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TECHNICAL NOTE

D-721

EXPLORATORY INVESTIGATION OF TRANSPIRATION COOLING OF A 40° DOUBLE WEDGE USING NITROGEN AND HELIUM AS COOLANTS AT STAGNATION TEMPERATURES FROM 1,295° F TO 2,910° F

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EXPLORATORY INVESTIGATION OF TRANSPIRATION COOLING OF A 40° DOUBLE WEDGE USING NITROGEN AND HELIUM AS COOLANTS AT STAGNATION TEMPERATURES FROM 1,295° F TO 2,910° F [1]

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SUMMARY

An investigation of transpiration cooling has been conducted in the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va. The model consisted of a double wedge of 40° included angle having a porous stainless-steel specimen inserted flush with the top surface of the wedge. The tests were conducted at a free-stream Mach number of 2.0 for stagnation temperatures ranging from 1,295° F to 2,910° F.

Nitrogen and helium were used as coolants and tests were conducted for values ranging from approximately 0.03 to 0.30 percent of the local weight flow rate. The data for both the nitrogen and helium coolants indicated greater cooling effectiveness than that predicted by theory and were in good agreement with the results for an 8° cone tested at a stagnation temperature of 600° F.

The results indicate that the helium coolant, for the same amount of heat-transfer reduction, requires only about one-fourth to one-fifth the coolant flow weight as the nitrogen coolant.

INTRODUCTION

The development of long-range ballistic missiles and the steadily increasing flight speeds of other missiles and fighter and bomber airplanes require a thorough investigation of all the high-temperature problems associated with their trajectories and speeds. The destructive effects of aerodynamic heating for stagnation temperatures comparable to a flight Mach number of 7.0 have already been reported in reference 1. In hot-air-jet tests, copper and stainless-steel models

[1]Supersedes declassified NACA Research Memorandum L57F11 by Bernard Rashis, 1957.

were melted in slightly less than 12 seconds. It is apparent that considerable effort must be expended towards improving materials and developing various methods of cooling.

Transpiration cooling systems have already been investigated (refs. 2 to 5) and do indicate considerable merit; however, the results were obtained for a relatively low stagnation temperature. As an initial effort in the study of transpiration cooling at high stagnation temperatures, a series of tests were conducted in the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va.

The tests were conducted for stagnation temperatures ranging from 1,295° F to 2,910° F. The coolants used were nitrogen and helium, and the flow rates ranged from approximately 0.03 to 0.30 percent of the local weight flow. The model tested consisted of a double wedge of 40° included angle, in which a porous stainless-steel specimen was inserted flush with the top surface. The free-stream Mach number of the tests was 2.0, and the Reynolds numbers, based on the surface conditions and the distance from the leading edge to the thermocouple locations, varied from 0.578×10^6 to 8.2×10^6. The purpose of this paper is to present these high-stagnation temperature results and to compare them with the data of reference 2 and the theories of references 3 and 4, which apply to nitrogen and helium coolants, respectively.

SYMBOLS

t	thickness of porous specimen, ft
c_f	local skin-friction coefficient
c_p	specific heat at constant pressure, Btu/lb-°F
G	weight flow rate, lb/(sq ft)(sec)
h	heat-transfer coefficient, Btu/(sq ft)(sec)(°F)
k	thermal conductivity, Btu/(ft)(sec)(°F)
p	pressure, lb/sq in. abs
T	temperature, °F

q	heating rate, Btu/(sq ft)(sec)
x	distance from leading edge of specimen, in.
F	ratio of coolant weight flow rate to local weight flow rate
M	Mach number
N_{St}	Stanton number

Subscripts:

aw	adiabatic wall for no coolant flow
c	coolant values
r	boundary-layer recovery value with coolant flow
l	local values
t	stagnation values
s	local values outside porous surface
∞	free-stream values
0	theory for $G_c = 0$

APPARATUS AND PROCEDURE

The present tests were conducted in the preflight jet which is capable of producing a hot jet having a free-stream Mach number of 2.0 and a maximum stagnation temperature of 3,500° F. A detailed description of this facility is given in appendix A of reference 6.

The test model and stand are shown in figure 1, and a sectional drawing of the model is given in figure 2. The test model consisted of a double wedge of 40° included angle. The leading edge of the wedge had a 0.38-inch radius, and the walls were constructed of 1/2-inch-thick cold-rolled steel.

The test specimen was of 1/8-inch-thick porous stainless steel having approximately 25 percent porosity. It was inserted into the top surface of the wedge flush with the surface. All joints and connections were sealed with a high-temperature paste which hardens after curing and acts as an insulation. The inside surfaces of the wedge were also covered with this paste. Surface static-pressure orifices were located as shown in figure 2. The inside coolant pressure was measured by means of an orifice located directly under the center of the porous specimen. The specimen temperatures were obtained from thermocouples which were spot-welded to the inside surface of the specimen. The incoming coolant temperature was measured by means of a thermocouple mounted approximately one-eighth of an inch below the specimen, a slight distance from the pressure tube. The thermocouples were No. 30 gage chromel-alumel wires. The pressure tubes were constructed of stainless-steel tubing having an inside diameter of 0.060 inch.

The temperature instrumentation was calibrated before and after each run. The maximum error for the system was ±1 percent of the maximum range.

For each test, the model was inserted into the jet stream only after steady conditions had been achieved for both the jet and the coolant flow.

The coolant weight flow rates through the porous material were obtained from the manufacturer's specified calibration curve, which is given in figure 3. The manufacturer's curve gives the values of the volume flow rate of air at a temperature of 70° F and an ambient pressure of 1 atmosphere against the pressure drop across the porous material. Since the pressure drop was measured for all the tests, the volume flow rate was read from the curve and converted to weight flow rate by multiplying the volume flow rate by the corresponding coolant density.

