REON

SACRAMENTO PLANT

REPORT NO. RN-S-0092
(Revision A)

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

REVIEW OF HEAT TRANSFER ANALYSIS

NERVA PROGRAM

CONTRACT SNP-1

OCTOBER 1965

MASTER

AEROJET-GENERAL CORPORATION

4400 JEFFERSON AVENUE, PASADENA, CALIF. 91107

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

REPORT NO. RN-S-0092
(Revision A)

REVIEW OF HEAT TRANSFER ANALYSIS

OCTOBER 1965

ROCKET ENGINE OPERATIONS - NUCLEAR

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

AEROJET - GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

SW

ABSTRACT

The heat transfer literature presenting information pertinent to the NERVA system published since the publication of REON Report RN-S-0092 is reviewed. While significant contributions toward advancing the "state of the art" are made it is concluded that the recommended equations presented in Report RN-S-0092 are still valid and no changes are required at this time. For further information contact Dr. C. F. Warner or R. J. Pickering of REON.

for W. D. Stinnett
Program Manager
REON

CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
II. GASEOUS PHASE, SUBCRITICAL AND SUPERCRITICAL PRESSURES AT TEMPERATURES ABOVE 150°R	3
A. Heat Transfer Coefficients	3
B. Friction Factors	5
C. Conclusions and Recommendations	8
III. GASEOUS PHASE AT TEMPERATURES BELOW 150°R	9
IV. NEAR CRITICAL FLUID	9
A. Discussion	9
B. Conclusions and Recommendations	11
V. FORCED CONVECTIVE BOILING HEAT TRANSFER	13
A. Discussion	13
B. Conclusions and Recommendations	15
VI. REFERENCES	17

I. INTRODUCTION

REON Report RN-S-0092, issued June 1964, presented and discussed the heat transfer and pressure drop correlations together with the digital computer codes available at WANL for use in predicting the heat transfer and fluid flow phenomena for each of the operating phases encountered in normal reactor operation. Since that date, new information pertinent to the operation of the NERVA system has appeared in the heat transfer literature. This current report is a review of the heat transfer literature appearing between the publication of RN-S-0092 in June 1964 and June 1965. To maintain consistency the subject material is presented with the same subdivision and headings as those employed in Report RN-S-0092.

II. GASEOUS PHASE, SUBCRITICAL AND SUPERCRITICAL PRESSURES AT TEMPERATURES ABOVE 150°R

A. HEAT TRANSFER COEFFICIENTS

The results of an extensive study of the heat transfer characteristics of hydrogen are presented in Reference 1. Included in that report are the results of previous investigations as well as new information concerning the influence of the roughness of the inside passage surface upon the heat transfer coefficient and friction factor.

The complete equation for estimating hydrogen heat transfer presented in Reference 1 is:

$$Nu_b = 0.025 (Re_b)^{0.8} (Pr_b)^{0.4} (T_w/T_b)^{-0.55} \phi_1 \phi_2 \phi_3 \phi_4 \quad (1.)$$

WHERE

Nu_b = Nusselt number

Re_b = Reynolds number

Pr = Prandtl number

T_w = Wall temperature

T_b = Bulk fluid temperature

Subscript "b" indicates fluid properties evaluated at T_b

ϕ_1 = Correction for critical temperature region where the physical properties change drastically with temperature (bulk temperature effect).

ϕ_2 = Correction for the entrance region where the thermal boundary layer is not yet established (X/D effect).

ϕ_3 = Correction for heating, over only a portion of the tube wall periphery (asymmetric heating effect).

ϕ_4 = Correction for tube inside surface roughness (roughness effect).

ϕ_1 will be discussed in Section 8. In a previous work Wolf and McCarthy (Reference 2) propose that the value of ϕ_2 is given by the relation:

$$\phi_2 = 1.53 (X/D)^{-0.15} \quad (2.)$$

More recent data (presented in Reference 1) indicate that the relation for ϕ_2 is

$$\phi_2 = 1 + \frac{D}{X} \quad (3.)$$

Both equation (2) and equation (3) are for values of $\phi_2 > 1$.

