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AN INTERIM STUDY OF SINGLE PHASE HEAT TRANSFER CORRELATIONS
USING HYDROGEN

MASTER

REACTOR ANALYSIS
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Astronuclear Laboratory
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USING HYDROGEN

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**REACTOR ANALYSIS
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G. R. Thomas
April, 1962

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ABSTRACT

A review is made of current information available on single phase heat transfer correlations resulting from recent heat transfer measurements with hydrogen. An analysis of the applicability of the various correlations to the regions of interest for NERVA is made and a tentative correlation is recommended.

1.0 SUMMARY

The work of several investigators is reviewed for the purpose of choosing a single phase heat transfer correlation to be used for Project NERVA. The following conclusions are reached:

1. The recommended form of the local heat transfer correlation is:

$$N_{u_b} = .025 \operatorname{Re}_b^{.8} \operatorname{Pr}_b^{.4} \left(\frac{T_w}{T_b} \right)^{-.55} \left[1 + .3 \left(\frac{X}{D} \right)^{-.7} \right]$$

2. The use of properties data which is not consistent between investigators, as well as the fact that applicable work is now in progress, suggests the need for correlation at a later date of all the applicable data as a unit using uniform properties.

2.0 INTRODUCTION

Experimentors have measured heat transfer coefficients for helium and hydrogen over a wide range of conditions and channel length-to-diameter ratios. The work thus far reported in the literature is generally characterized by a lack of data directly applicable to the NERVA Rocket Program. For example, measurements on helium⁽¹⁾⁽²⁾ are of interest but one would prefer direct measurements using hydrogen; especially at high temperatures (above 4000°R) where the effects of hydrogen dissociation and variation of fluid properties is more pronounced. Secondly, with few exceptions, investigators have correlated data on the basis of measurements averaged over the length of the test section. In a reactor which employs a variable heat flux in the direction of coolant flow, one must use relationships which will predict local values for the heat transfer coefficient. Consequently, the treatment of these correlations for use as local relationships is necessarily subject to some degree of error. Until better data in the range of conditions of direct interest and for local heat transfer coefficients are available, the following data must be used to guide the selection of an interim correlation.

It would be noted that there has not been general agreement in the past on the exact fluid properties to use when evaluating dimensionless parameters for data correlation. Consequently, it can be expected that an error or discrepancy between investigators beyond the usual experimental error has been introduced. An analysis of some of the more applicable data using uniform properties would, therefore, be informative.

3.0 SOURCES OF DATA

Papers studied to permit a tentative choice of a heat transfer correlation are listed in References 1 through 10 inclusive. A tabulation of the correlations recommended by each author (or authors) and some of the more pertinent information on the tests conducted is given at the back of this report. The following are some comments on these sources:

Durham, Neal and Newman⁽¹⁾ carried out work with helium in a graphite tube which was operated up to temperatures in excess of 5000°R but generally at low ratios of wall to bulk temperature. The use of helium as well as the correlating form correction for L/D (discussed later in this report) tends to place some doubt upon the applicability of the correlation to NERVA conditions. An effort was made, however, to measure local coefficients.

Taylor and Kirchgessner⁽²⁾ also carried out measurements with helium at high wall temperatures. The correlations are based upon average conditions over the length of the tube.

McCarthy and Wolf⁽³⁾⁽⁸⁾⁽⁹⁾ measured heat transfer coefficients for both helium and hydrogen over a wide range of T_w/T_b but maximum wall temperatures were in the vicinity of 2600°R. Their measurements were made at several locations along the tube and correlations are proposed for the average along the tube and for a short section farthest from the entrance which is taken to yield data useful for a local heat transfer relationship. Their work includes the ratio T_w/T_b in their correlations as suggested in theory by Deissler⁽¹¹⁾.

Fowler and Warner⁽⁴⁾ made measurements with hydrogen. They found that average heat transfer coefficients agreed reasonably well with the measurements of average coefficients made by Taylor and Kirchgessner although they suggest a slightly higher correlating coefficient, possibly part of the reason was because their test section had a smaller L/D.

Hendricks et.al.⁽⁵⁾⁽⁶⁾ use a form suggested by Taylor's single phase work to correlate two phase film boiling heat transfer coefficients but they correct their data using a correlated correction which is dependent upon the Martinelli parameter X_{tt} ⁽¹²⁾. This work is not, therefore, of any direct use in determining single phase coefficients.

Wright and Walton⁽⁷⁾ carried out experiments with hydrogen but at very low wall temperatures. Their correlation exhibits a T_w/T_b relationship similar to that of McCarthy and Wolf. Thompson and Geery⁽¹⁰⁾ made measurements with hydrogen. They correlate their data for local heat fluxes but found there was considerable variation in behavior of the data between two regimes they define as "A" and "B". The coefficients appear to be considerably improved in regime "A" and McCarthy and Wolf⁽³⁾ suggest the possibility that acoustic resonance may have taken place. The "B" regime data behaves in normal fashion and seems to agree generally with other investigators.