Since manufacturer's specifications were available only for pressure-drop values up to 10 pounds per square inch, several measurements were made at higher pressure-drop values by using flowmeters. These measurements were made with nitrogen and helium, the volume flow rates through the flowmeters being read off curves computed from previous calibration tests of the flowmeters where water was used. Although the flowmeter measurements shown in figure 3 are not extremely precise, the extrapolation of the manufacturer's specification is reasonably accurate, particularly since only extrapolation of the data to pressure-drop values of 20.0 pounds per square inch were required.

ANALYSIS

The general form of the heat-balance equation is

$$q_{aerodynamic} - q_{absorbed\ by\ coolant} = q_{transient} \pm q_{radiation} \pm q_{conduction} \quad (1)$$

Only that portion of the data obtained after equilibrium conditions had been achieved by the porous specimen was used in the reduction of the data. Calculations of the radiation and conduction terms, assuming a value of emissivity of 0.8 and values of thermal conductivity that were 60 percent (ref. 7) of the nonporous stainless steel, indicated that these terms were at most of the order of 1.0 to 2.0 Btu/(sq ft)(sec). The values of q absorbed by the coolants ranged from 40 to 225 Btu/(sq ft)(sec); thus, the radiation and conduction terms were assumed to be negligible and were not used in the reduction of the data.

Thus the general heat-balance equation becomes

$$q_{aerodynamic} = q_{absorbed\ by\ coolant}$$

or

$$h\left(T_r - T_s\right) = G_c c_{p,c}\left(T_s - T_c\right) \quad (2)$$

or, in nondimensional form,

$$\frac{N_{St}}{N_{St,0}} = \frac{F}{N_{St,0}} \frac{c_{p,c}}{c_{p,l}} \frac{T_s - T_c}{T_r - T_s} \quad (3)$$

where $N_{St,0}$ was computed from the local skin-friction values of the zero-pressure-gradient theory of reference 3, by using the local values of Mach and Reynolds numbers, the x-distance being taken from the wedge leading edge to the thermocouple location. The values of $N_{St,0}$ are obtained from the relation

$$N_{St,0} = 1.24\left(\frac{c_f}{2}\right) \quad (4)$$

The values of T_r were computed by using values of recovery factor as computed from the theory of reference 8, which gives the variation of recovery factor with Mach number, coolant flow rate, and Reynolds number. Although the recovery factors varied from approximately 0.88 for no coolant flow to 0.70 for a coolant flow rate of 0.3 percent of the local weight flow for the nitrogen coolant, the percentage change in the ratio $N_{St}/N_{St,0}$ was less than 3.0 percent. Since the variation in recovery factors as given in reference 8 was virtually the same as the experimental values for air reported in reference 5, the effect of cooling on the recovery factor for the nitrogen coolant for the present tests can L
be considered very minor. The variation in recovery factor for the 1
helium coolant as measured in reference 4 indicates that the present 3
data for helium would be even less affected than the nitrogen data, and 8
for the low flow rates of the present tests, the theoretical values of 1
reference 7 which apply to air could be used for the present helium data.

Since the incoming coolant temperature is much lower than the porous-material temperature, the passage of the coolant through the porous specimen causes a temperature gradient across the thickness. The temperature difference between the inside and outside surfaces may be calculated from

$$\frac{\Delta T}{T_{aw} - T_c} = \frac{\dfrac{N_{St} c_{p,l}}{F c_{p,c}}}{1 + \dfrac{N_{St} c_{p,l}}{F c_{p,c}}} \left(1 - e^{\frac{-G_c c_{p,c} t}{k}}\right) \tag{5}$$

as given in reference 9. The values of T_s used in equation (3) were obtained by adding the calculated values of ΔT to the measured local inside surface temperatures.

The porous specimen used for these tests was specified by the manufacturer as having approximately 25 percent porosity.

Since the composition of the combustion products of the jet exhaust is essentially the same as that of air, the properties for air were used in the evaluation of the jet exhaust flow. The specific heat values for air, nitrogen, and helium, and the viscosity values for air were obtained from reference 10.

The values of local weight flow G_l were calculated from

$$G_l = G_\infty \frac{p_l}{p_\infty} \frac{M_l}{M_\infty} \sqrt{\frac{T_\infty}{T_l}} \tag{6}$$

Figure 4 shows the measured temperature distribution along the porous specimen and the measured pressure distribution taken on the solid surface 2.0 inches from the thermocouples. The values shown are for the nitrogen coolant for a stagnation temperature of 2,910° F. The coolant temperature was 49.5° F. The reason for the pressure dropoff is not definitely known. A check run was made with the wedge shown in figure 2 modified by the addition of side pieces. This modification made the top surface of the wedge a rectangular section 12 inches wide by approximately 13 inches long; however, the pressure distribution was unchanged. It thus appears that the dropoff is not due to the configuration but is due to either a dropoff in the static pressure normal to the jet axis or perhaps to an effect of the jet boundaries. Since the pressure at the downstream end of the specimen is roughly one-half of the theoretical sharp-wedge pressure, the low measured values cannot be considered as due to the blunted leading edge. The temperature variation results from the difference in flow rates caused by the variation of the pressure drop along the specimen.

Since the quantity

$$\frac{p_l M_l}{\sqrt{T_l}}$$

was virtually constant for the different values of p_l, the value of G_l was considered to be constant along the specimen.

RESULTS AND DISCUSSION

Figure 5 shows time histories of the measured inside surface temperature for several nitrogen coolant flow rates at a stagnation temperature of 2,910° F. The coolant temperature was 49.5° F. The curve for $F = 0.135$ percent is for $x = 0.5$ inch; the curve for $F = 0.175$ percent is for $x = 4.5$ inches; the curve for $F = 0.255$ percent is for $x = 6.5$ inches, the x-distance being measured from the leading edge of the porous specimen. Also shown is the time history of calculated inside surface temperature for no coolant flow or $F = 0$ percent. The x-distance for this curve is 4.5 inches. The curve was calculated by using a value of $N_{St,0}$ from reference 3, assuming a turbulent boundary layer, and using the local values of Mach and Reynolds number.

