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COMPARISON OF PREDICTED NOZZLE COOLANT SIDE HEAT TRANSFER AND FLUID FLOW WITH EXPERIMENTAL VALUES FROM PHOEBUS-2A NUCLEAR TESTS

by Maynard F. Taylor

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Cleveland, Ohio

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ABSTRACT

A recently reported method of predicting heat-transfer coefficients for the extreme conditions encountered in the cooling passages of regeneratively cooled nuclear rocket nozzles is used to predict pressures and temperatures at 34 stations in the Phoebus 2A nozzle. The predicted pressure and temperatures at the exit of the cooling passages are compared with the measured values of EP-IV nuclear tests and found to be in very good agreement. Incremental values of coolant temperatures and pressures, coolant passage wall temperatures, and heat flux to the coolant are calculated and shown. It is shown that a constant C_g of 0.026 yields values for coolant exit pressure and temperature that are in very good agreement with measured values.

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SUMMARY

A recently reported method of predicting heat-transfer coefficients for the extreme conditions encountered in the cooling passages of regeneratively cooled nuclear rocket nozzles is used to predict pressures and temperatures at 34 stations in the Phoebus 2A nozzle. The predicted pressure and temperatures at the exit of the cooling passages are compared with the measured values of EP-IV nuclear tests and found to be in very good agreement. Incremental values of coolant temperatures and pressures, coolant passage wall temperatures, and heat flux to the coolant are calculated and shown. A constant gas coefficient C_g of 0.026 yields values for coolant exit pressure and temperature that are in very good agreement with measured values. Maximum wall temperature and heat flux are in good agreement with those calculated using the conventional varying C_g.

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 per second per square inch (32.7 mW/m^2) and higher may be reached.

A number of experimental investigations have been conducted with single-phase hydrogen flowing turbulently through tubes for a wide range of conditions approximating those encountered in the cooling passages of a nuclear rocket nozzle. Each investigation resulted in a correlation for heat-transfer coefficients, which was limited to a particular range of conditions. All these investigations are reviewed in reference 1, and a single correlation equation for predicting heat-transfer coefficients over a much greater range of conditions was reported therein.

The use of the correlation equation from reference 1 along with the correction factors for entrance effects (ref. 2) and curvature (ref. 3) as a method of predicting heat-transfer coefficients in the cooling passages of nuclear rocket nozzles was recommended in reference 4. An existing digital computer program for calculating heat transfer and fluid flow in convectively cooled rocket nozzles (ref. 5) was revised to incorporate the recommended heat-transfer correlation equations from reference 4.

The purpose of this report is to compare the values calculated by the revised computer program with experimental values obtained from nuclear rocket tests. The Phoebus 2A EP-IV nuclear tests were selected because of its wide range of test conditions. The thermal power of the Phoebus 2A EP-IV tests varied from 490 to 4080 megawatts.

PHOEBUS 2A TESTS

Some overall dimensions of the Phoebus 2 rocket nozzle are shown in figure 1. Figure 2 is a photograph of the Phoebus 2A nozzle. The design, fabrication, and nonnuclear testing of the Phoebus 2 nozzles is reported in reference 6.

