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A METHOD OF PREDICTING HEAT TRANSFER COEFFICIENTS IN THE COOLING PASSAGES OF NERVA AND PHOEBUS-2 ROCKET NOZZLES

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TECHNICAL PAPER proposed for presentation at the Fourth Joint Propulsion Specialists Conference sponsored by the American Institute of Aeronautics and Astronautics
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Abstract

The generally accepted methods of predicting heat-transfer coefficients often give values which are in poor agreement with the measured coefficients for single phase hydrogen flowing through straight symmetrically heated circular tubes for the extreme conditions encountered in the NERVA or Phoebus-2 nozzle. A thorough study of the 4600 experimental heat-transfer coefficients for hydrogen flowing through straight tubes is made which results in an equation which predicts coefficients with acceptable accuracy over a wide range of conditions. The prediction equation for straight tubes is modified to predict coefficients for hydrogen on both the "swept concave surface" and the "upswept convex surface" of curved symmetrically heated circular tubes. Without further modification the equation predicts heat-transfer coefficients which are in good agreement with values measured in asymmetrically heated noncircular channels simulating the throat region of the NERVA and Phoebus-2 nozzles. These tests were run under the actual anticipated heat flux, pressure, temperature, and flow rate. The prediction equations are recommended for use in predicting heat-transfer coefficients in the cooling passages of the actual NERVA and Phoebus-2 rocket nozzles.

Introduction

The extreme conditions encountered in regeneratively cooled nuclear rocket nozzles produce severe heat-transfer problems in the coolant passages. An effective method of predicting heat-transfer coefficients in the cooling passages is essential to the optimization of any nozzle design. Of particular concern is the high heat flux throat region where fluxes of 20 Btu/(sec)(in.^{2}) and higher are reached.

A number of investigations have been conducted with single phase hydrogen flowing turbulently through tubes. The range of conditions in these investigations have approximated those encountered in the cooling passages of a nuclear rocket nozzle. These studies resulted in several correlation equations each of which was limited to a particular range of conditions. A recent study found that a single equation can be used to predict heat-transfer coefficients over a much greater range of conditions than was previously possible.[1]

In this presentation the most recent straight tube prediction equation[1] is first compared with the two prediction equations most widely used in rocket nozzle design.[10,12,13] The straight tube prediction equation[1] is then modified to include the effects of curvature and compared to some existing experimental data for single curved tubes. Finally the suggested application of these prediction equations to the cooling passages of a nuclear rocket nozzle is discussed.

Heat-Transfer Coefficients in Straight Tubes

A study of all available turbulent single phase hydrogen heat-transfer data has been reported in Ref. 1. These 4622 data points resulted from 10 investigations using symmetrically heated straight circular tubes with a straight unheated approach length.[2 to 11] The complete range of experimental conditions covered by the investigations is shown in table I. The study reported in Ref. 1 gave as a result the correlation equation

$$Nu_b = 0.023\ Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \qquad (1)$$

which was tested for the range of inlet pressure and inlet temperature shown in Fig. 1. The use of the temperature-entropy diagram is a convenient method of showing the location of measured inlet pressure and temperature in relation to the saturation lines and critical pressure p_c and critical temperature T_c.

The hydrogen data are separated into regions 1 and 2 as shown in Fig. 1. These regions are the result of the study of the effect of inlet temperature T_i, inlet pressure p_i, and the transposed critical temperature (the temperature at which the specific heat at constant pressure reaches a maximum) T^*. In region 1, 87 percent of the 3674 heat-transfer coefficients predicted by equation (1) deviates less than ±25 percent from the measured values. Region 2 is defined by $45^\circ\ R < T_i < T^*$ and $p_c < p_i < 530$ psia and is often referred to as the near-critical region. In region 2, 40 percent of the 948 predicted heat-transfer coefficients deviates less than ±25 percent from the measured valves. At present there is considerable doubt about the transport properties in this region.