Figure 6 shows the variation of the cooling "efficiency parameter"

$$\frac{T_s - T_c}{T_{aw} - T_c}$$

with the nondimensional flow-rate parameter $F/N_{St,O}$. This parameter is useful in that it correlates the results obtained for different local weight flow rates. Also shown are the results of reference 2 for the 8° cone for both nitrogen and helium coolants. The good agreement between them and the present results is clearly indicated.

The flagged symbol in figure 6 represents an average of the results obtained from the test made with the helium coolant at a stagnation temperature of 1,295° F. This procedure was used because the incoming coolant flow rate was in the high range of the calibration curve and excessive cooling of the porous specimen resulted. The surface temperatures averaged 120° F, and sensitivity of the instrumentation was too low to give a proper evaluation of the effect of the slight differences in the coolant flow rates.

Figure 7 shows the variation of the ratio of the Stanton number to theoretical Stanton number for no coolant flow with the flow parameter $F/N_{St,O}$. Included for comparison are the data of reference 2 and the theoretical curves computed from the theories of references 3 and 4.

The present results for the nitrogen coolant indicate slightly greater reduction of the aerodynamic heat input than values computed from the theory of reference 3, which assumes that the coolant and local properties are identical.

The present data for the helium coolant also indicate slightly greater cooling than the values computed from the theory of reference 4, which is a modification of film theory. The value of surface coolant concentration was assumed to be 1.

Also shown in figure 7 is the curve computed from the theory of reference 4 for the nitrogen coolant. Comparison of the two theoretical curves shows that modified film theory does not indicate the same degree of cooling effectiveness as indicated either by reference 3 or by the present data.

The present data and those of reference 2 agree for the nitrogen coolant. There is some discrepancy between the two sets of data for the helium coolant. It should be noted, however, that both sets of data for the helium coolant are for small flow rates and any small errors in the measurement of the flow rates would shift the data either downwards and to the left or upwards and to the right for the parameters of figure 7.

The present results indicate that the helium coolant requires approximately one-fourth to one-fifth the coolant flow rate of the nitrogen to achieve the same amount of heat-transfer reduction. It should be noted that this ratio for required coolant flow rates is approximately the same as the ratio of the heat capacities of helium to nitrogen.

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In figure 8, there is shown the variation of the heat capacity with the final temperature of the coolant for both nitrogen and helium. For the same final coolant temperatures, 300° to 1,000° F, the helium has approximately four times the heat capacity of the nitrogen.

CONCLUDING REMARKS

An exploratory investigation has been made of the transpiration cooling on the surface of 40° wedge using nitrogen and helium as coolants at stagnation temperatures of 1,295° to 2,910° F for a free-stream Mach number of 2.0.

Substantial reduction of the aerodynamic heat input was obtained at high stagnation temperatures by means of transpiration cooling. For a nitrogen coolant which has essentially the same properties as air, slightly greater reduction of the aerodynamic heat input was obtained than was predicted by a theory which assumes that the coolant and local properties are identical. For a helium coolant, slightly greater cooling was obtained than was predicted by a modified film theory.

The present results indicate that the helium coolant is from four to five times more effective than the nitrogen coolant. This ratio is approximately the same as the ratio of the heat capacities of helium and nitrogen.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 21, 1957.

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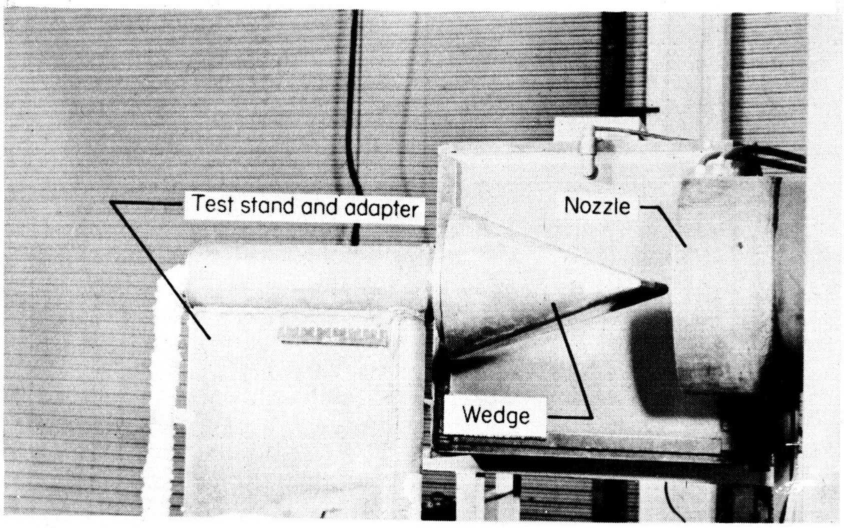
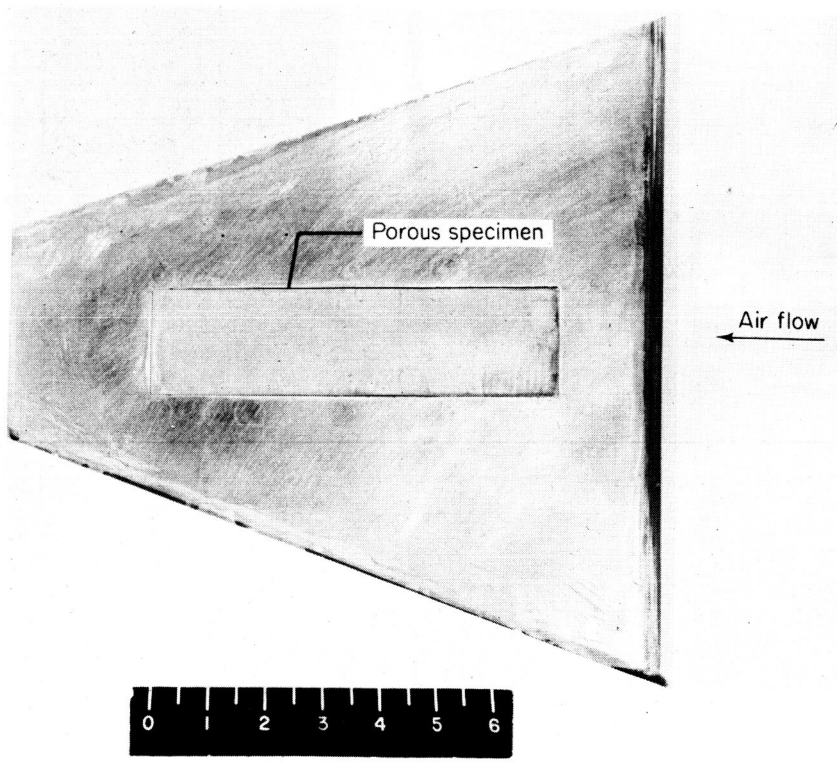