From the results of experiments conducted with gaseous hydrogen obtained for round tubes heated over 35% of the tube periphery it is concluded, in Reference 1, that the asymmetric effect reduced the heat transfer by approximately 10% in the high Reynolds number region. Thus, it is recommended in Reference 1 that for the asymmetric heating condition:

$$\phi_3 = 0.90 \quad \text{for } Re_b > 500,000 \quad (4.)$$

A detailed description of a series of experiments designed to compare the heat transfer and friction factors for rough and smooth tubes for gaseous hydrogen flowing at very high Reynolds numbers is presented in Reference 1. Values of inside tube surface relative roughness (e/D) investigated were 0.00055, 0.00025, 0.00048, 0.00015, 0.00023 and 0.00005. It was found that the effect of roughness on the heat transfer appeared to start at Reynolds numbers of about 500,000. A maximum increase in heat transfer of about 15% was observed at a Reynolds number of 4×10^6 .

It is suggested, in Reference 1, that the correction for roughness is given by the relationship:

$$\phi_4 = \left[1 + 1000(e/D) (\log_{10} Re_b - 5.625) \right] \quad (5.)$$

McEligot, Magee and Leppert (Reference 3) present the results of an investigation of the heat transfer to air, nitrogen and helium flowing inside heated electrical tubes for wall to bulk temperature ratios from unity to 2.5 for entering Reynolds numbers from 15,000 to 233,000. These authors recommend the following equation:

$$Nu_b = 0.021 (Re_b)^{0.8} (Pr)^{0.4} (T_w/T_b)^{-0.5} [1 + (X/D)^{-0.7}] \quad (6.)$$

Equation (6) should not be used for tube entrance regions of less than two diameters in length.

B. FRICTION FACTORS

As was pointed out in the preceding section, Reference 1 presents the results of an investigation of the effect of tube surface roughness upon heat transfer and pressure drop obtained with gaseous hydrogen flowing in electrically heated tubes. The adiabatic Fanning friction factors were found to agree well with the friction factors calculated by the modified Colebrook equation

$$\frac{1}{\sqrt{f}} = 2.28 + 4.0 \log_{10} (\sqrt{f} Re) - 4.0 \log_{10} [(e/D) \sqrt{f} Re + 4.67] \quad (7.)$$

It was suggested, in Reference 1, that the effect of surface roughness upon the friction factor could be considered negligible for value of Reynolds numbers below 300,000.

No mention is made in Reference 1 of the effect of heat transfer upon the friction factor.

The results presented in Reference 3, by McEligot et al., indicate that the friction factor with heat addition tends to be lower than the adiabatic friction factor at the same Reynolds number; and, in addition, the authors state that other investigators have observed similar trends. McEligot et al. state that a six percent decrease in friction factor at a Reynolds number of 30,000 was observed. The experimental results of Reference 3 were correlated by the equation:

$$f = f_{ad} (T_w/T_b)^{-0.1} \quad (8.)$$

In Reference 4 Taylor presents the results of an experimental study of the heating of hydrogen and helium flowing in electrically heated tubes. The following is a quotation taken from Reference 4. "As would be expected, the hydrogen and helium runs with no heat addition are in good agreement with the Karman-Nikuradse relation. The hydrogen runs with heat addition are in agreement with the predicted line above a Reynolds number of 20,000, and in agreement with the data of References 3 and 6, which fall above the Karman - Nikuradse line below a Reynolds number of 20,000. The few runs using helium fall somewhat higher than either the predicted line or the data of References 3 and 6." The Reference 6 given by Taylor is the work of McEligot et al., as presented in an earlier report (TID - 13485).

Since the apparent discrepancy between the results of McEligot (which indicate a decrease in "f" with heating) and those of Taylor (which indicate an increase in "f" with heating) are unresolved at this time, no conclusions can be drawn concerning the effect of heating upon the friction factor. Fortunately the effect, whatever it is, appears to be of low magnitude especially at Reynolds numbers above 20,000.

