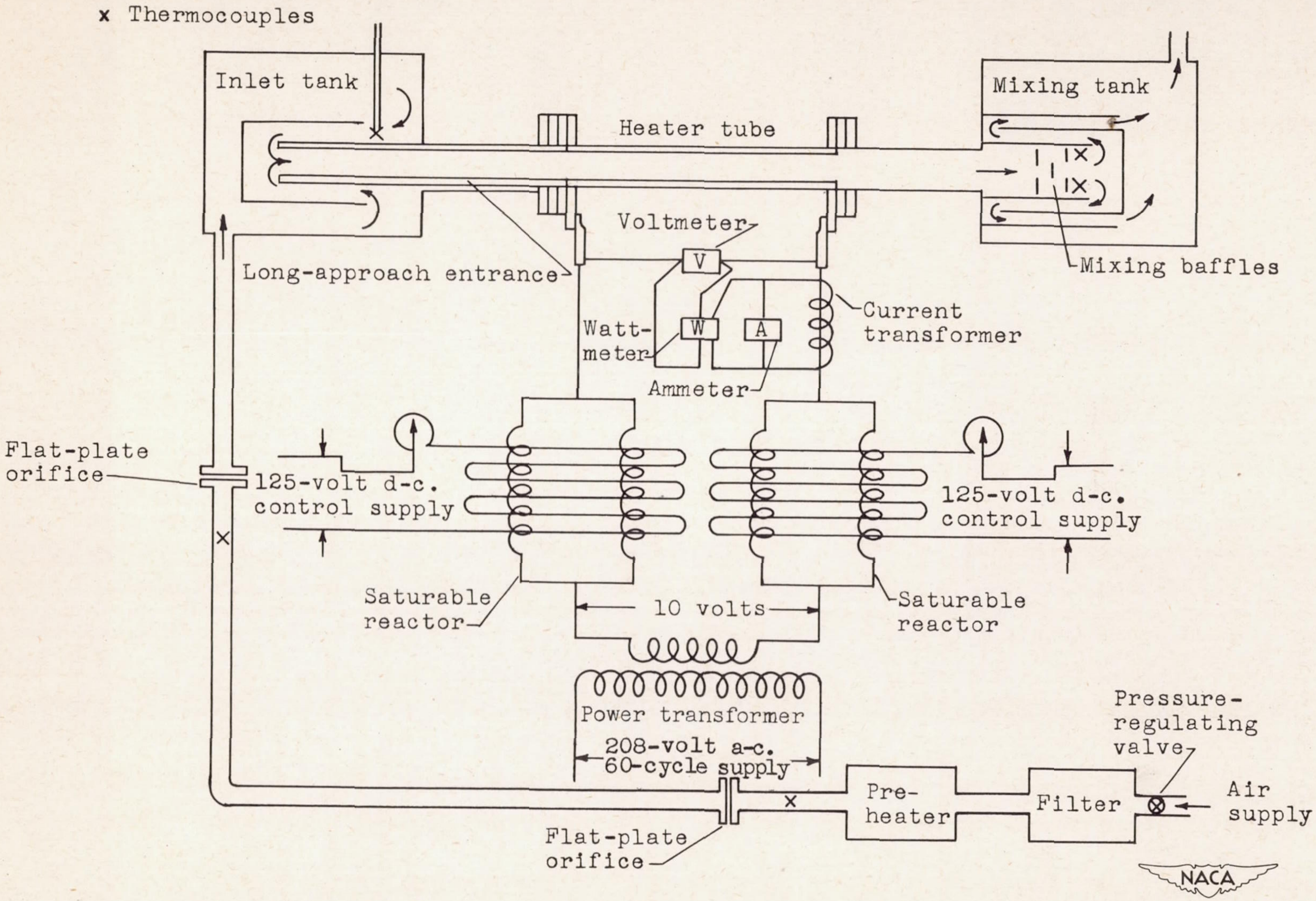

Figure 1. - Schematic diagram showing arrangement of experimental equipment.