(a) Test stand and model.



(b) Top view of model. L-57-1605

Figure 1.- Test stand and model.

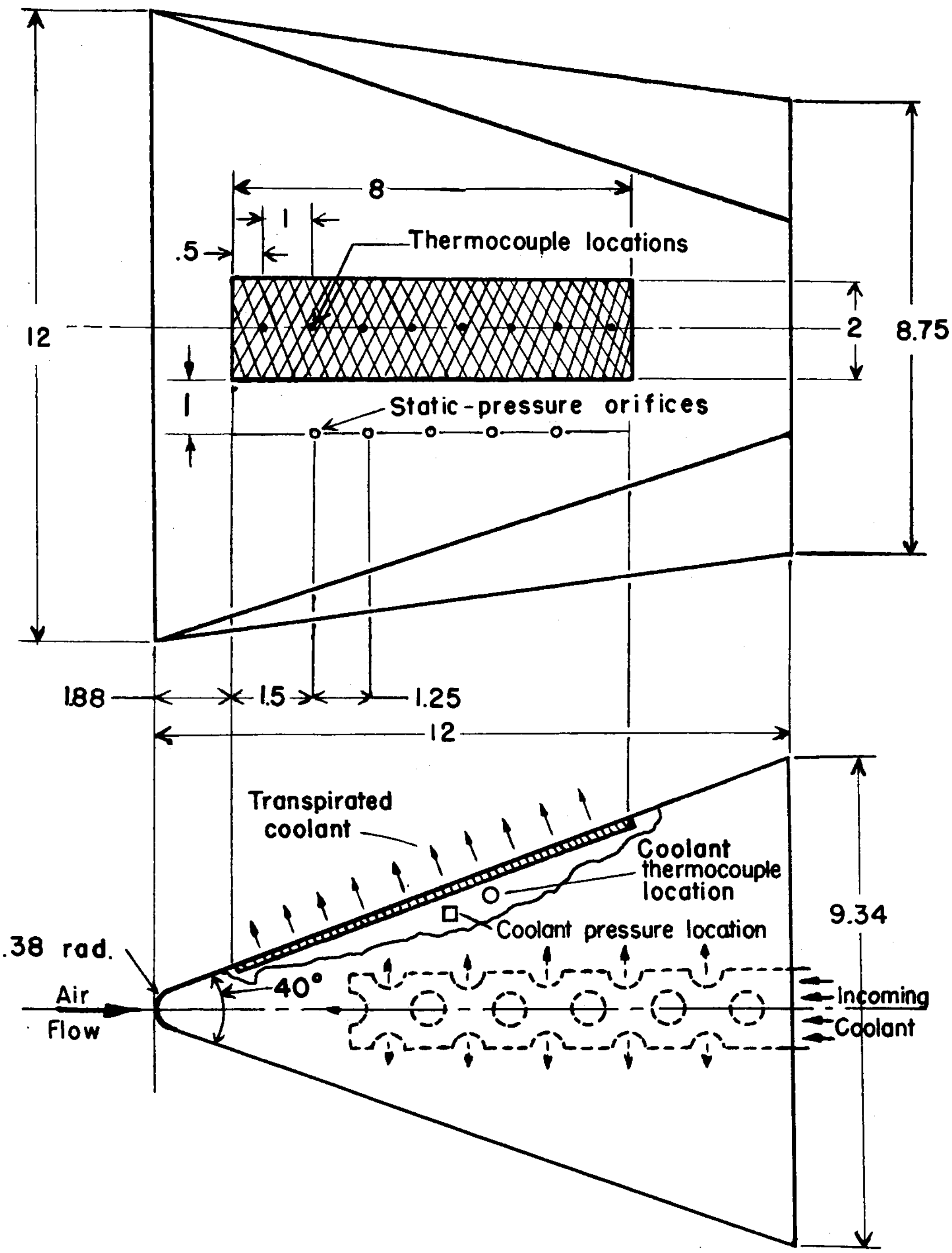


Figure 2.- Test model showing locations of porous specimen, thermocouples, and static-pressure orifices. All dimensions are in inches.