There are two equations commonly used in predicting heat-transfer coefficients in the cooling passages of a regeneratively cooled nuclear rocket nozzle. One of these is the Hess and Kunz equation[12]

$$Nu_f = 0.0208\ Re_f^{0.8} Pr_f^{0.4} \left(1 + 0.01457 \frac{\nu_w}{\nu_b}\right) \qquad (2)$$

The other one is the modified Hess and Kunz equation[10 and 13]

$$Nu_f = 0.0208\ C_L Re_f^{0.8} Pr_f^{0.4} \left(1 + 0.01457 \frac{\nu_w}{\nu_b}\right) \qquad (3)$$

The quantity C_L varies nonlinearly as follows:

Coolant temperature, ^oR	C_L
50	2.0
55	1.73
60	1.48
65	1.26
70	1.07
75	.93
80	.87
85	.85

For coolant temperatures above 85^o R C_L is constant at 0.85.

Equations (1) to (3) are used to predict heat-transfer coefficients which can be compared to the most recent experimental data for the range of conditions encountered in nuclear rocket nozzles. The ratio of these predicted coefficients to the measured values are shown as a function of the ratio of wall to fluid bulk temperatures in Fig. 2. Figure 2 shows that 94 percent of the heat-transfer coefficients predicted using equation (1) deviated less than ±20 percent from the measured values compared to 42 percent using equation (2) and 66 percent using equation (3).

Heat-Transfer Coefficients in Curved Tubes

Heat transfer measurements have been reported for both the concave or "swept" side and the convex or "unswept" side of curved circular tubes.[14] Equation (1) was first tried without any change from the form that correlated straight tube data to predict heat-transfer coefficients for both the concave and convex sides of the symmetrically heated test sections. The ratio of the heat-transfer coefficient predicted by equation (1) to the measured coefficient is shown as a function of temperature ratio in Fig. 3. As might be expected, the predicted heat-transfer coefficient is lower than the measured value on the concave side and higher than the measured value on the convex side. The calculated heat-transfer coefficient is as small as one-half the experimental value on the concave side and as large as almost twice the experimental value on the convex side. These effects of curvature on the heat-transfer coefficients have been noted elsewhere.[15,16]

Equation (1) is modified in this paper with the Itō correction factor for curvature[17] to give the equation

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \times \left[Re_b \left(\frac{r}{R}\right)^2\right]^{0.05} \qquad (4)$$

for the concave side.

The convex side of a curved tube is rarely given any consideration, but in this study the reciprocal of the Itō factor was used to modify equation (1) to give

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \times \left[Re_b \left(\frac{r}{R}\right)^2\right]^{-0.05} \qquad (5)$$

for the convex side.

The results of using equations (4) and (5) to predict the heat-transfer coefficients on the concave and convex sides of a tube are shown in Figs. 4(a) and (b), respectively. The experimental data in Fig. 4 is the same data used in Fig. 3. Approximately 90 percent of the predicted heat-transfer coefficients deviated less than ±20 percent from the experimental values.

It appears that the Itō correction does improve the correlation and that equations (4) and (5) will predict heat-transfer coefficients on the concave and convex sides of curved tubes, respectively.

Thus far, both the straight and curved tube data were for symmetrically heated circular tubes. In a rocket nozzle the cooling passages are noncircular and they heated from only one side. Some data are available for asymmetrically heated circular and noncircular passages curved to simulate the throat and high flux region of the NERVA and Phoebus-2 nozzles.[10] Heat-transfer coefficients predicted by equation (4) were compared to these experimental values for conditions as near as possible to those for the actual nozzle.

Figure 5 shows the ratio of the heat-transfer coefficients calculated by equation (4) to the experimental coefficients as a function of the dimensionless distance from the entrances. In Fig. 5(a) the ratio of coefficients are for the NERVA contour and in Fig. 5(b) the ratio is for the Phoebus-2 contour. The agreement between predicted and measured heat-transfer coefficients is considerably better for the Phoebus-2 configuration than for the NERVA configuration. The ratio of coefficients seems to vary more erratically for NERVA data than for the Phoebus-2 data.

One possible explanation for this behavior might be that for the NERVA contour. The calculated temperature drop through the wall is up to ten times the temperature difference between the inside wall and the hydrogen. For this condition an error of 2 percent in the measured outside wall temperature can result in a 30 percent error in the heat-transfer coefficient. A 2 percent error in outside wall temperature will result in only 10 percent in the Phoebus-2 contour where wall temperature drop is never more than three times the temperature difference between the inside wall and the hydrogen. Another explanation might be due to the difference in curvature of the two contours.