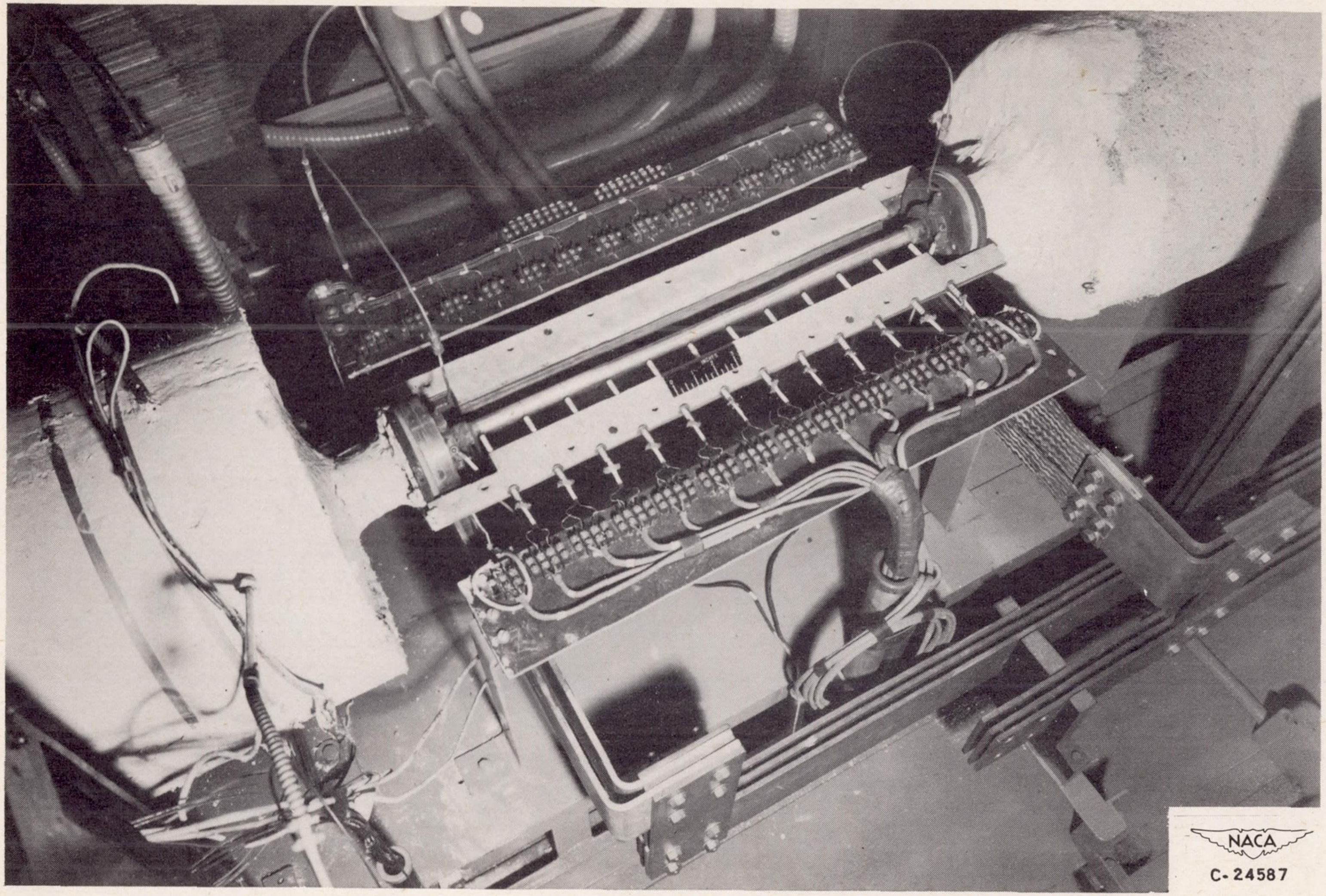

Figure 2. - Heater-tube installation.

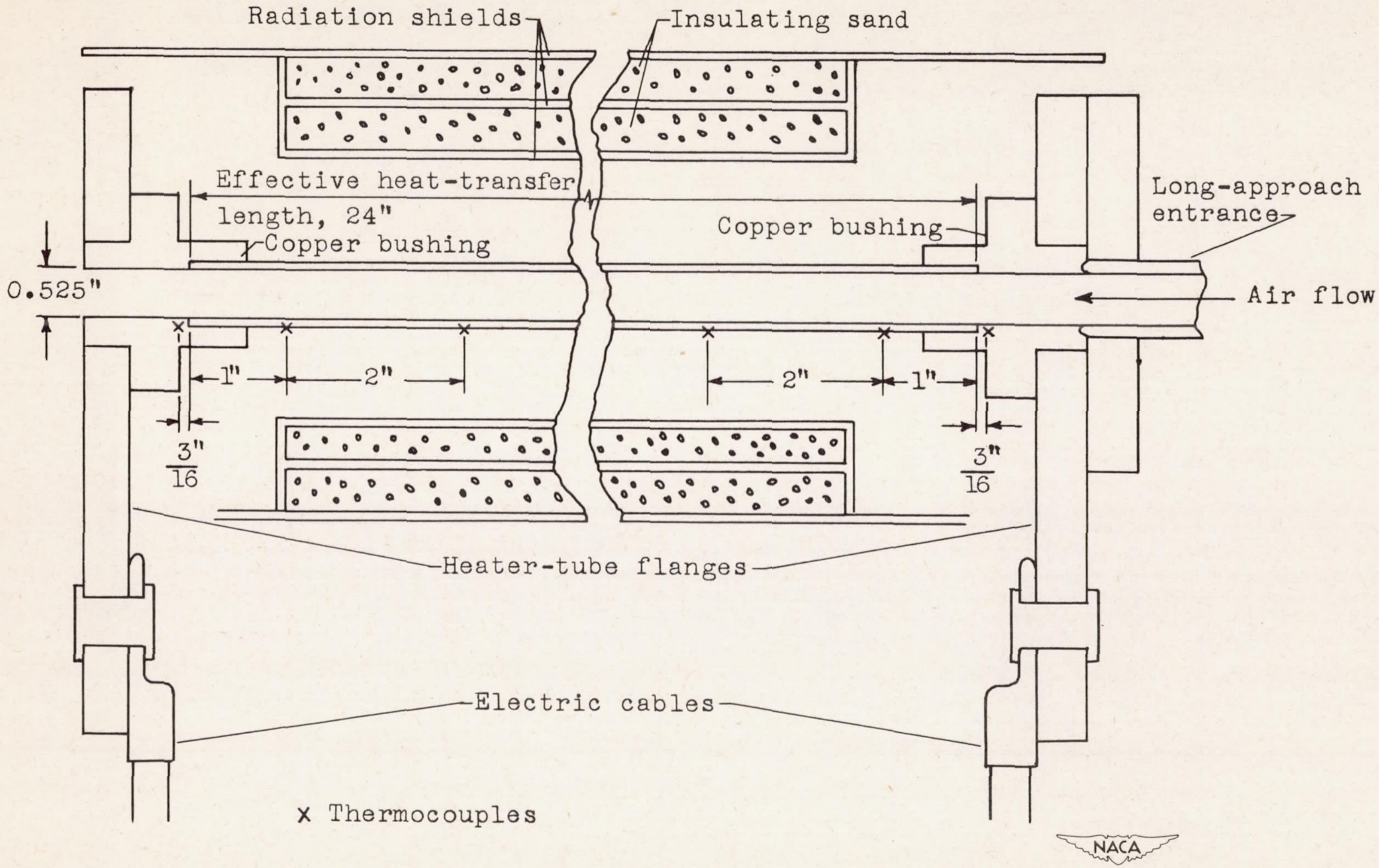

Figure 3. - Schematic diagram of heater tube showing thermocouple locations.