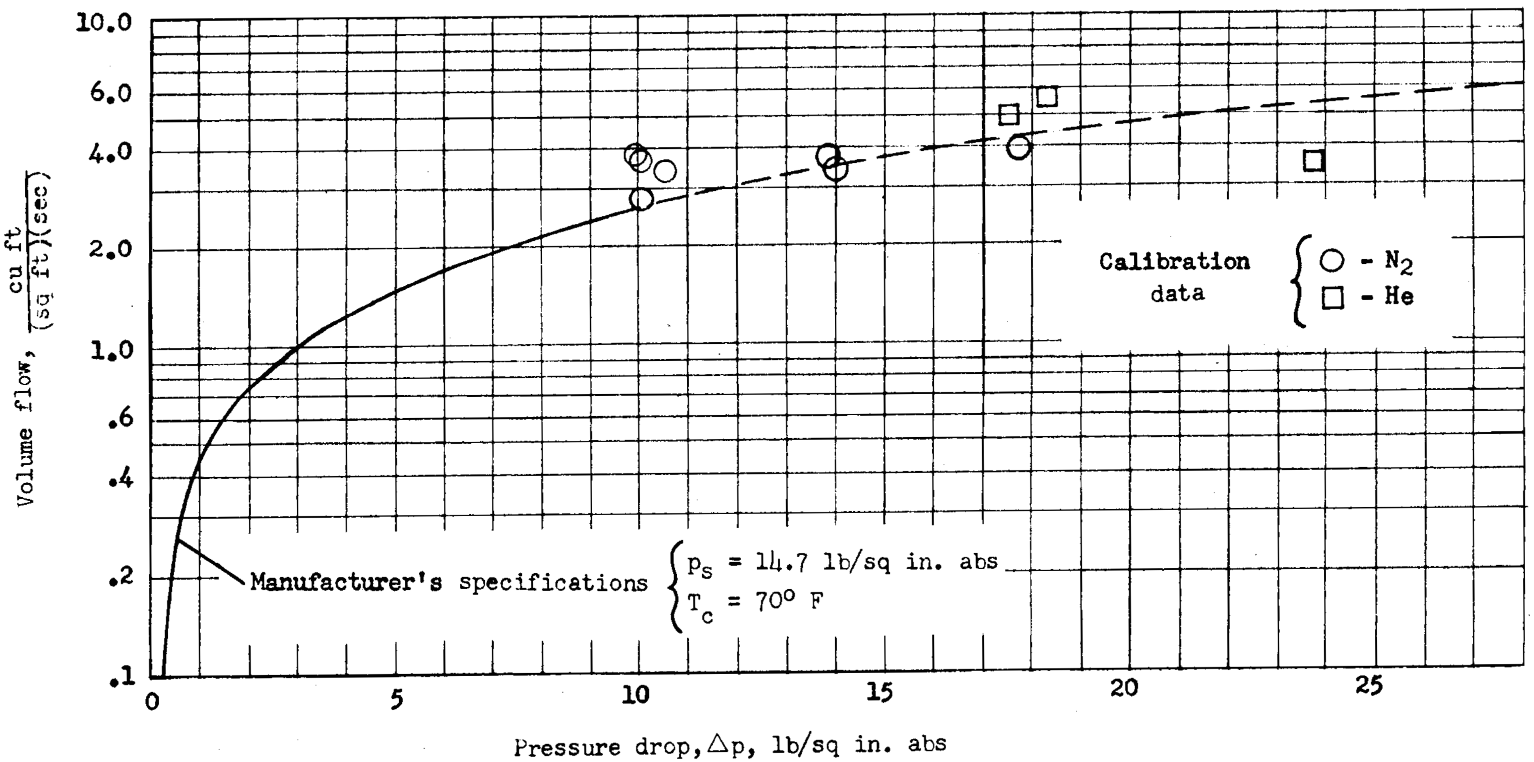


Figure 3.- Volume-flow variation through $\frac{1}{8}$ - inch-thick porous-stainless-steel specimen with pressure drop across specimen.