An important use of the heat-transfer coefficient is in the prediction of wall temperatures. Equation (4) is used to predict the inside wall temperatures shown in Fig. 6. The experimental wall temperatures and the wall temperatures predicted by a modified Hess and Kunz equation are taken directly from Ref. 10. Only the two runs shown in Figs. 6(a) and (b) were shown in Ref. 10 and, therefore, are the only ones shown in this paper. As shown both equations usually predict wall temperatures higher than the experimental values with the modified Hess and Kunz values being more conservative.

Heat-Transfer Coefficients in Rocket Nozzle Cooling Passages

Regeneratively cooled rocket nozzles are made up of noncircular passages formed to give the desired area ratios, and are essentially combinations of straight and curved tubes. The success demonstrated in predicting heat transfer coefficients in straight with tubes using equation (1) and curved tubes using equations (4) and (5) encourages the use of these equations in predicting heat transfer coefficients in the coolant passages of a rocket nozzle.

To predict the heat transfer coefficients in the cooling passage of a nozzle, the following equations are recommended:

Entrance of Coolant Passage

Straight entrance $x/D > 1$

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \qquad (1)$$

45^o and 90^o angle bend entrance $x/D > 5$

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \times \left(1 + F_1 \frac{D}{x}\right) \qquad (6)$$

where $F_1 = 3.5$ for the 45^o angle bend and 5 for the 90^o angle bend entrance.[18] F_1 differs from the value given[18] by 1.4 (the value for F_1 for a straight entrance and which is included in the exponent of T_w/T_b).

Throat Section (Concave Curvature)

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \times \left[Re_b \left(\frac{r}{R}\right)^2\right]^{0.05} \qquad (4)$$

Exit Section (Convex Curvature)

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \times \left[Re_b \left(\frac{r}{R}\right)^2\right]^{-0.05} \qquad (5)$$

Any Straight Sections

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b}\right) \exp - \left(0.57 - \frac{1.59}{x/D}\right) \qquad (1)$$

At present it is not known how far the effects of curvature on the heat-transfer coefficient will extend downstream of the point of tangency where a curved tube becomes straight. It is reasonable to assume that the effect of curvature would diminish with x/D rather than change abruptly at the point of tangency. The curvature effect appears to be present at the last instrumented station shown in Fig. 6(b) which is 2 diameters downstream of the tangency point.

Equations (1), (4), (5), and (6) are the best available for the prediction of heat-transfer coefficients in the cooling passages of hydrogen cooled rocket nozzles. The use of equations (1), (4), (5), and (6) should allow the design of more efficiently and reliably cooled rocket nozzles.

Symbols

c_p	specific heat of gas at constant pressure
D	inside diameter of test section
G	mass flow rate per unit cross-sectional area
h	local heat-transfer coefficient
k	thermal conductivity of gas
Nu	Nusselt number, hD/k
Pr	Prandtl number, $c_p \mu/k$
p	absolute static pressure
q	rate of heat transfer to gas per unit area
R	radius of curvature
Re_b	bulk Reynolds number, GD/μ_b
Re_f	modified film Reynolds number, $\rho_f V_b D/\mu_f$
r	inside radius of passage
T	temperature
T^*	transposed critical temperature (temperature at which specific heat of fluid at constant pressure reaches a maximum)
v	velocity
x	distance from entrance of test section
μ	absolute viscosity of gas
ν	kinematic viscosity of gas, μ/ρ
ρ	density of gas

Subscripts:

b	bulk (when applied to properties, indicates evaluation at bulk temperature T_b)
c	critical

f film (when applied to properties indicates evaluation at film temperature T_f)

i inlet

w wall

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x/D	2.0	252
T_w/T_b	1.1	27.6
T_i, °R	4.5	573
p_i, psia	18	2500
q, Btu/(sec)(in.^{2})	0.036	27.6
Re_b	7500	13 800 000
T_w, °R	53	5600