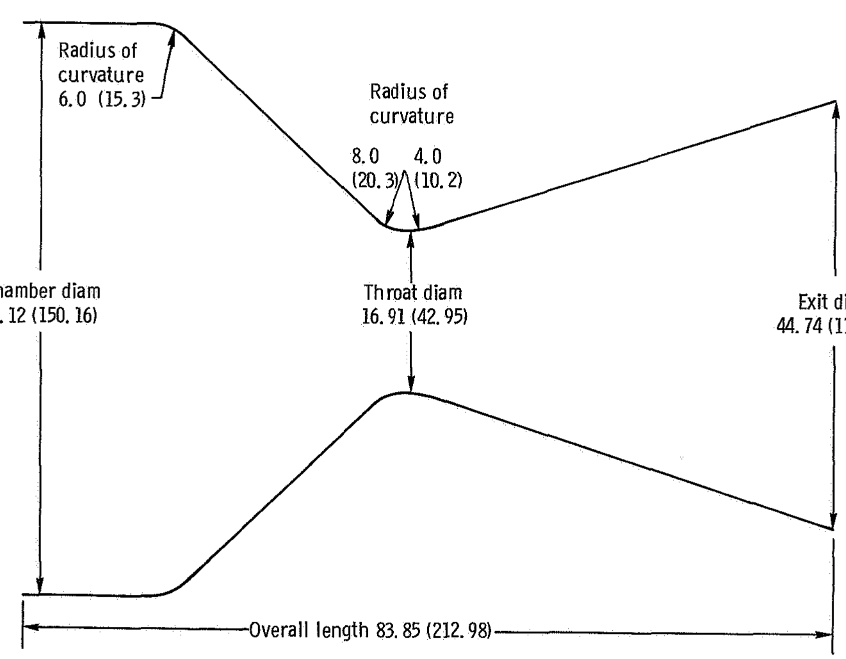


Figure 1. - Phoebus 2A nuclear rocket nozzle with some important dimensions. (All dimensions in inches (cm).)

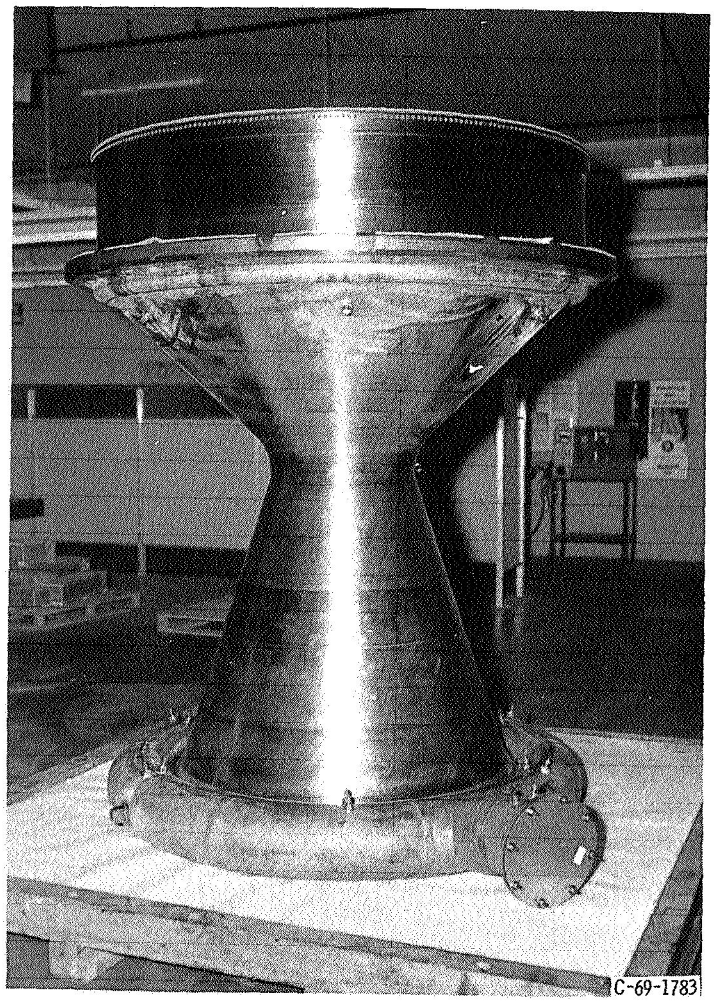


Figure 2. - Phoebus-2 nuclear rocket nozzle.

TABLE I. - OPERATING CONDITIONS FOR PHOEBUS 2A EP-IV NUCLEAR ROCKET TESTS[a]

(a) U. S. Customary Units

Test	Flow rate, lbm/sec		Chamber conditions		Nozzle inlet conditions		Thermal power, MW
	Hot gas	Coolant	Pressure, psia	Temperature, ^{o}R	Pressure, psia	Temperature, ^{o}R	
1	108.6	97.9	124	1240	197	40.8	490
2	142.0	125.6	214	2120	362	43.0	1090
3	192.2	176.6	351	3080	650	47.2	2190
4	244.1	219.8	435	2940	820	50.9	2650
5	245.2	219.5	506	3890	975	52.1	3630
6	262.3	234.9	555	4060	1080	53.9	4080

(b) S.I. Units

Test	Flow rate, kg/sec		Chamber conditions		Nozzle inlet conditions		Thermal power, MW
	Hot gas	Coolant	Pressure, MN/m^2	Temperature, K	Pressure, MN/m^2	Temperature, K	
1	49.3	44.4	0.855	689	1.36	22.6	490
2	64.4	57.0	1.48	1178	2.50	23.9	1090
3	87.2	80.1	2.42	1711	4.48	26.2	2190
4	110.7	99.7	3.00	1633	5.65	28.3	2650
5	111.2	99.6	3.49	2161	6.72	28.9	3630
6	119.0	106.6	3.83	2256	7.45	29.9	4080

[a]Unpublished data received from Donald L. Hanson, Los Alamos Scientific Laboratory.