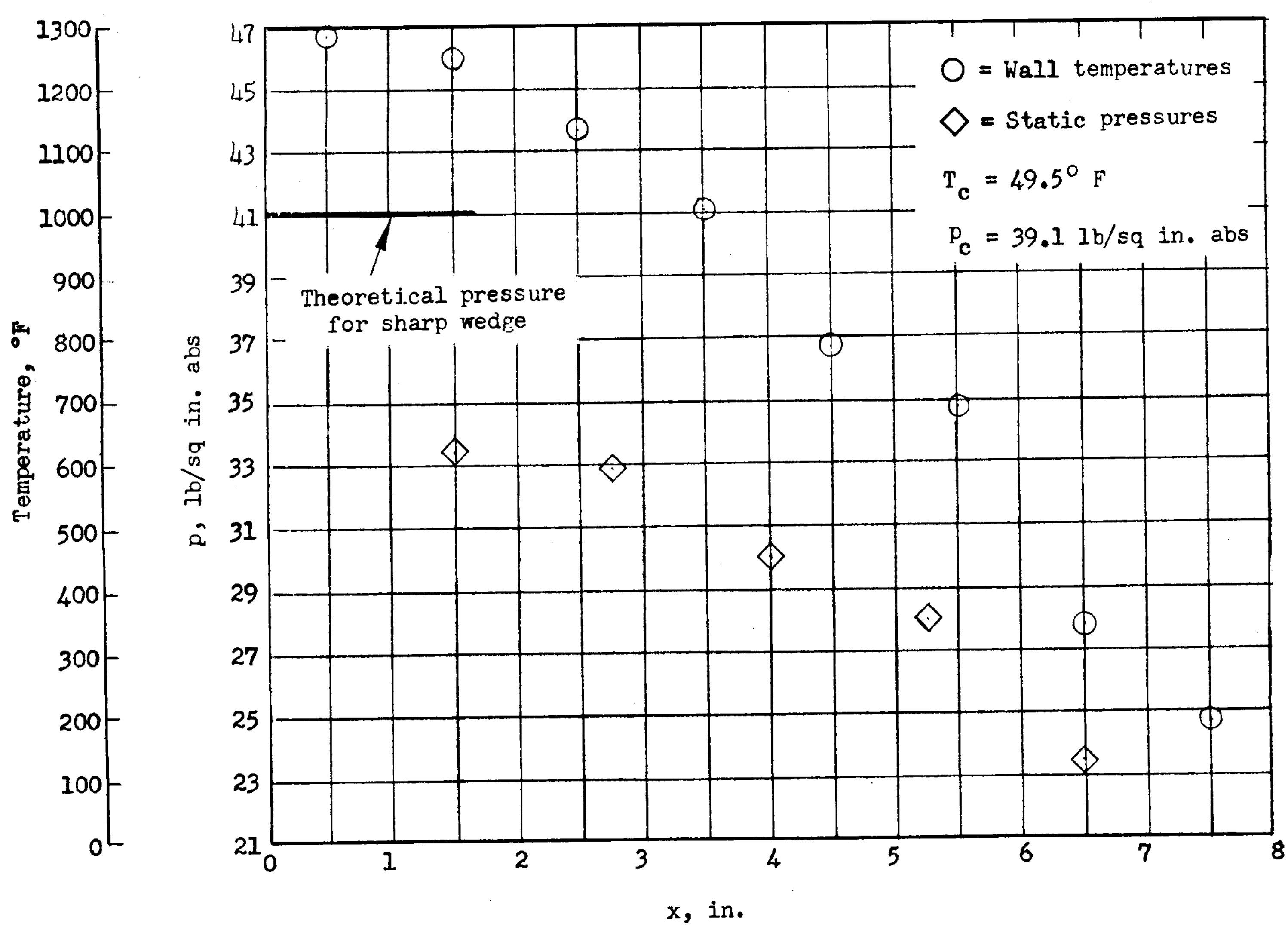


Figure 4.- Wall temperatures and static-pressure distribution along porous specimen for a stagnation temperature of 2,910° F, for a nitrogen coolant.

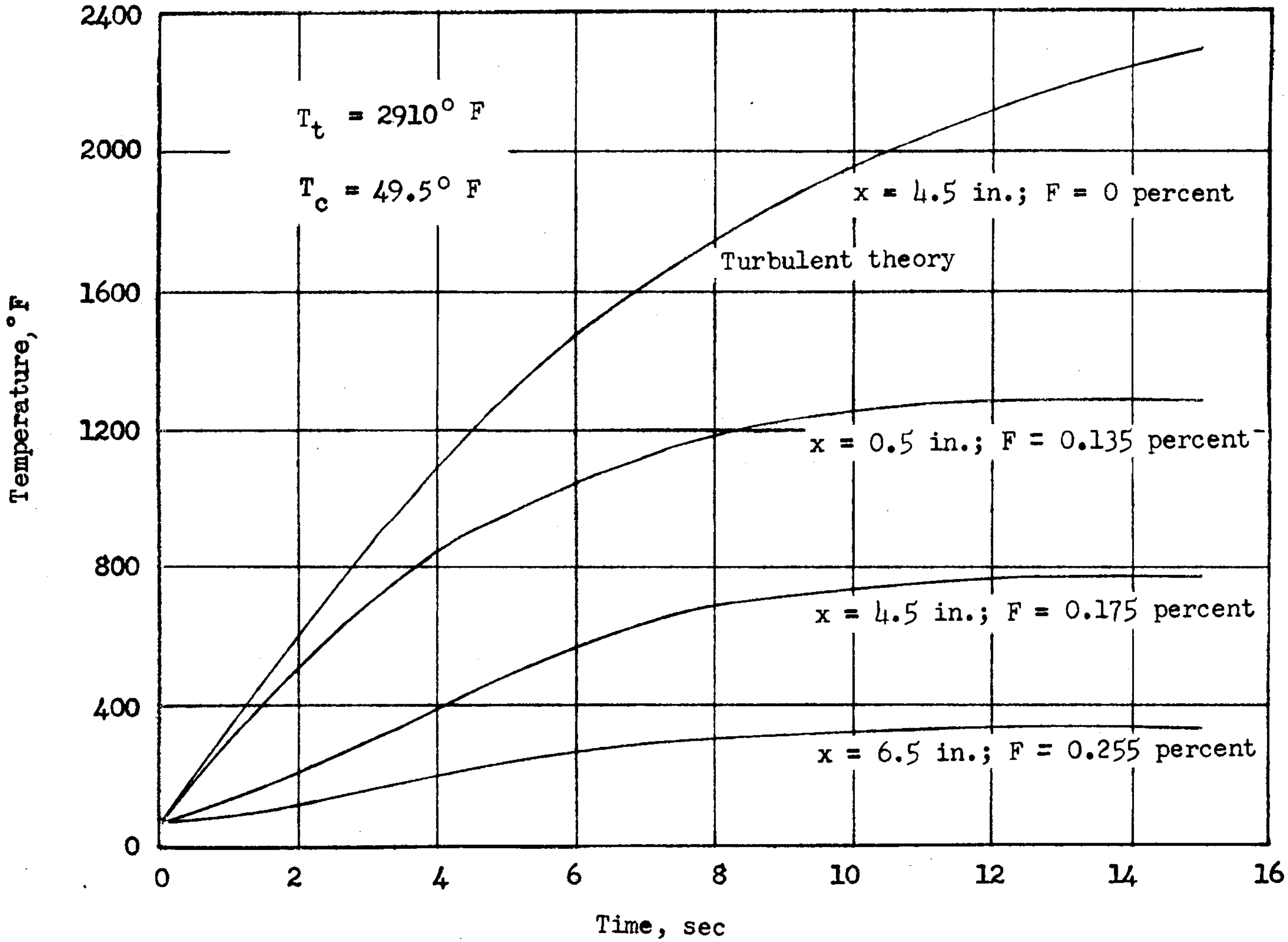


Figure 5.- Comparison of time histories of measured inside surface temperature for nitrogen coolant with time history of calculated inside surface temperature for no coolant flow.