TABLE I. - RANGE OF EXPERIMENTAL CONDITIONS

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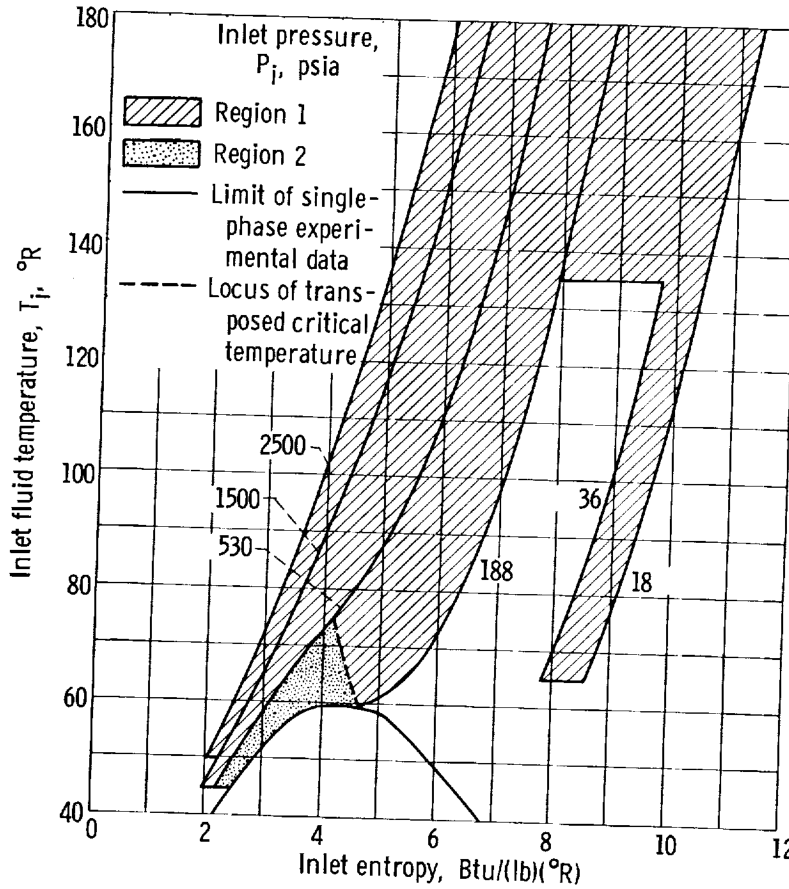

Figure 1. - Range of hydrogen inlet temperature and inlet pressure for which equation (1) has been experimentally checked.