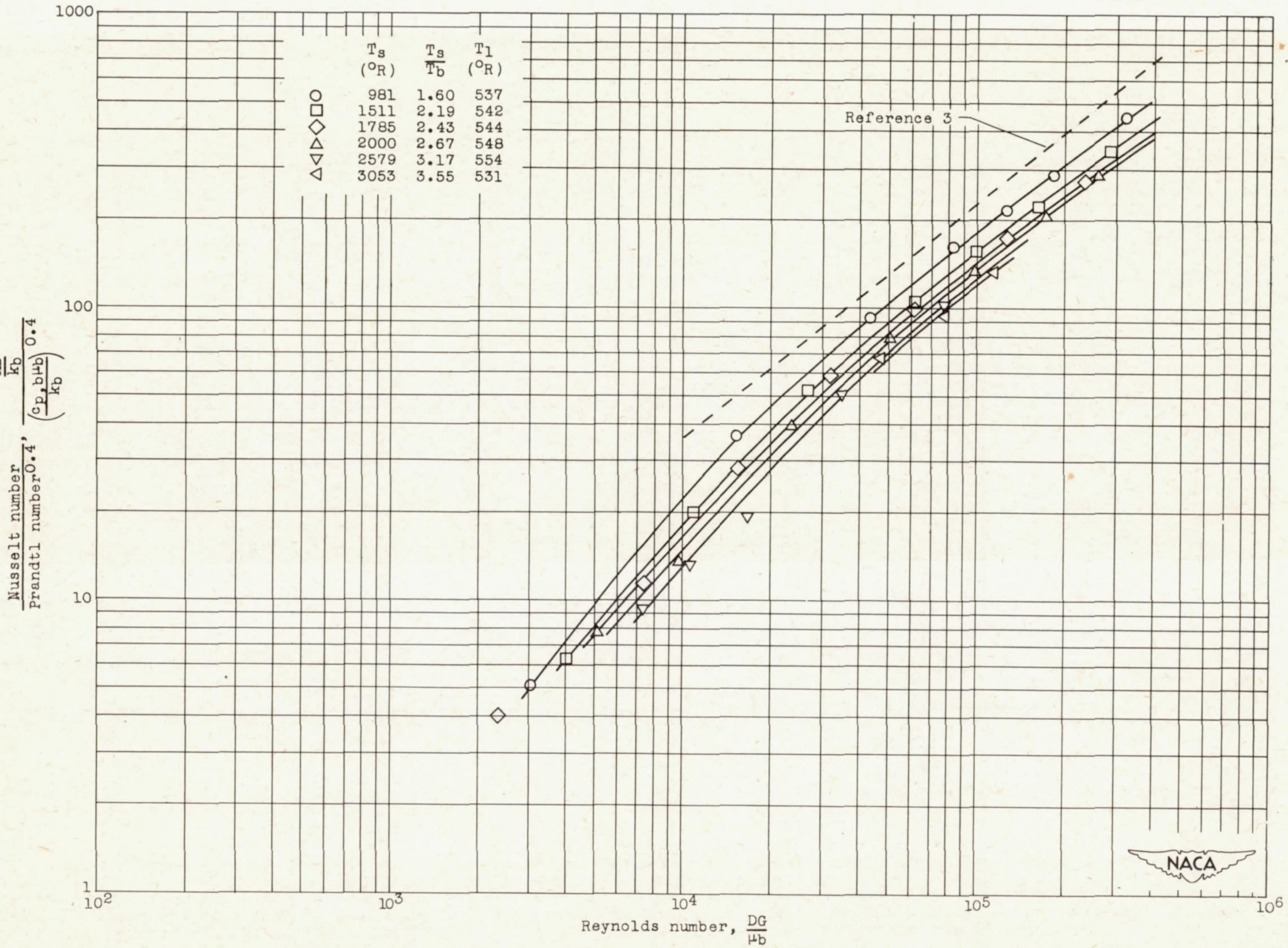

Figure 4. - Correlation of heat-transfer data at inlet-air temperature of 540° R. Physical properties of air evaluated at bulk temperature T_b.

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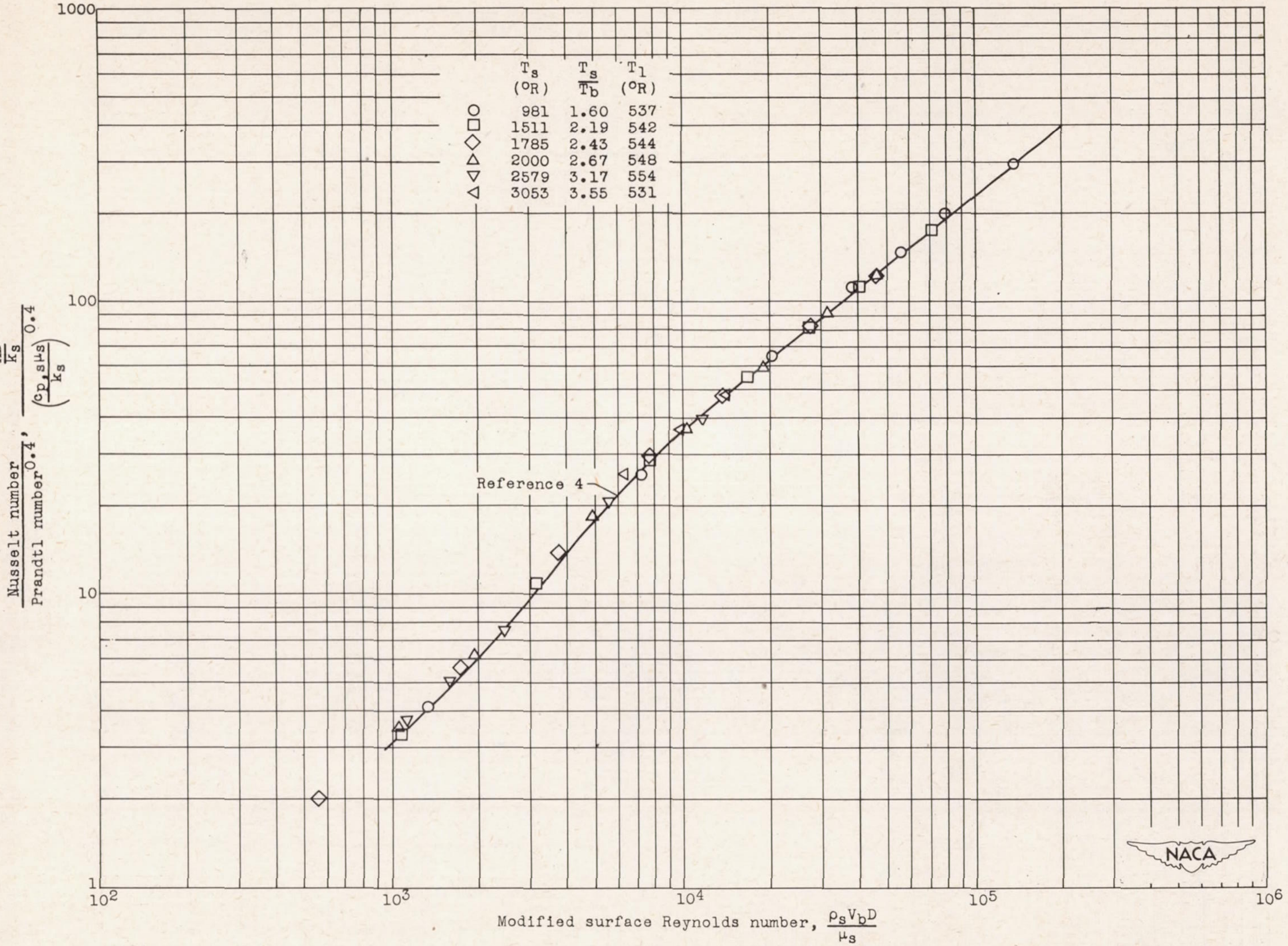