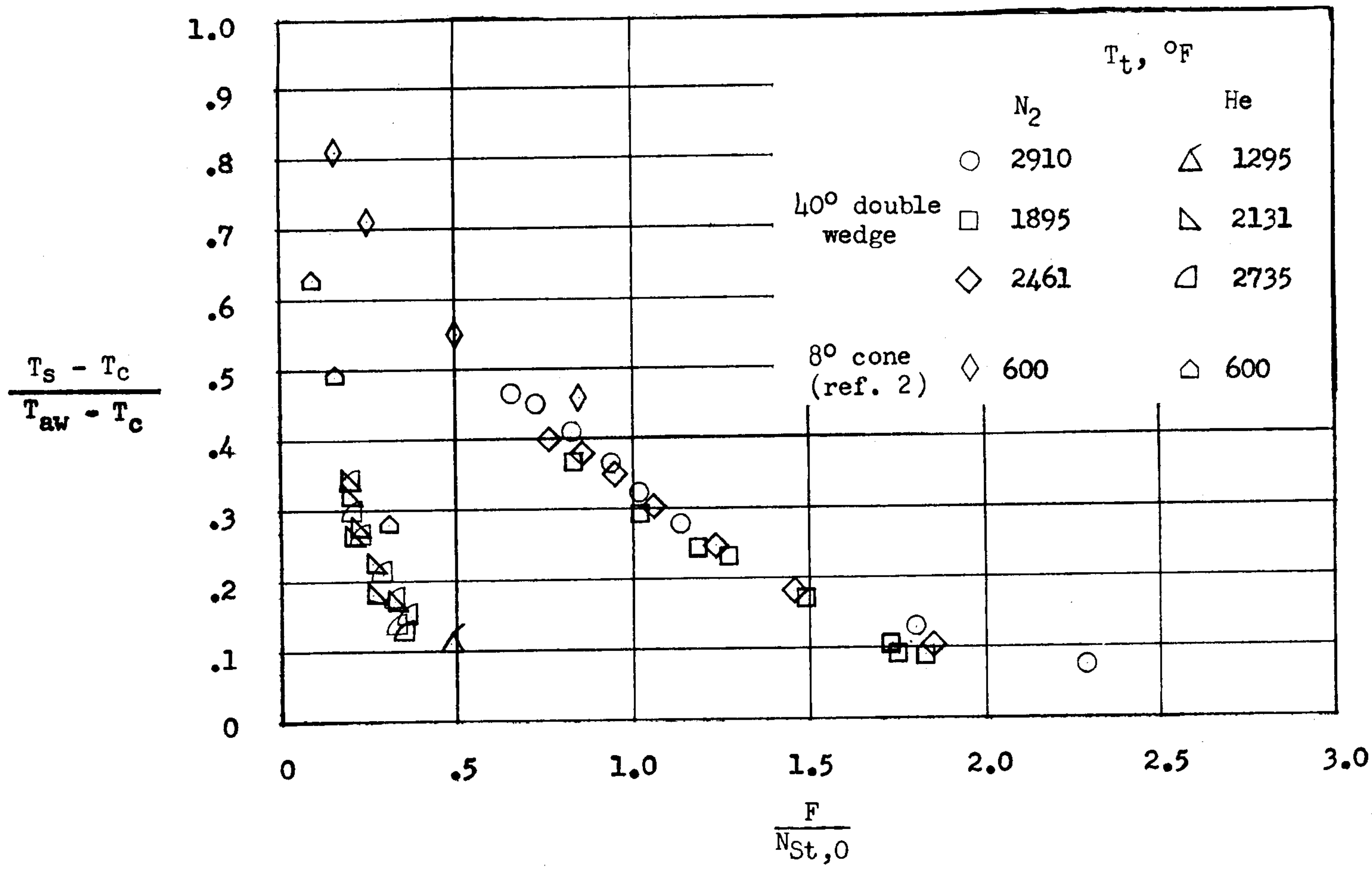


Figure 6.- Variation of cooling efficiency parameter with coolant flow parameter. $M_\infty = 2.0$.