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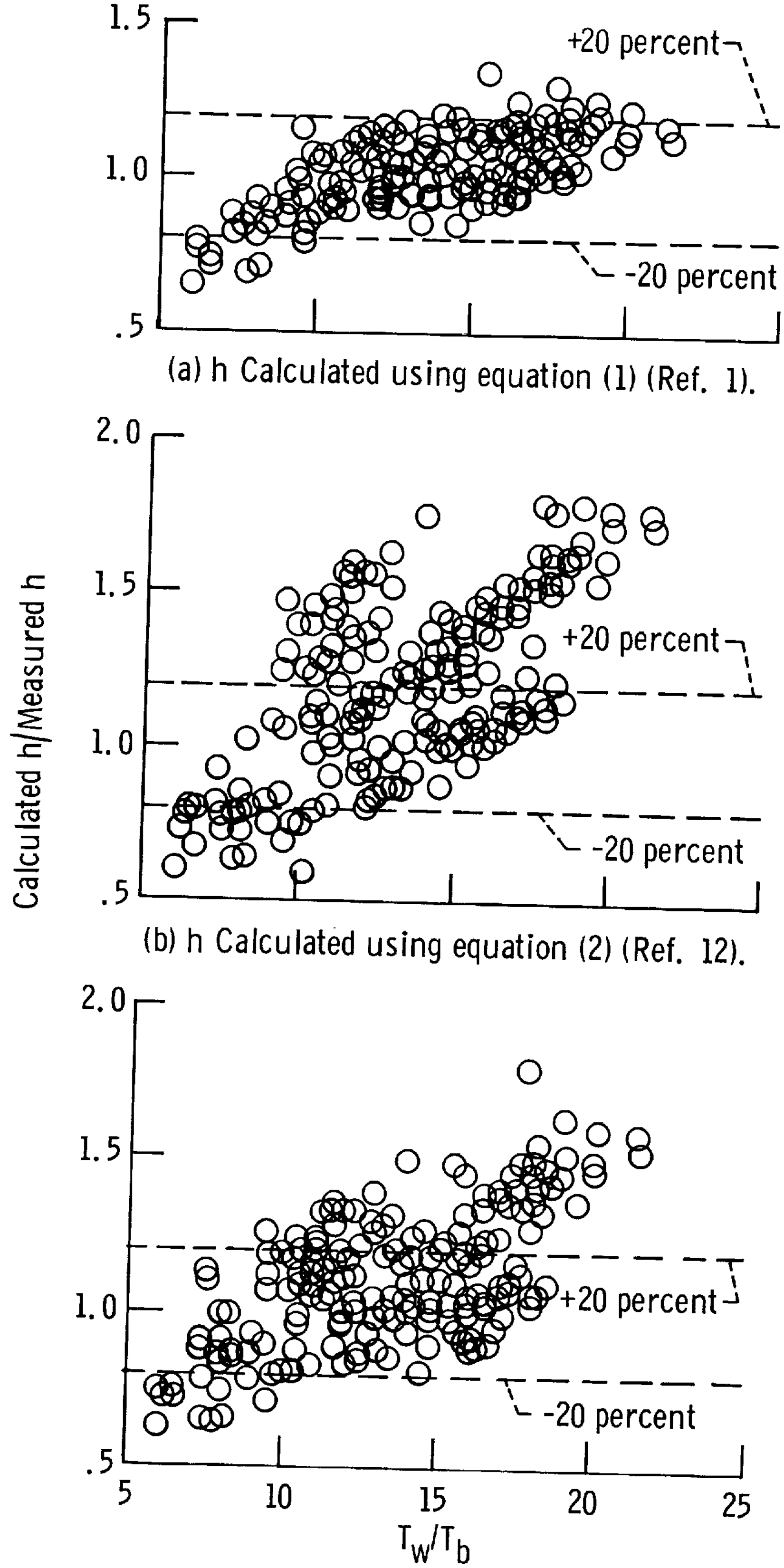

(c) h Calculated using equation (3) (Refs. 10 and 13).

Figure 2. - Variation of the ratio of calculated to measured heat transfer coefficients with temperature ratio. Straight tube data from reference 10, x/D from 6.7 to 33.9, heat flux from 6.4 to 27.6 Btu/(sec)(in.^{2}).