The power reactor group at the Argonne National Laboratory reported (in Reference 5) the results of an extensive evaluation of currently available heat transfer and fluid friction correlations applicable to nuclear rocket systems. An attempt was made to isolate the best available hydrogen heat transfer and friction correlations, and to reconcile these if possible, with the best available computer subroutine for hydrogen properties. Seventeen empirical heat transfer correlations, twelve heat transfer analogies, and five friction factor equations were studied. In the report it is stated that - - - "Despite the evident theoretical advantage of the analog, the fact remains that much more work has been done in the realm of smooth-tube flow than in rough tube flow, and the results of the former have tended to produce more consistent results." The O.A. Farmer property code was employed to calculate hydrogen physical properties. (Farmer, O.A. Digital Programs for Para-Hydrogen Properties, IAMS-2762, September 1962).

The conclusion reached as the result of the study reported in Reference 5 is as follows:

"The Seader-Rocketdyne correlation equation (9) is believed to represent the best available relationship for calculations of rough-tube hydrogen flow. It is based upon the same set of hydrogen transport properties as those from which the well-established smooth-tube Wolf-McCarthy correlation was derived and uses the same correction for variation of boundary - layer fluid properties. It employs the Colebrook friction equation, and it fairs rather well into the Wolf-McCarthy equation at low values of Reynolds number or roughness."

"For temperatures between 50 and 150R, an empirical correction curve will be applied to the correlation, in order to compensate for supercritical and two-phase flow effects."

The Seader-Rocketdyne correlation is:

$$St_b = \frac{C_1 (f/2) (T_w/T_b)^{C_2} (0.7/P_{rb})^{0.6}}{0.92 + \sqrt{f/2} [\phi(\epsilon^* - 8.48)]} \quad (9.)$$

Where

$$\begin{aligned} \epsilon^* &= Re_b \quad f/2 \quad (\quad /D) \\ \phi(\epsilon^*) &= 4.50 + 0.57 (\epsilon^*)^{0.75} \quad * 7.0 \\ \phi(\epsilon^*) &= 4.70 (\epsilon^*)^{0.2} \quad (* 7.0 \\ T_w/T_b &= 2.5, C_1 = 1.00, C_2 = -0.55 \\ T_w/T_b &= 2.5, C_1 = 0.92, C_2 = -0.30 \end{aligned}$$

Since the bulk of the flow passages encountered in the NERVA system are of the smooth-tube variety, the advantages of used equation (9) in place of equation (1) are not apparent at this time.

C. CONCLUSIONS AND RECOMMENDATIONS

The new data reviewed in the preceding sections confirm the case of heat transfer equations recommended in the preceding report REON RN-S-0092 for use at Reynolds numbers up to 500,000. In the high Reynolds number range $Re_b > 500,000$, the effect of tube roughness should be considered as indicated by equations 1 and 5.

The equations giving the friction factor for adiabatic flow appear to be valid for flow with heat addition especially in the Reynolds number range above 20,000.

III. GASEOUS PHASE AT TEMPERATURES BELOW 150°R

No new information for this phase was found.

IV. NEAR CRITICAL FLUID

A. DISCUSSION

In Reference 1 it is recommended that the effect of variations in the physical properties of hydrogen in the critical region can be taken into account by employing the correction parameter ϕ_1 of equation 1 for pressures to at least 1000 psia. The recommended values of ϕ_1 (which for pressures less than 900 psia are independent of pressure) are presented in the following table taken from Reference 1.

T_b	ϕ_1	T_b	ϕ_1
°R		°R	
40	1.0	80	0.70
50	1.0	90	0.80
60	0.38	100	0.92
70	0.51	110	0.96
		120	1.0