Figure 5. - Correlation of heat-transfer data at inlet-air temperature of 540° R using modified surface Reynolds number. Physical properties of air evaluated at average surface temperature T_s.

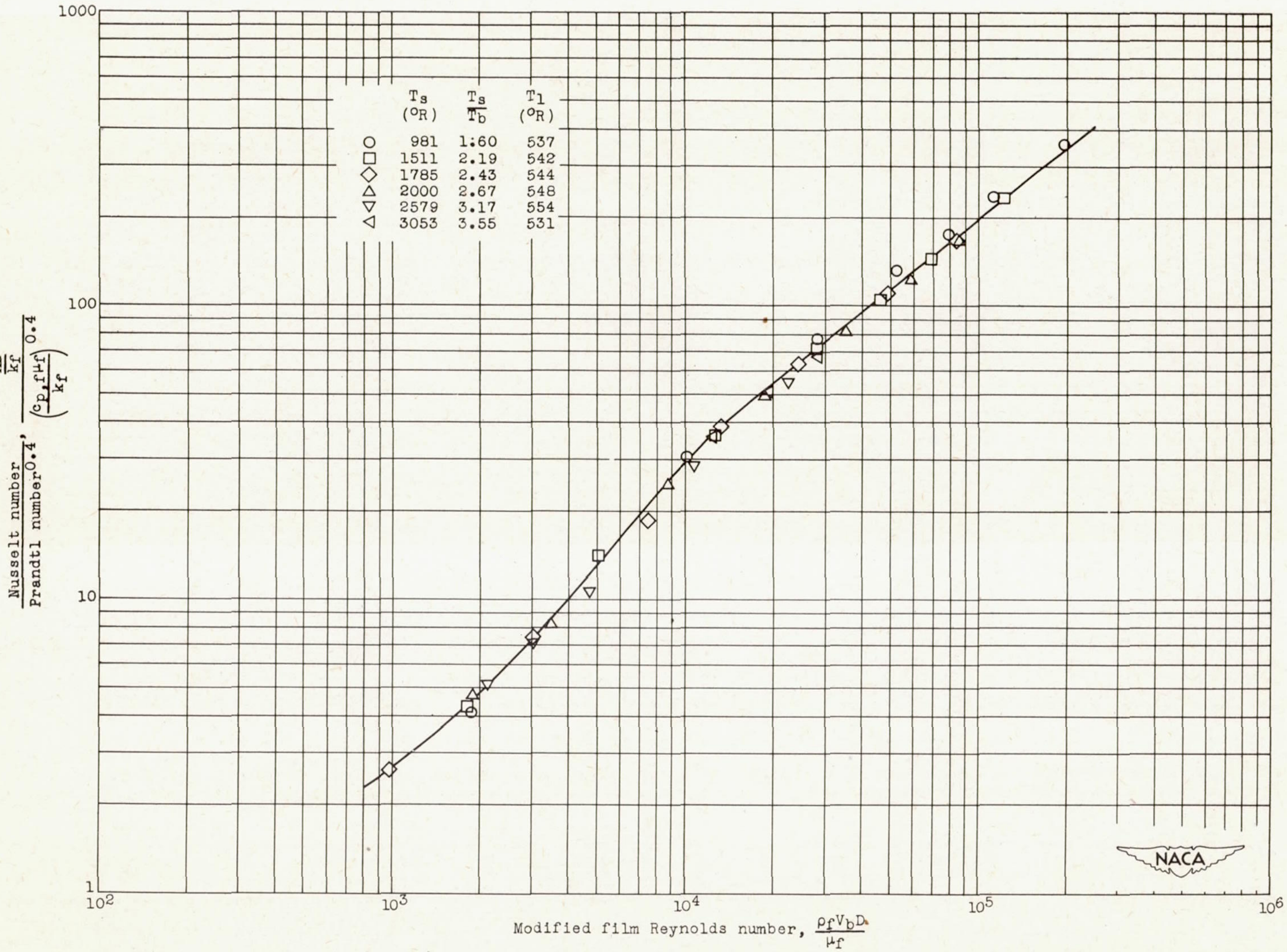

Figure 6. - Correlation of heat-transfer data at inlet-air temperature of 540° R using modified film Reynolds number. Physical properties of air evaluated at average film temperature T_f.