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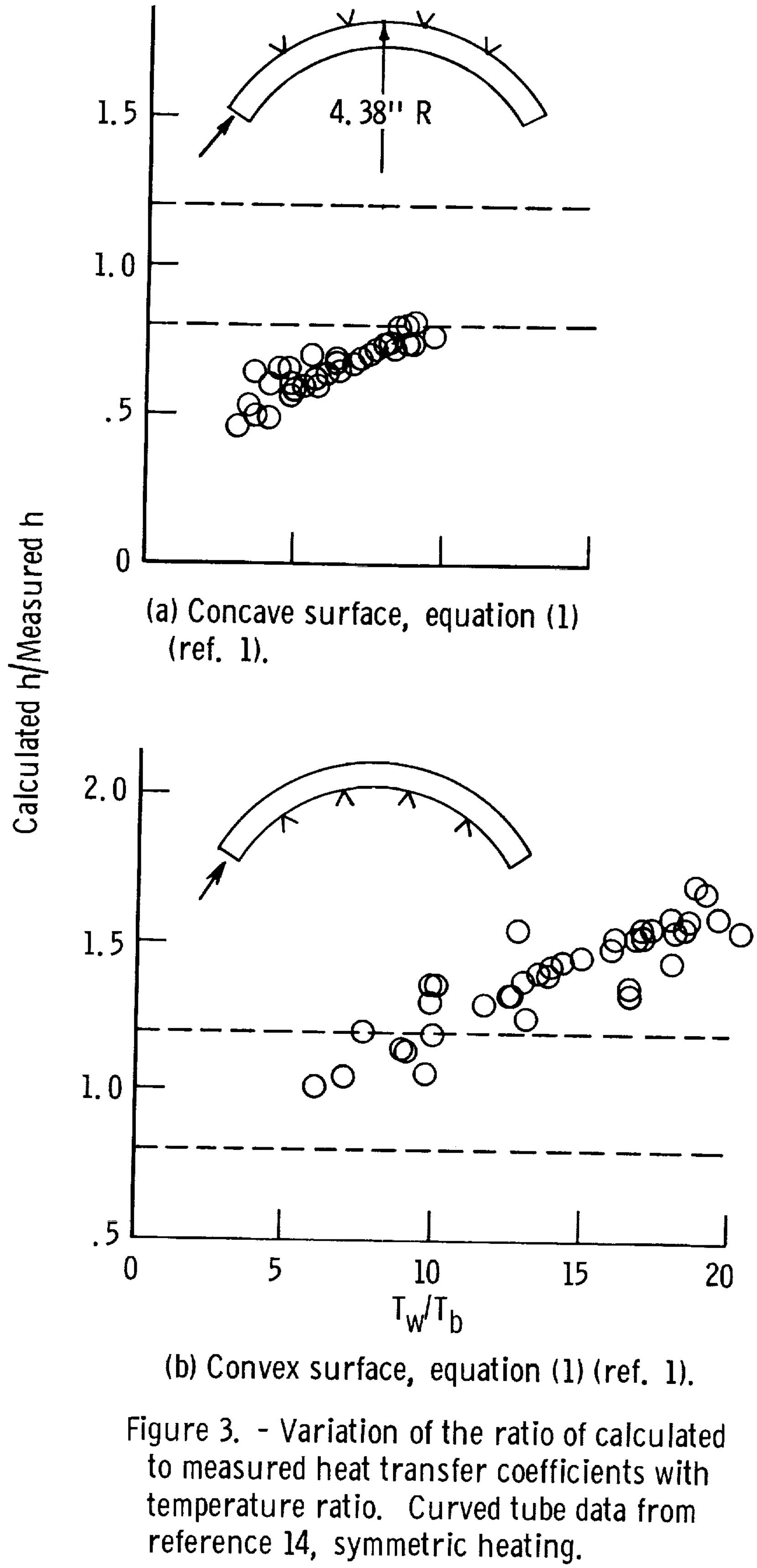
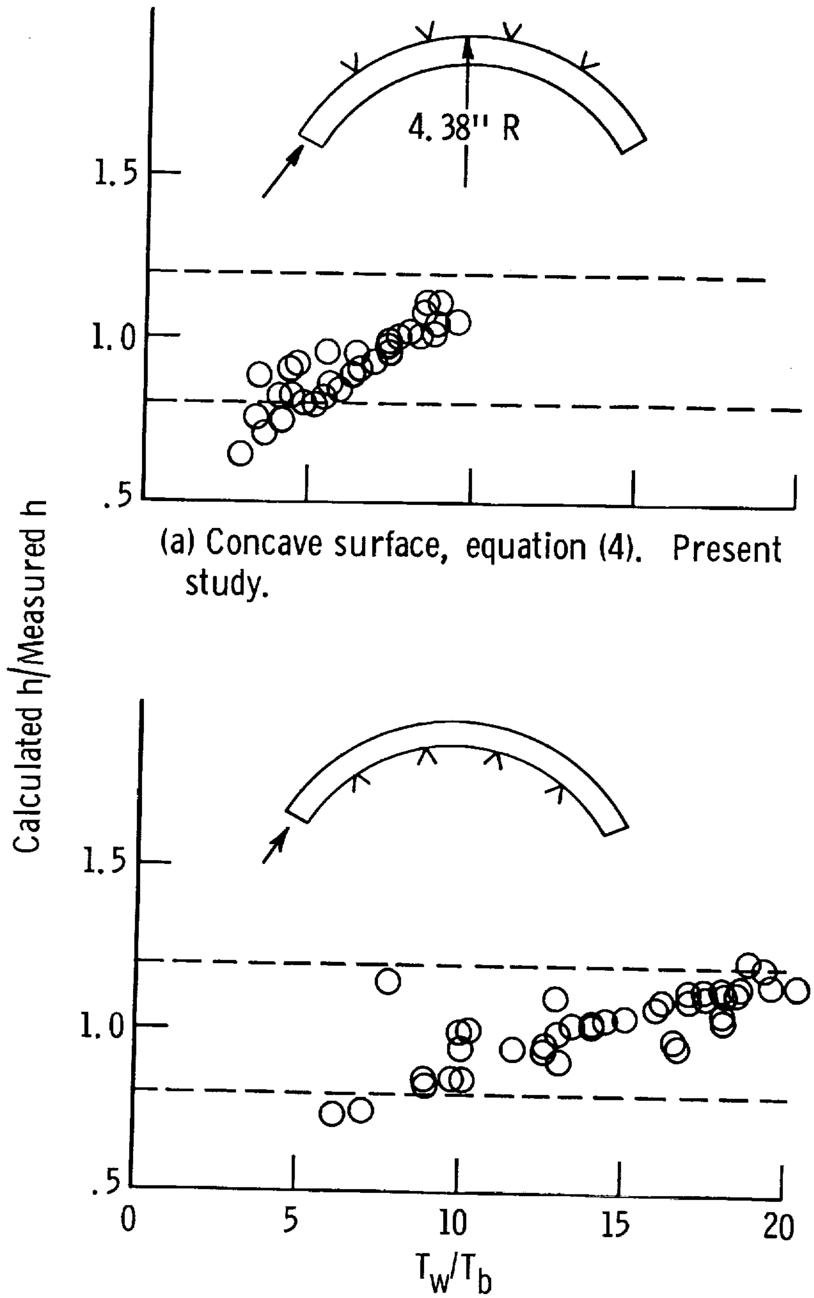