Because the Phoebus 2A EP-IV tests covered the widest range of conditions of any other Phoebus tests, they were selected for use in this investigation. The test conditions for the EP-IV tests are shown in table I.

METHOD OF CALCULATION

The digital computer program reported in reference 5 was revised to incorporate the recommended heat-transfer equation from reference 4.

Heat-Transfer Calculations

Heat-transfer equations for both the hot-gas side and the coolant side are required to obtain a heat balance through the coolant wall. It is important that the best available prediction equations be used on both sides of the coolant passage wall. The correlation equation for the hot-gas side has not been improved upon but the coolant side correlation has undergone considerable improvement (refs. 1 and 4). These changes will be discussed in the section on the coolant side.

Hot-gas side. - The Nusslet equation

$$Nu_f = C_g Re_f^{0.8} Pr_f^{0.3} \tag{1}$$

is used in the computer program. Common practice (ref. 5) is to use a C_g that is a function of nozzle area ratio. In this investigation both a constant C_g of 0.026 and a

TABLE II. - AREA RATIO AND GAS COEFFICIENT

FOR EACH CALCULATION STATION[a]

Region	Station	Area ratio	Gas coefficient, C_g	Region	Station	Area ratio	Gas coefficient, C_g
Divergent	1	7.00	0.032	Convergent	21	2.34	0.027
	2	6.44	.033		22	3.17	.028
	3	5.90	.033		23	4.13	.028
	4	5.39	.033		24	5.21	.029
	5	4.90	.034		25	6.42	.032
	6	4.43			26	7.76	.035
	7	3.98			27	9.22	.038
	8	3.56		Knuckle	28	10.81	0.042
	9	3.17			29	11.85	.045
	10	2.79			30	12.22	.048
	11	2.44		Chamber	31	12.22	0.056
	12	2.12	.032		32		.064
	13	1.81	.030		33		.075
	14	1.53	.028		34		.080
	15	1.28	.024				
Throat	16	1.04	0.018				
	17	1.00	.018				
	18	1.07	.028				
	19	1.27	.029				
	20	1.63	.029				

[a]Unpublished data received from James O. Sane, Aerojet-General Corp.

variable C_g are used and the results compared. The variable C_g and the area ratio for the 34 stations in the nozzle is shown in table II. The equation for the gas-side heat-transfer coefficient used in the computer program is

$$h_g = \frac{C_g k_{g,f}}{D_{H,g}} \left[\left(\frac{\dot{w}}{A_{fl}}\right)\frac{D_H \rho_f}{\mu_f \rho_b}\right]_g^{0.8} \left(\frac{c_p \mu}{k}\right)_{g,f}^{0.3} \tag{2}$$

The heat-transfer surface area used in the computer program is

$$A_{ht} = \Delta l \pi R_{t,o,av} \epsilon_{c,av} \tag{3}$$

where $\epsilon_{c,av}$ is a heat-transfer area correction, which compensates for the variation of heat flux around the perimeter of the coolant tube. The generally accepted $\epsilon_{c,av}$ of value 0.8 (ref. 5) is used in this investigation.

Although the radiative heat flux at each station may be inserted as input data to the computer program, it was neglected in this investigation. There is no provision in the computer program for the small amount of film cooling on the hot-gas side of the chamber wall. The maximum effect can be estimated by assuming no heat addition at the last 4 stations (about 12.5 in. or 32 cm).

Hot-gas static temperature and pressure calculations for hydrogen at equilibrium conditions for assigned chamber pressure, chamber temperature, and nozzle area ratios were made using the computer program of reference 7.