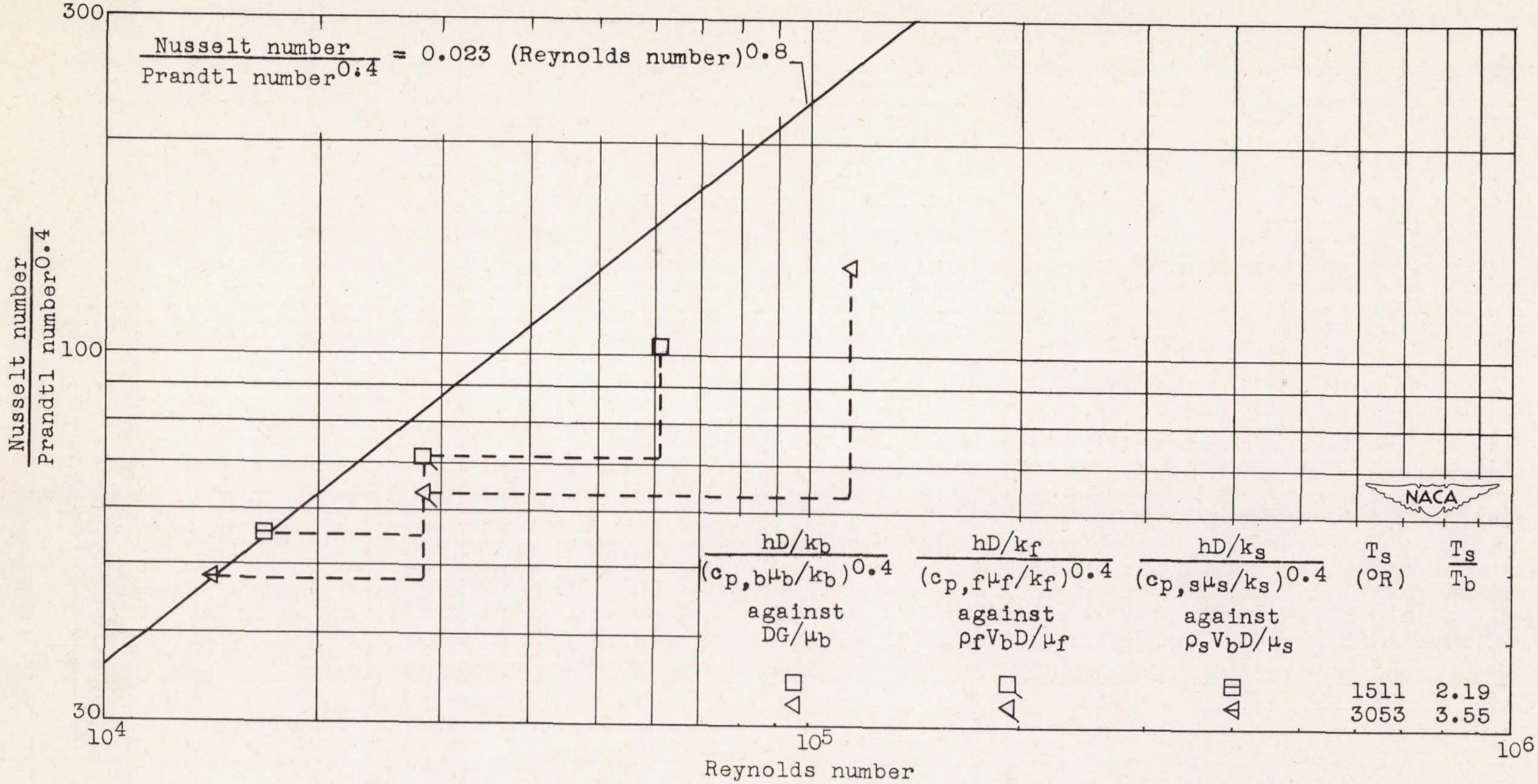

Figure 7. - Comparison of methods of evaluating heat-transfer data. Inlet-air temperature, 540° R.