In Reference 6, Miller, Seader and Trebes present the results of an extensive investigation of forced convection heat transfer to liquid hydrogen at super-critical pressures. In addition to presenting the results of their own experimental study, Miller, et al., reviewed the work of thirteen previous investigations. Their investigation covered hydrogen bulk temperatures from 50.9 R to 185 R for pressures from 381 to 2415 psia. Heat flux values varied from 1.37 to 24 Btu/in.² sec. Reynolds numbers varied from 1.93×10^6 to 13.4×10^6 . From the study, Miller et al. found that the high pressure (> 900 psia) data could be correlated satisfactorily by the equation:

$$Nu_{0.4} = 0.023 \left(\frac{\rho_{0.4} \dot{V}_b D}{\mu_{0.4}} \right)^{0.8} \left(P_{r0.4} \right)^{0.4} \quad (10.)$$

Where the subscript 0.4 indicates that the physical properties were evaluated at a temperature defined by the relationship:

$$T_{0.4} = T_b + 0.4 (T_w - T_b) \quad (11.)$$

The lower pressure limit of 900 psia was arbitrarily chosen.

For pressures below 900 psia Miller et al. found that their data could be correlated with an average absolute deviation of 17.4 percent by a modified Hess and Kunz (Reference 7) equation:

$$Nu_{0.4} = 0.0204 \left(\frac{\rho_{0.4} \dot{V}_b D}{\mu_{0.4}} \right)^{0.8} \left(P_{r0.4} \right)^{0.4} \quad (12.)$$

$$(1 + 0.00983 \mu_w / \mu_b)$$

Where all physical properties are evaluated at the temperature given by equation (11) the original equation of Hess and Kunz is:

$$Nu_{0.5} = 0.0208 \left(\frac{\rho_{0.5} \dot{V}_b D}{\mu_{0.5}} \right)^{0.8} \left(P_{r0.5} \right)^{0.4} (1 + 0.01457 \mu_w / \mu_b) \quad (13.)$$

Where all physical properties are evaluated at the temperature

$$T_{0.5} = T_b + 0.5 (T_w - T_b) \quad (14.)$$

Miller et al. show that the majority of the data of Thompson and Geery, McCarthy and Wolf, Hendricks et al. and Szetela can be correlated within ± 20 percent by equation (12).

Landrucks, Simoneau and Friedman present the results of an investigation of heat transfer to cryogenic hydrogen at pressures from 1000 to 2500 psia in Reference 8. Values of T_b at tube inlet ranged from 60 to 200R for maximum tube wall temperatures of 1200R. The Reynolds number range was from 10^5 to 4×10^6 . Local values of the heat transfer coefficient for values of L/D from 30 to 69 were correlated by the equation:

$$Nu_f = 0.021 (Re_f)^{0.8} (Pr_f)^{0.4} \quad (15.)$$

Where subscript "f" indicates that the fluid properties were evaluated at

$$T_f = \frac{T_w + T_b}{2} .$$

At certain combinations of heat flux and mass flow rate high frequency oscillations of the tube were encountered during which up to a four fold increase in heat transfer was observed.

B. CONCLUSIONS AND RECOMMENDATIONS

The flow of hydrogen at near critical temperature is restricted primarily to the nozzle, however such flow may exist for very short periods of time in the reflector during the chill-down and shut-down transients. Should it be deemed necessary to analyze the heat transfer in detail during those periods, it is recommended that equation (12) be used.

V. FORCED CONVECTIVE BOILING HEAT TRANSFER

A. DISCUSSION

The results of a critical review of the literature treating boiling heat transfer for cryogenics is presented by Seader et al. in Reference 9. For the heat transfer regime where a net change of phase takes place (termed forced convection saturated boiling) Seader et al. present the following quotation:

"In a very recent paper, Chen (Reference 10) made a major contribution to bulk boiling theory. He distinguished between the various flow regimes for convective flow of saturated fluids: (1) subcooled nuclear boiling, (2) slug flow, (3) annular or annular - mist flow, and (4) liquid deficient conditions. For vertical, axial, stable flow at heat fluxes below the critical, he developed the following additive relation for the (no slug) annular or annular - mist flow regime which extends from about 1- to 70- percent quality. The relation is based upon the McAdams forced convection relation corrected for the presence of vapor by the Martinelli two-phase parameter X_{tt} and the Foster-Zuber pool boiling expression corrected for suppression of bubble growth due to flow.