Coolant side. - A Nusselt type correlation equation with the physical properties and density evaluated at the film temperature is part of the computer program in reference 5. This correlation equation was replaced by the one reported in reference 1 and used as recommended by reference 4. The correlation equation from reference 1 is

$$Nu_{b,l} = 0.023\, Re_{b,l}^{0.8} Pr_{b,l}^{0.4} C_3 \tag{4}$$

where

$$C_3 = \left(\frac{T_{w,l}}{T_{b,l}}\right)^{-\left[0.57 - 1.59/(l/D_{H,l})\right]} \tag{5}$$

The correlation for entrance effects from references 2 and 4 is

$$C_4 = \left(1 + F\,\frac{D_{H,l}}{l}\right) \tag{6}$$

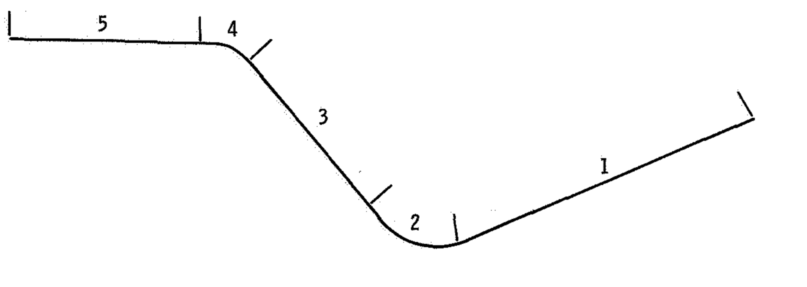
where $F = 11$ for an orifice entrance. The correction for curvature effects from references 3 and 4 is

$$C_5 = \left[\mathrm{Re}_b\left(\frac{R_{t,i}}{R_c}\right)^2\right]^{C_6} \tag{7}$$

where $C_6 = 0.05$ for the concave or swept surface and -0.05 for the convex or unswept surface. Equations (4) to (7) are combined to give the single correlation equation

$$\mathrm{Nu}_{b,l} = 0.023\,\mathrm{Re}_{b,l}^{0.8}\mathrm{Pr}_{b,l}^{0.4}C_3C_4C_5 \tag{8}$$

which is used in the computer program with C_4 and C_5 being used only where appropriate. Figure 3 shows the form of equation (8) used in the various coolant flow regions.



$$\mathrm{Nu}_{b,l} = 0.023\,\mathrm{Re}_{b,l}^{0.8}\mathrm{Pr}_{b,l}^{0.4}C_3C_4C_5$$

where

$$C_3 = \left(\frac{T_{w,l}}{T_{b,l}}\right)\exp - \left(0.57 - \frac{1.59}{\frac{l}{D_{H,l}}}\right)$$

$$C_4 = \left(1 + \frac{11\,D_{H,l}}{l}\right)$$

$$C_5 = \left[\mathrm{Re}_{b,l}\left(\frac{R_{t,i}}{R_c}\right)^2\right]^{C_6}$$

Region	
1	$C_5 = 1$
2	$C_4 = 1,\ C_6 = 0.05$
3	$C_4 = 1,\ C_5 = 1$
4	$C_4 = 1,\ C_6 = -0.05$
5	$C_4 = 1,\ C_5 = 1$

Figure 3. - Five regions of the coolant passage and constants applicable to each region.

Fluid Flow Calculations

Both friction and momentum pressure drops were calculated in the computer program. The equations used to calculate these pressure drops in reference 5 were not changed and are repeated here for the reader's convenience.

Friction pressure drop. - The friction pressure drop was calculated using the equations already in the computer program reported in reference 5. The friction pressure drop was calculated by the equation

$$\Delta p_{fr} = \frac{2G_{av}^2 f_c \Delta l}{\rho_{s,av} D_{H,av} g} \tag{9}$$

Two equations for calculating friction coefficients are available in the program: one for smooth tube conditions, the other for rough tube conditions. Since the Phoebus nozzle cooling passages have a relative roughness e of 60 microinches (1.52 μm), the rough tube equation

$$\frac{1}{\sqrt{f}} = -4.0 \log \frac{e}{3.7\, D_{H,av}} + \frac{1.255}{Re_{av}\sqrt{f}} \tag{10}$$

is used.

The friction coefficient is increased by the curvature of the throat and knuckle regions. The Itō correction factor (ref. 3) for curvature

$$C_7 = \left[Re_{av}\left(\frac{R_{t,i}}{R_c}\right)^2\right]^{0.05} \tag{11}$$

is applied as follows:

$$f_c = C_7 f$$

with f_c being used in equation (9).