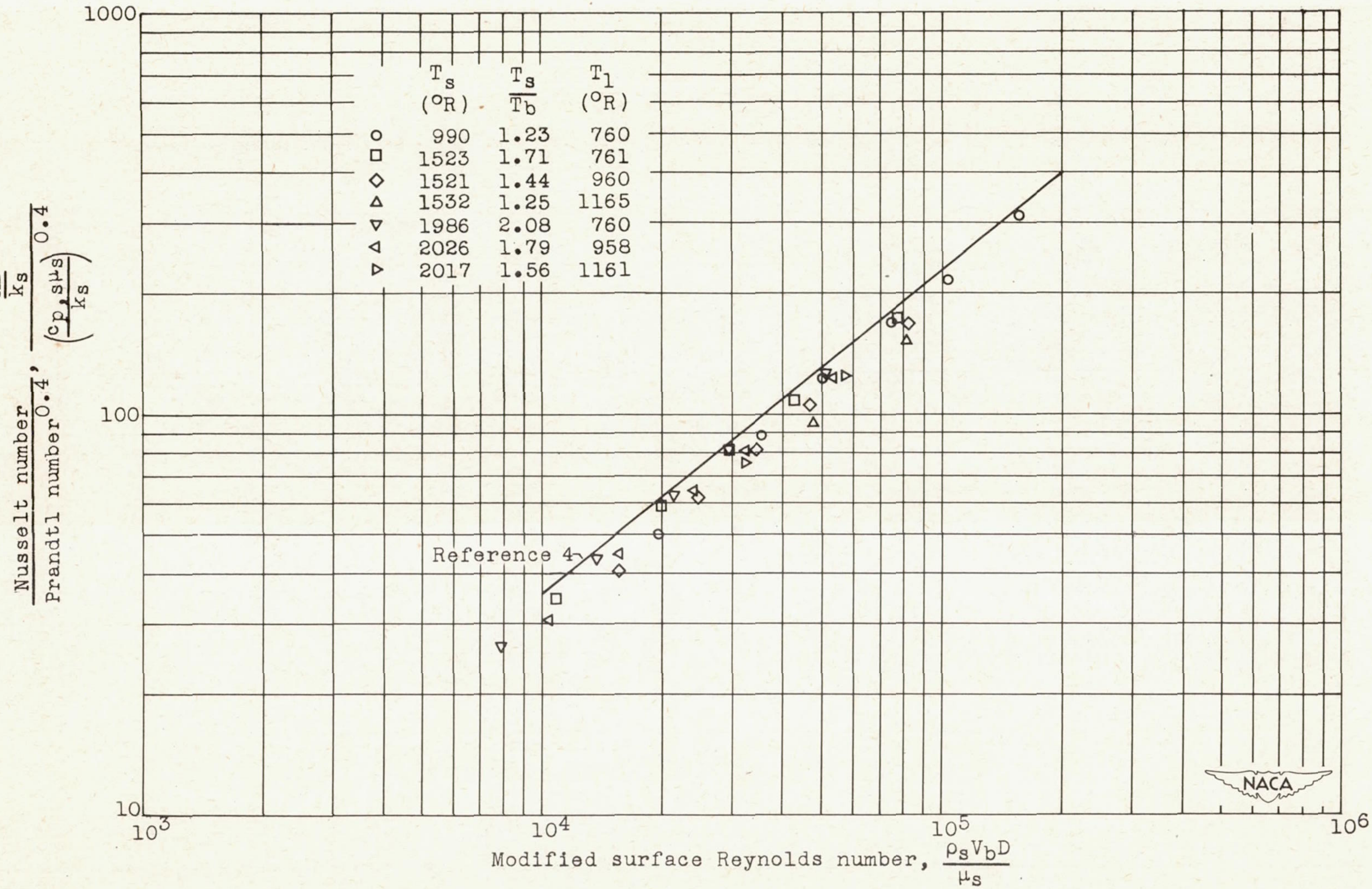

Figure 8. - Correlation of heat-transfer data at elevated inlet-air temperatures using modified surface Reynolds number. Physical properties of air evaluated at average surface temperature T_s.

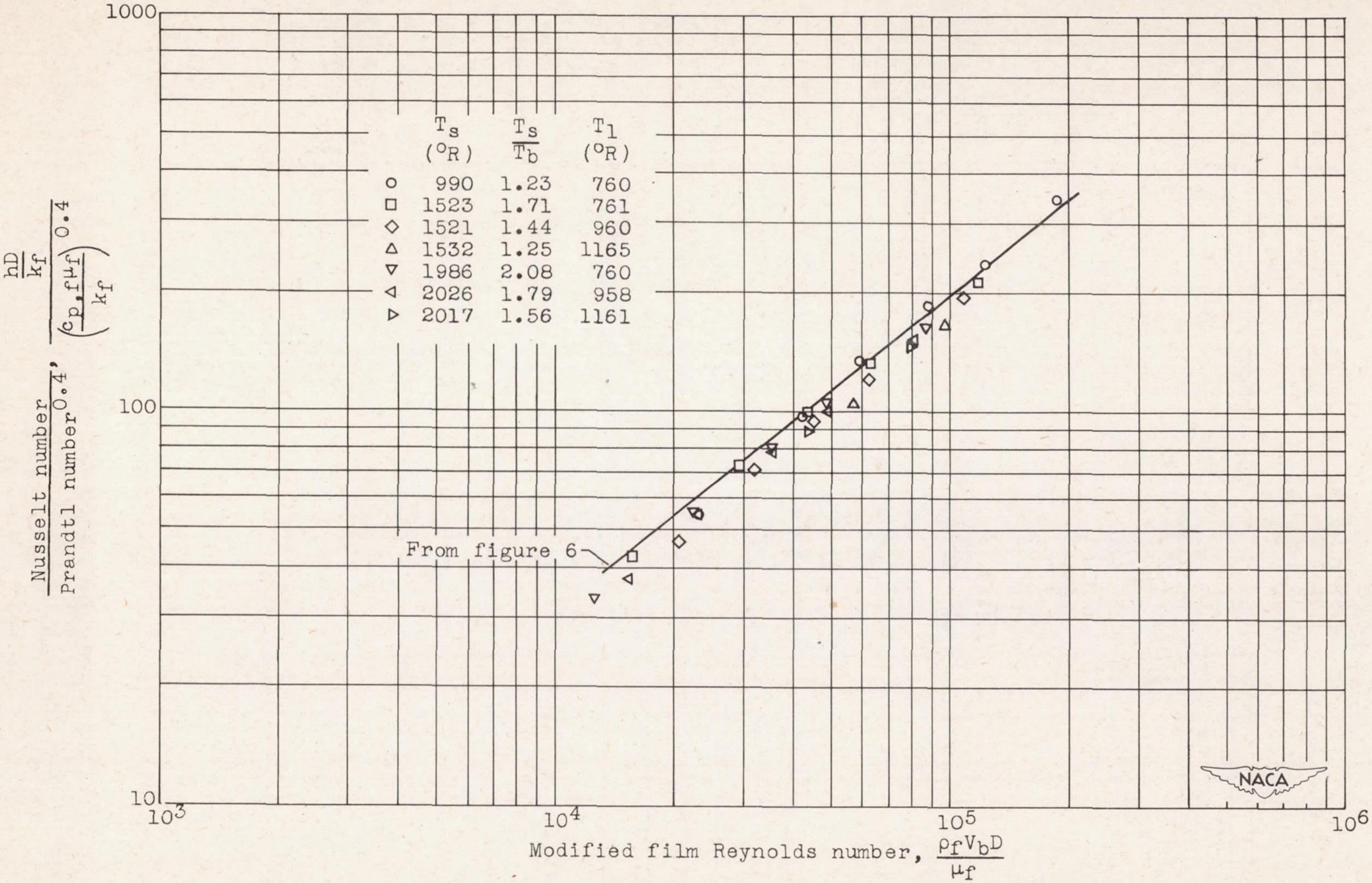

Figure 9. - Correlation of heat-transfer data at elevated inlet-air temperatures using modified film Reynolds number. Physical properties of air evaluated at average film temperature T_f.