Thus:

$$q/A = \left[(h_{Fc}) F + (h_{F-Z}) S \right] \Delta T \quad (16.)$$

Where

$$h_{Fc} \text{ is given by } Nu_b = 0.023 (Re_b)^{0.8} (Pr_b)^{0.4}$$

$$h_{F-Z} = 0.00122 \frac{k_L^{0.79} C_L^{0.45} \rho_L^{0.49} g_c^{0.25} (\Delta T)^{0.24} (\Delta P)^{0.75}}{\sigma^{0.5} \mu_L^{0.29} \lambda^{0.24} \rho_v^{0.24}}$$

"F" is a two-phase correction as a function of X_{tt} given in Figure 24 (presented in Reference 9). It accounts for an increase in convective turbulence due to the presence of vapor.

$$X_{tt} = \text{Martinelli two-phase parameter}$$

$$= (Z/X)^{0.9} (\rho_v/\rho_l)^{0.5} (\mu_l/\mu_v)^{0.9}$$

"S" is a suppression factor as a function of $Re_L F^{1.25}$ given in Figure 25 (presented in Reference 9). It accounts for the suppression of bubble growth due to flow.

k_L = Thermal conductivity of liquid phase

C_L = Specific heat of liquid phase

ρ_L = Density of liquid phase

ρ_v = Density of vapor phase

σ = Surface tension

λ = Heat of vaporization

μ_L = Viscosity of liquid phase

g_c = Constant

ΔT = Wall superheat = $T_w - T_s$ where T_w = wall temperature,
 T_s = saturation temperature

ΔP = Pressure difference corresponding to ΔT

Z = Weight fraction liquid

X = Weight fraction vapor

More theoretical development is required to extend Chen's theory to other flow regimes and geometric configurations.

The following quotation, also taken from Reference 7, summarizes the current state of knowledge in the subject area.

"However, for saturated forced convective (bulk) boiling and the accompanying complex two-phase flow phenomena, only a start has been made and little known."

9. CONCLUSIONS AND RECOMMENDATIONS

No satisfactory method of treating forced convective boiling is available at this time. Investigation indicates that more experimental and theoretical work is needed in this area.

VI. REFERENCES

1. Investigation of Cooling Problems at High Chamber Pressures, Final Report, Rocketdyne, Report R-3999, May 1963.
2. Wolf H., and J. R. McCarthy, Heat Transfer to Hydrogen and Helium with Wall-to-Fluid Temperature Ratios to 11.09, Paper presented at AIChE Annual Meeting, 4-7 December 1960.
3. McEligot, D. M., P. M. Magee, and G. Leppert; "Effect of Large Temperature Gradients on Convective Heat Transfer: The Downstream Region", Journal of Heat Transfer, ASME Transactions, Series C, Vol. 87, No. 1, February 1965, pp 67-76.
4. Taylor, M. F., Experimental Local Heat-Transfer and Average Friction Data for Hydrogen and Helium Flowing in a Tube at Surface Temperatures up to 5600°R, NASA Technical Note TTN-S-2280, April 1964.
5. Argonne National Laboratory, Quarterly Progress Report, ANL 7036, pp 100-121.
6. Miller, W. S., J. D. Seader, and D. M. Trebes; Forced Convection Heat Transfer to Liquid Hydrogen at Supercritical Pressures, Rocketdyne Division of North American Aviation, June 1965.
7. Mess, H. L., and E. R. Kunz; "A Study of Forced Convection Heat Transfer to Supercritical Hydrogen," Trans. ASME, Journal of Heat Transfer, 87, Series C, 1965, 41-48.
8. Hendricks, R. C., R. J. Simoneau, and R. F. Friedman; Heat Transfer Characteristics of Cryogenic Hydrogen From 1000 to 2500 psia Flowing Upward in Uniformly Heated Straight Tubes, NASA, to be published.
9. Seader, J. D., W. S. Miller, and L. A. Kalvinskis; Boiling Heat Transfer for Cryogenics, NASA Report CR-243, June 1965.
10. Chen, J. C., A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow, ASME Paper No. 63-HT-34, August 1963.