Momentum pressure drop. - The momentum pressure drop equation reported in reference 5 is

$$\Delta p_{mom} = \frac{\dot{w}^2}{gA_{fl,av}} \left[\frac{1}{\left(\rho_s A_{fl}\right)_2} - \frac{1}{\left(\rho_s A_{fl}\right)_1}\right] \tag{12}$$

It is used in this investigation to calculate the momentum pressure drop in the coolant passages of Phoebus 2A nozzle.

DISCUSSION OF RESULTS

Coolant temperatures and pressures, wall temperatures, and heat fluxes at 34 stations along the coolant passages were calculated using the revised computer program

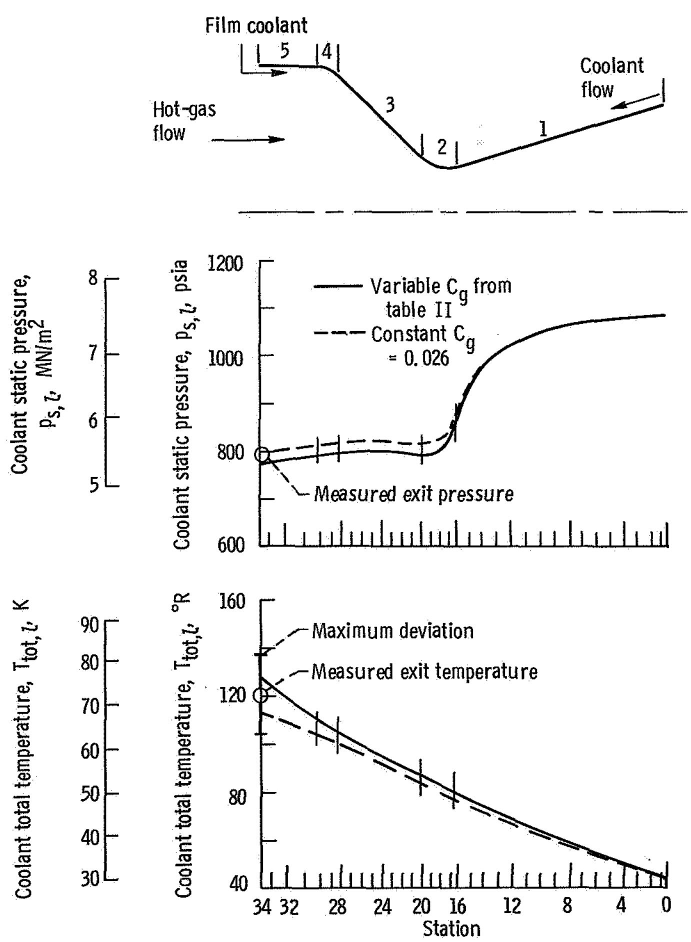


Figure 4. - Variation of coolant total temperature and static pressure with axial location. Thermal power 4080 megawatts; chamber pressure to 555 psia (3.83 MN/m^2); chamber temperature, 4060° R (2256 K).

from reference 5. Total temperature and static pressure of the coolant at each axial station for test EP-IV-6 are shown in figure 4. The only measured values for comparison with the calculated temperatures and pressures are taken at the exit of the coolant passages (the inlet of the reactor core reflector). The measured values for test EP-IV-6 are shown in figure 4. The solid line represents the calculated values with C_g varying as shown in table II. The dashed line represents the calculated values using a constant C_g of 0.026. The agreement between both calculated values and the measured values is very good. The measured and calculated exit pressures and temperatures and percent deviation for several other EP-IV tests are shown in table III. For the case of no heat addition in the last 4 stations (corresponding to film cooling of the chamber wall), both the exit temperature and pressure fell within the range of accuracy of the measured values and are not shown in table III.

In figure 5 the local hot-gas side wall temperature and the local coolant side heat flux is shown as a function of axial position. The solid line represents the values calculated using the variable C_g from table II and the dashed line represents the values resulting from the use of a constant C_g of 0.026. The greatest differences resulting from the calculations using the different C_g's are in the chamber. The use of temperature rise and pressure drop measurements indicates little of what happens locally in a rocket nozzle.

The maximum wall temperature is 1936° R (1076 K) for a constant C_g of 0.026 compared with 1838° R (1021 K) for the variable C_g from table II with both appearing at approximately the same location. The maximum heat flux to the coolant is 17.4 Btu per second per square inch (28.4 MW/m^2) for $C_g = 0.026$ and 16.9 Btu per second per square inch (27.6 MW/m^2) for C_g from table II. The maximum heat flux and maximum wall temperature do not appear at the same axial location.