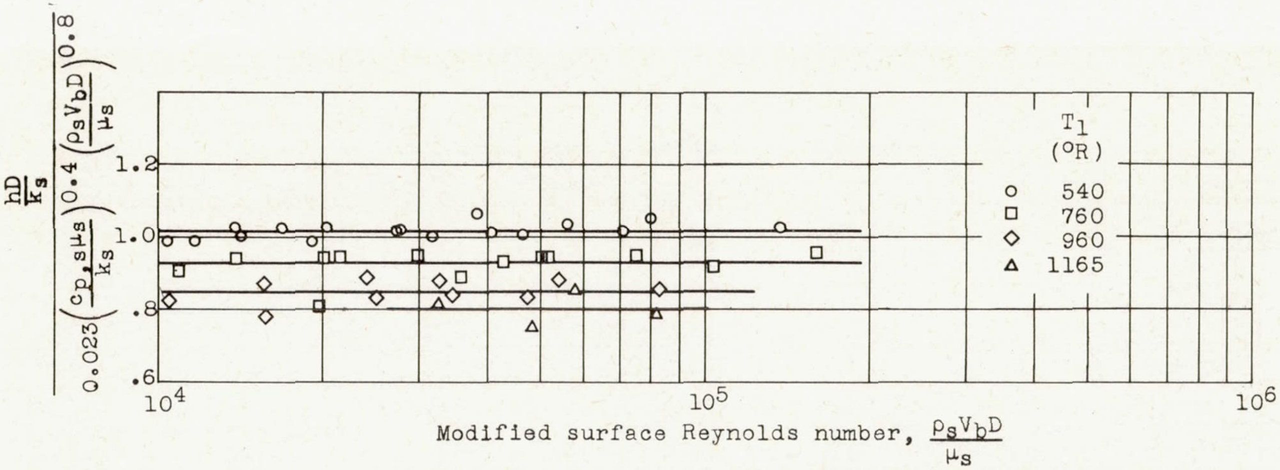

Figure 10. - Variation of constant in heat-transfer equation with inlet-air temperature. Physical properties of air evaluated at average surface temperature T_s. Average surface temperatures up to 3053° R.

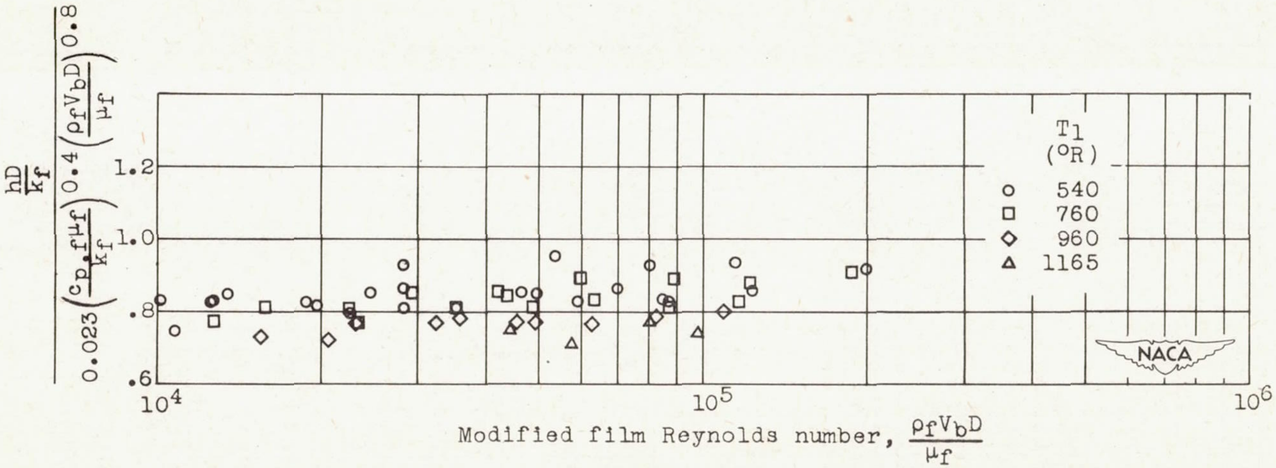

Figure 11. - Variation of constant in heat-transfer equation with inlet-air temperature. Physical properties of air evaluated at average film temperature T_f. Average surface temperatures up to 3053° R.