Figure 3. - Variation of the ratio of calculated to measured heat transfer coefficients with temperature ratio. Curved tube data from reference 14, symmetric heating.



(a) Concave surface, equation (4). Present study.

(b) Convex surface, equation (5). Present study.

Figure 4. - Variation of the ratio of calculated to measured heat transfer coefficients with temperature ratio. Curved tube data from reference 14, symmetric heating.

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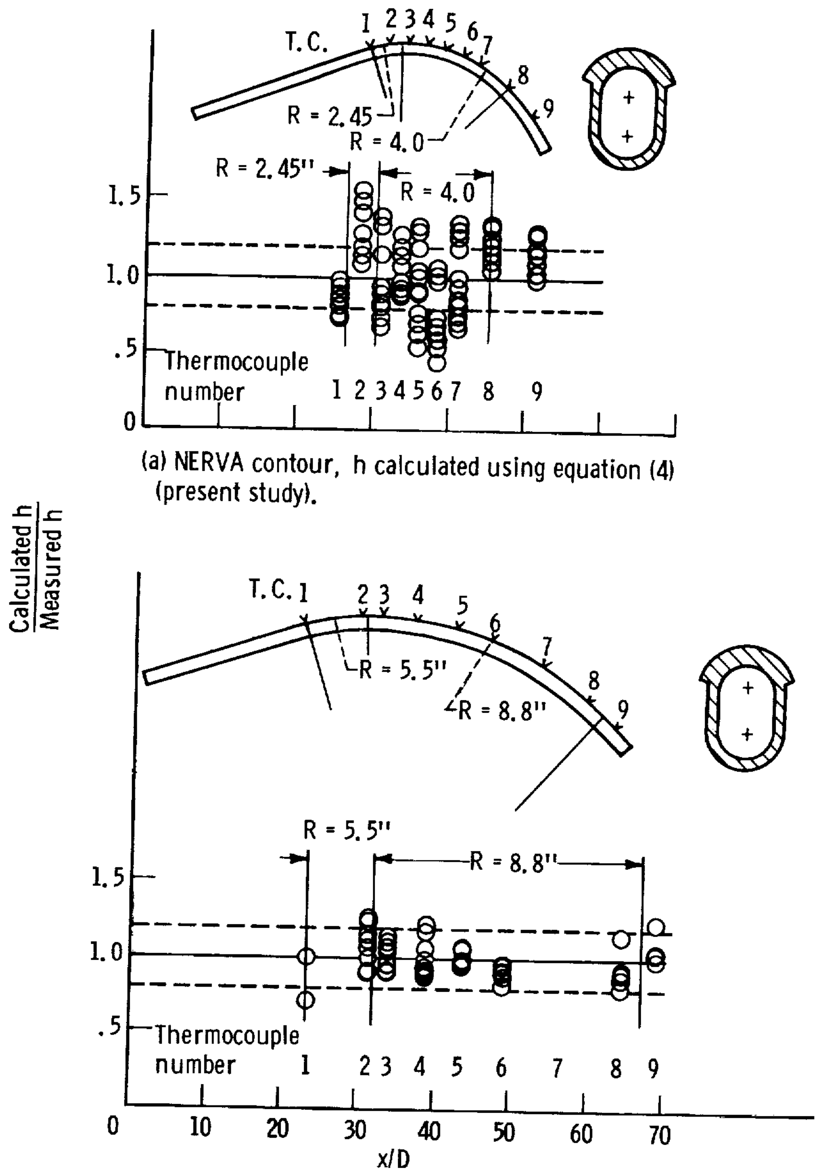
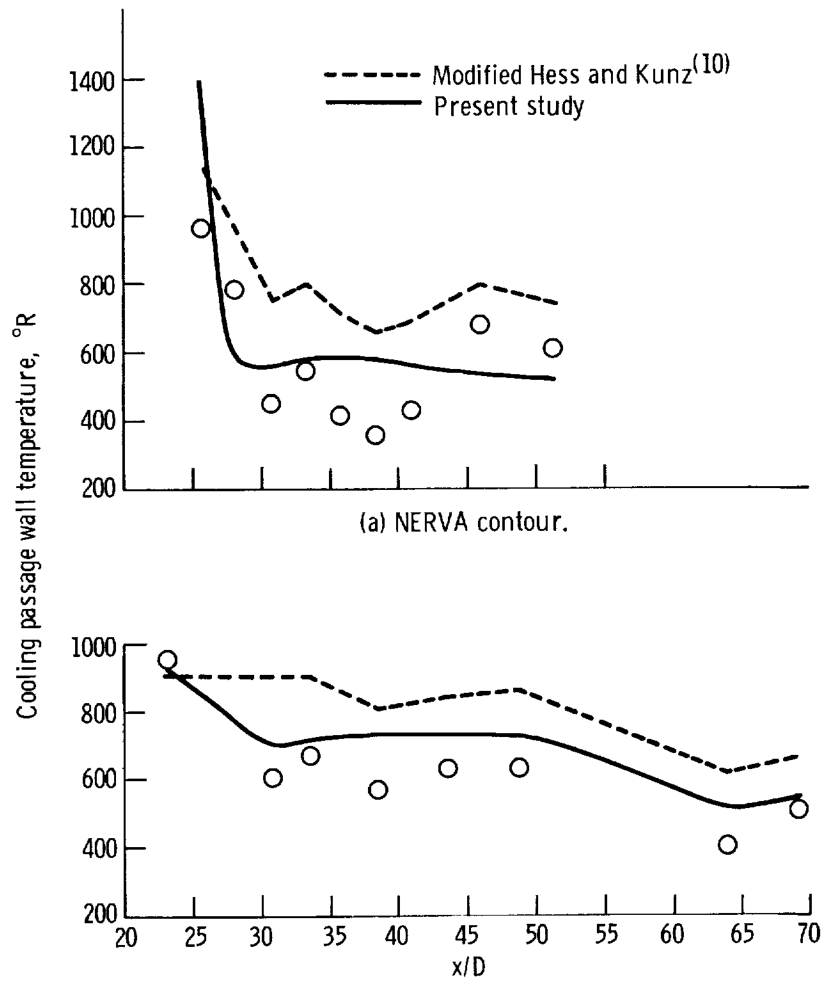


(a) NERVA contour, h calculated using equation (4) (present study).

(b) Phoebus-2 contour, h calculated using equation (4) (present study.

Figure 5. - Variation of the ratio of calculated to measured heat transfer coefficients with axial distance from entrance. Curved tube data from reference 10, asymmetric heating.



(b) Phoebus-2 contour.

Figure 6. - Variation of inside wall temperature with axial distance from entrance. Data from reference 10.