Calculations using either a variable C_g or a constant C_g of 0.026 both give coolant exit pressures and temperatures that are in good agreement with measured values. The maximum heat flux and wall temperature for the constant C_g varies little from those computed with a variable C_g. Since the variation of C_g with area ratio varies a great deal with both investigator and nozzle configuration (ref. 5), the capability of using a constant C_g for reliable nozzle calculations is of great value.

The rather abrupt changes in wall temperature is due to the application of the curvature correction which increased the heat-transfer coefficient on the concave or swept surface (decreasing the wall temperature) and decreased the heat-transfer coefficient on the convex or unswept surface (increasing the wall temperature). In the actual nozzle wall these changes would probably not be so abrupt because of axial heat conduction in the coolant passage wall. Axial heat conduction was not accounted for in the computer program.

TABLE III. - CALCULATED AND MEASURED TEMPERATURES AND PRESSURES

AT EXIT OF COOLANT PASSAGES FOR PHOEBUS 2A EP-IV TESTS

(a) U.S. Customary Units

Test EP-IV	Measured exit temperature, T_m, °R (a)	Gas coefficient				Measured exit pressure, P_m, psi (a)	Gas coefficient			
		C_g from table II		$C_g = 0.026$			C_g from table II		$C_g = 0.026$	
		Calculated exit temperature, T_c, °R	$\frac{T_c - T_m}{T_m} \times 100$, percent	Calculated exit temperature, T_c, °R	$\frac{T_c - T_m}{T_m} \times 100$, percent		Calculated exit pressure, P_c, psi	$\frac{P_c - P_m}{P_m} \times 100$, percent	Calculated exit pressure, P_c, psi	$\frac{P_c - P_m}{P_m} \times 100$, percent
1	71	59	-17	59	-17	168	176	4.8	167	-0.6
2	75	74	-1.3	69	-8.0	296	288	-2.7	298	.7
3	95	102	7.4	91	-4.2	499	483	-3.2	502	.6
4	96	103	7.3	93	-3.1	616	593	-3.7	614	.3
5	124	131	5.6	117	-5.6	720	701	-2.6	729	1.2
6	130	137	5.4	122	-6.1	790	769	-2.7	799	1.1

(b) S.I. Units

Test EP-IV	Measured exit temperature, T_m, K (a)	Gas coefficient				Measured exit pressure, P_m, MN/m^2 (a)	Gas coefficient			
		C_g from table II		$C_g = 0.026$			C_g from table II		$C_g = 0.026$	
		Calculated exit temperature, T_c, K	$\frac{T_c - T_m}{T_m} \times 100$, percent	Calculated exit temperature, T_c, K	$\frac{T_c - T_m}{T_m} \times 100$, percent		Calculated exit pressure, P_c, MN/m^2	$\frac{P_c - P_m}{P_m} \times 100$, percent	Calculated exit pressure, P_c, MN/m^2	$\frac{P_c - P_m}{P_m} \times 100$, percent
1	39	33	-17	33	-17	1.16	1.21	4.8	1.15	-0.6
2	42	41	-1.3	38	-8.0	2.04	1.99	-2.7	2.05	.7
3	53	57	7.4	51	-4.2	3.44	3.33	-3.2	3.46	.6
4	53	57	7.3	52	-3.1	4.25	4.09	-3.7	4.23	.3
5	69	73	5.6	65	-5.6	4.96	4.83	-2.6	5.03	1.2
6	72	76	5.4	68	-6.1	5.45	5.30	-2.7	5.51	1.1

[a]Unpublished data received from Donald L. Hanson, Los Alamos Scientific Laboratory.