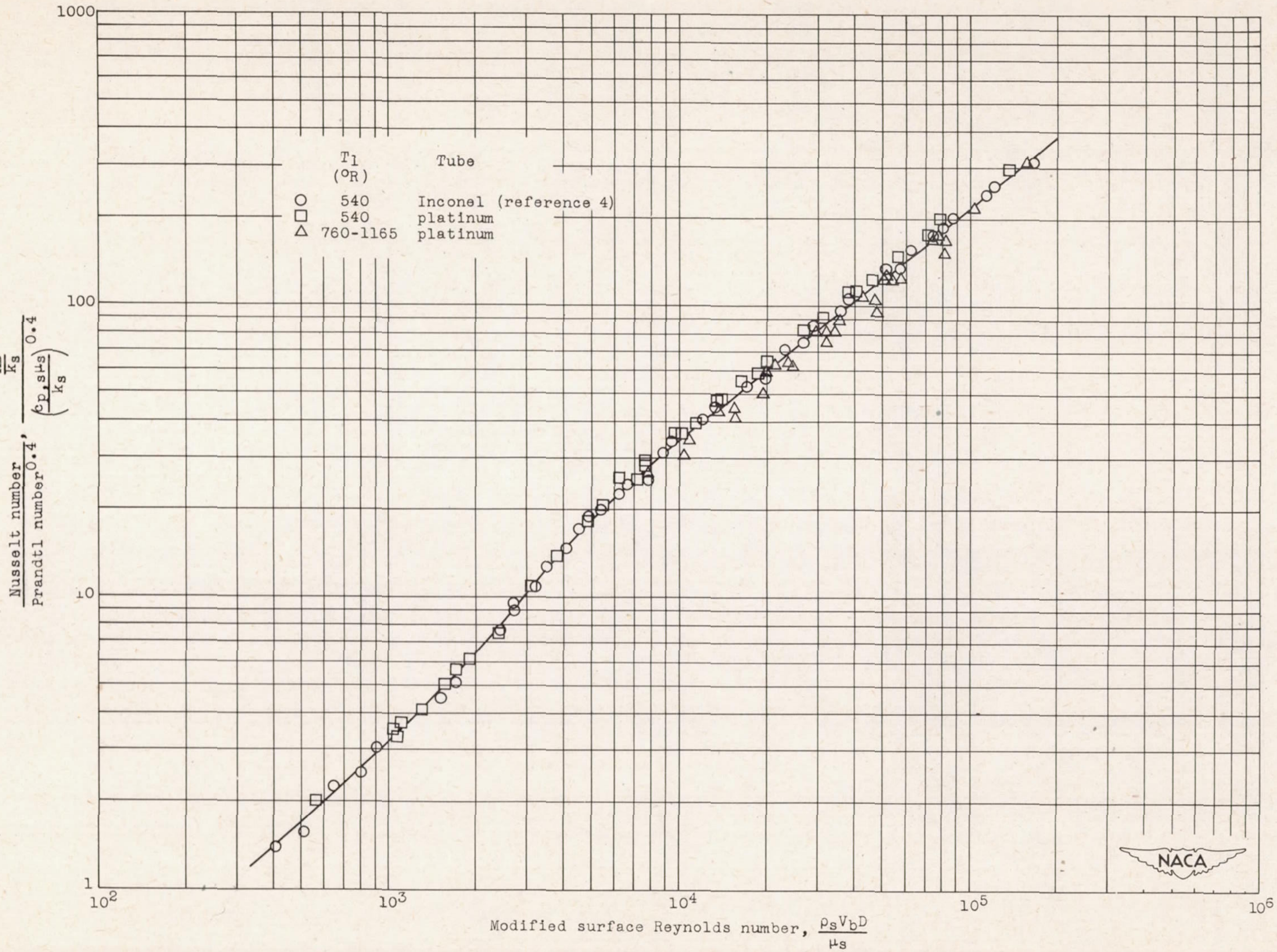

Figure 12. - Correlation of heat-transfer data obtained on two heater tubes at inlet-air temperatures from 540° to 1165° R using modified surface Reynolds number. Physical properties of air evaluated at average surface temperature T_s. Average surface temperatures up to 3053° R.

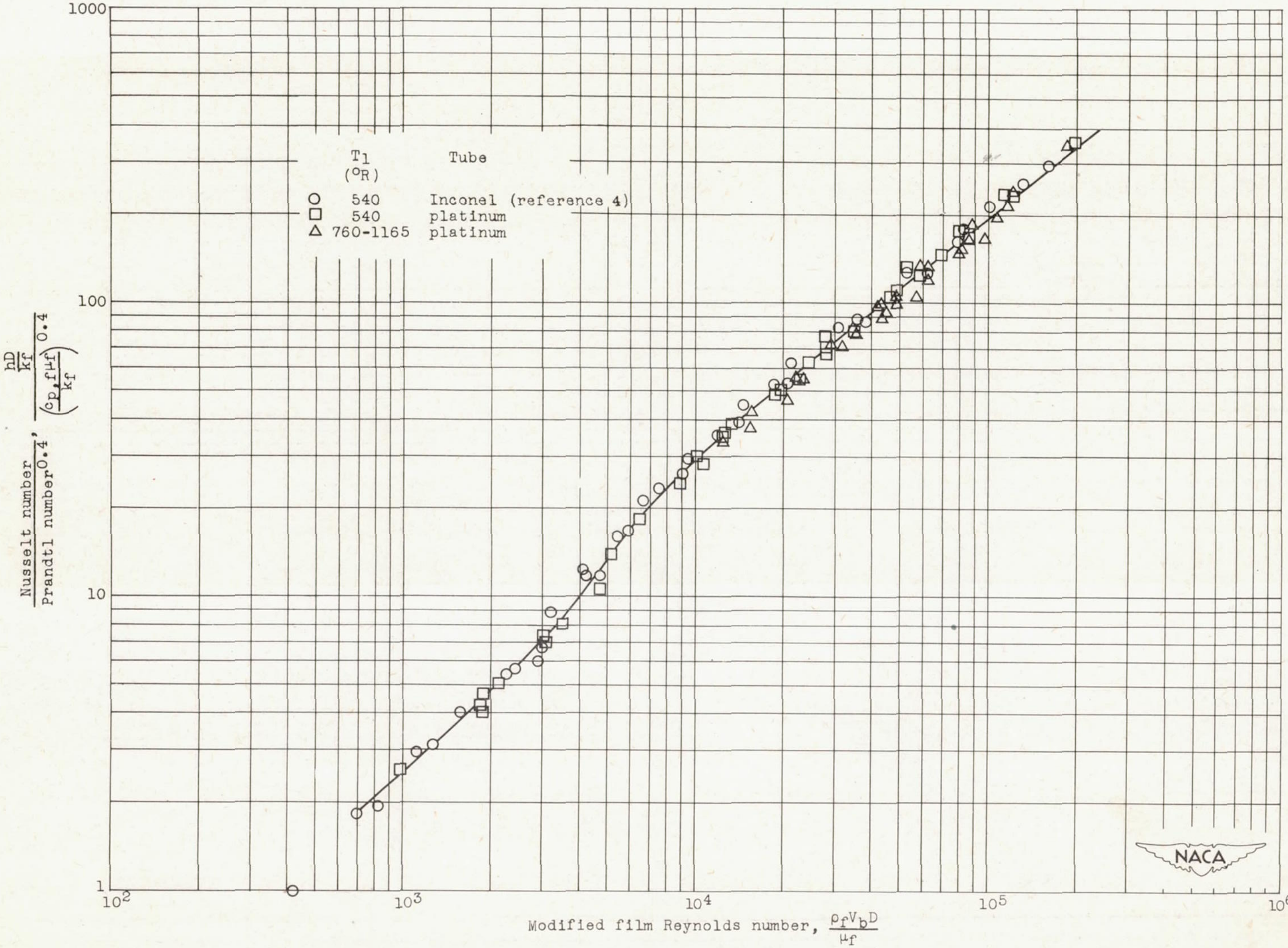

Figure 13. - Correlation of heat-transfer data obtained on two heater tubes at inlet-air temperatures from 540° to 1165° R using modified film Reynolds number. Physical properties of air evaluated at average film temperature T_f. Average surface temperatures up to 3053° R.