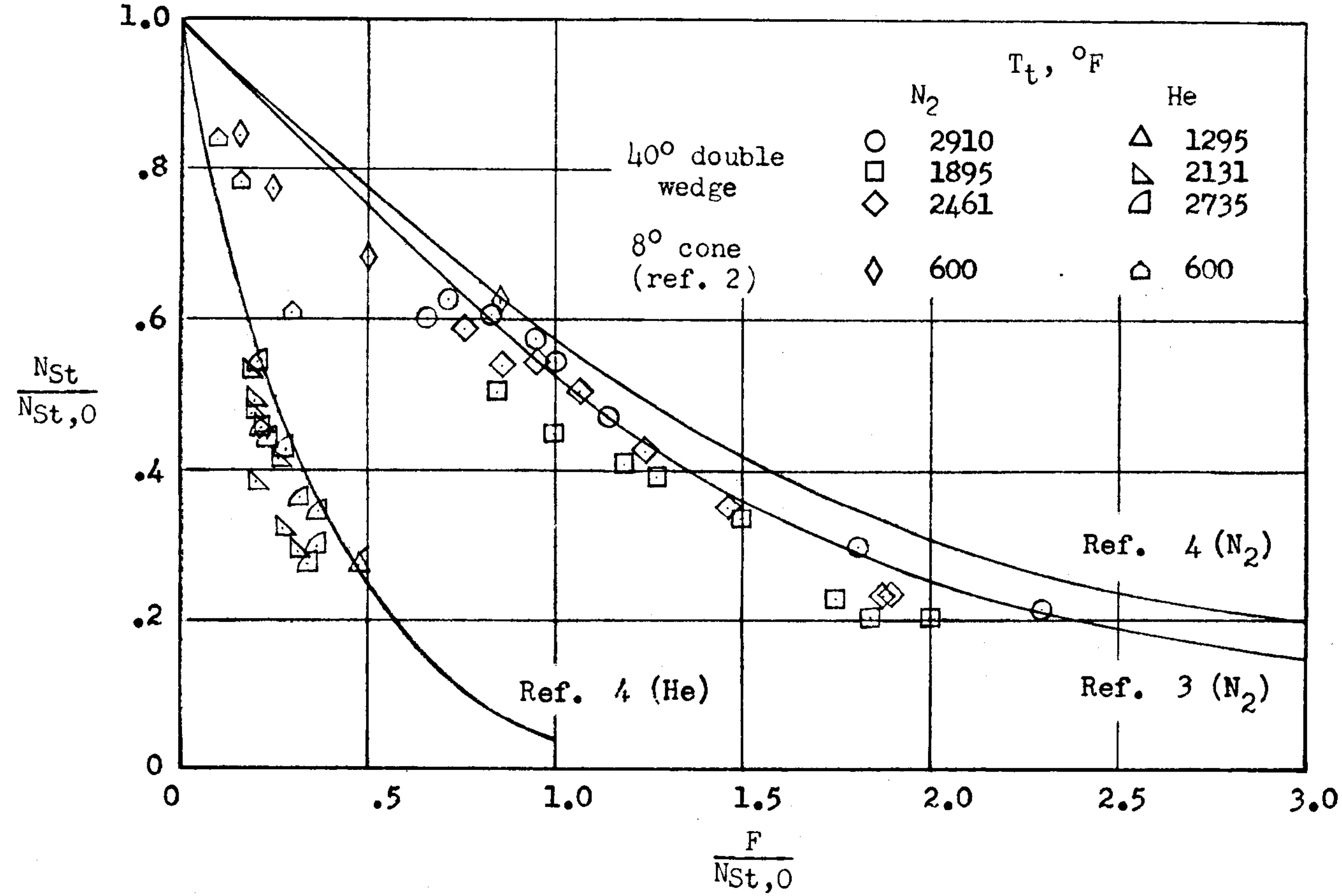


Figure 7.- Variation of ratio of Stanton number to theoretical Stanton number for no coolant flow with flow parameter. $M_\infty = 2.0$.

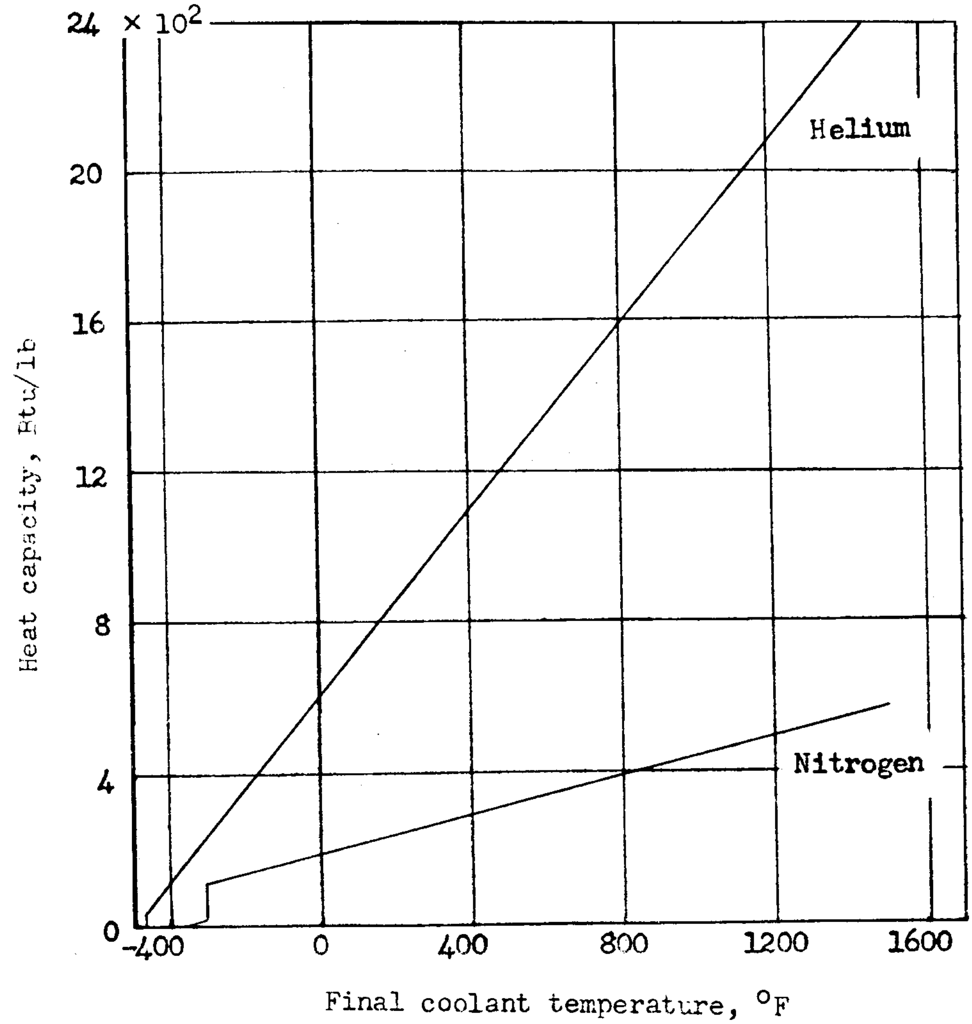


Figure 8.- Heat capacity of nitrogen and helium.