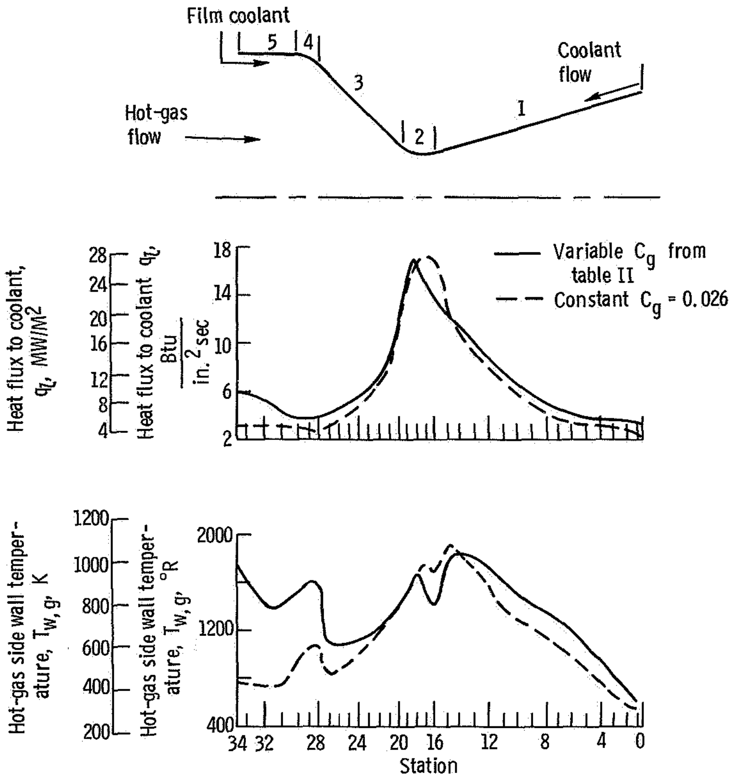


Figure 5. - Variation of hot-gas side wall temperature and coolant side heat flux with axial location. Thermal power, 4080 megawatts chamber pressure, 555 psia (3.83 MN/m^2); chamber temperature, 4060° R (2256 K).

CONCLUDING REMARKS

Recently reported equations, which accurately predict coolant heat-transfer coefficients (refs. 1 and 4), have been inserted into an existing computer program (ref. 5) to calculate coolant exit temperature and pressure. These calculated values are in very good agreement with measured values. One set of calculations used recommended C_g's that varied from 0.018 to 0.080, another set of calculations used a constant C_g of 0.026. Both sets of calculations yielded exit temperatures that are in good agreement with measured temperatures. The constant C_g calculations predicted exit pressures that were in a little better agreement with measured pressures than the variable C_g calculations. These calculations show that with accurate predictions on the coolant side the less well developed heat-transfer correlations on the hot-gas side are of secondary importance in predicting total temperature rise and static pressure drop. The hot-gas side heat-transfer does change the wall temperature distribution, which indicates that measured wall temperatures are needed to verify any hot-gas side equations.

The close agreement between predicted and actual performance gives confidence that now these prediction equations can be used to design nuclear rocket nozzles that are more reliable and possibly lighter in weight.

The small effect of whether a variable or a constant C_g was used in the calculation of coolant exit pressure and temperature and maximum heat flux and gas-side wall temperature indicates that reliable calculations can be made using a constant C_g of 0.026. Since C_g has always varied with both investigator and nozzle configuration, the capability of using a constant C_g greatly simplifies nozzle calculations.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1969,
122-28-02-33-22.

APPENDIX - SYMBOLS

A	area
C	numerical coefficient
C_3	convective heat-transfer coefficient correction for fluid properties variation
C_4	convective heat-transfer coefficient correction for entrance effects
C_5	convective heat-transfer coefficient correction for curvature effects
C_6	exponent of C_5, 0.05 for concave surface, -0.05 for convex surface
C_7	friction coefficient correction for tube curvature
c_p	specific heat at constant pressure
D	diameter
e	relative roughness of surface
F	entrance effect coefficient
f	friction factor for straight tubes
f_c	friction factor for curved tubes
G	mass flow per unit cross-sectional area
g	gravitational conversion factor
h	convective heat-transfer coefficient
k	thermal conductivity
l	linear distance along coolant passage wall
Δl	linear distance along coolant passage wall between stations
Nu	Nusselt number
Pr	Prandtl number
p	pressure
Δp_{fr}	friction static-pressure drop
Δp_{mom}	momentum static-pressure drop
q	local heat flow rate
R	radius
R_c	radius of curvature
Re	Reynolds number

T temperature

$\dot{w}$ mass weight of flow

ϵ_c heat-transfer surface-area correction factor

μ dynamic viscosity

ρ density

Subscripts:

av average

b bulk

c calculated

f film

fl flow

g gas

H hydraulic

ht heat transfer

i inside

l liquid or coolant

m measured

o outside

s static

t tube

w wall

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NASA-Langley, 1969 —— 33 E-5078

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