4.0 ENTRANCE EFFECTS

Several investigators⁽¹⁾⁽²⁾⁽³⁾⁽⁴⁾⁽⁷⁾ have attempted to account for the increase in heat transfer near the entrance region. Taylor and Kirchgessner have correlated their data in two forms. Since both equations are based on the data, there is some internal consistency which makes a comparison worthwhile. Both forms are reported for the coverage along the length of the tube;

$$(1) \overline{Nu} = .034 \overline{Re}_f^{.8} \overline{Pr}_f^{.4} \left(\frac{L}{D}\right)^{-.1}$$

$$(2) \overline{Nu} = .021 \overline{Re}_f^{.8} \overline{Pr}_f^{.4} \left[1 + \left(\frac{L}{D}\right)^{-.7} \right]$$

It can be seen that, in the first case, the Nusselt number continues to decrease as the length of the channel increases. The second relationship appears to have a form which is generally closer to the expected shape. That is, for very large L/D values, the correction approaches the limiting value of 1.0.

In order to determine the required local correction (remembering that the above correction terms are averages over the length of the channel), the following steps are taken:

Assume there is a function $f(x)$ which is independent of the fluid properties and is the function which corrects for entrance conditions, then:

$$\overline{Nu} = \frac{\int_0^L A f(x) dx}{L}$$

From the above, the following differential (local) forms of the above correlations result:

$$(1) \text{Nu}_x = .031 \text{Re}_f^{.8} \text{Pr}_f^{.4} \left(\frac{x}{D}\right)^{-.1}$$

$$(2) \text{Nu}_x = .021 \text{Re}_f^{.8} \text{Pr}_f^{.4} \left[1 + .3 \left(\frac{x}{D}\right)^{-.7}\right]$$

Note again that, in the second equation, the Nusselt number approaches some asymptotic value which we shall call Nu_∞ . Both local forms can then be compared with this limiting value:

$$(1) \frac{\text{Nu}_x}{\text{Nu}_\infty} = \frac{.031 \text{Re}_f^{.8} \text{Pr}_f^{.4} \left(\frac{x}{D}\right)^{-.1}}{.021 \text{Re}_f^{.8} \text{Pr}_f^{.4}} = 1.475 \left(\frac{x}{D}\right)^{-.1}$$

$$(2) \frac{\text{Nu}_x}{\text{Nu}_\infty} = 1 + .3 \left(\frac{x}{D}\right)^{-.7}$$

A plot of these two local forms are shown in Figure 1. Also shown for comparison are points taken from experimental curves given in Reference 13, normalized to 1.0 at their asymptotic values. It can be seen that agreement with data is much better with the second form of the equation than with the first. Consequently, this form of the entrance correction is recommended for use.

5.0 NUMERICAL COMPARISON

A comparison between the results to be expected from each correlation would be informative, especially since many differ in form in a way which makes a direct comparison difficult. Since the choice of a satisfactory correlation is most vital in the region of the hot spot, the correlations are best compared at a high temperature.

Consider the following conditions for comparison: $T_f = 4000^\circ\text{R}$ $\frac{T_w}{T_b} = 1.15$

$$L/D = 500$$

All correlations may be reduced to the form

$$\psi = \frac{Nu}{Re^{.8} Pr^{.4}} \quad (\text{evaluated at bulk properties})$$

For example:

Ref. 3, first equation (see table at back of report):

$$\psi = \frac{Nu_b}{Re_b^{.8} Pr_b^{.4}} = .023 \left(\frac{T_w}{T_b}\right)^{-.3}$$

In a case where the film properties are used in the correlation, as in

Reference 1:

$$\frac{Nu_b}{Re_b^{.8} Pr_b^{.4}} = .036 \left(\frac{X}{D}\right)^{-.1} \frac{K_f}{K_b} \left(\frac{\rho_f \mu_b^{.8}}{\rho_b \mu_f}\right) \left(\frac{Pr_f}{Pr_b}\right)^{.4}$$

The above relationship requires the use of properties data, which was taken from Reference 14.

Table 1 lists the values of ψ calculated at the above conditions and given in the order of the recommended correlations in the table at the end of the report. The table also compares the individual values of ψ with the average for the group (see "Normalized").

TABLE I

REFERENCE	EQUATION	Ψ	NORMALIZED
1	First	.0196	.88
2	First	.0212	.96
3	Phase I Bulk	.0220	.99
	Phase I Film	.0249	1.12
	Phase II Bulk	.0230	1.04
	Phase II Film	.0242	1.09
4	First	.0232	1.04
5 & 6		.0232	1.04
7		.0198	.89
8 & 9	Same as 3	-----	-----
10	Second	.0207	.93
Avg =		.0222	

Note that several equations from Reference 3 are compared. Phases I and II of this reference may be considered as separate programs so that the resulting correlations are somewhat independent. It is interesting to note that the correlations based on bulk and film properties for the same data do not yield the same results in the region of temperatures tested. They do, however, agree in the range of 2000°R where the tests were made. This emphasizes the need for better local heat transfer measurements in the high temperature range.

6.0 RECOMMENDED CORRELATION

The following form is recommended:

$$Nu = A Re^{.8} Pr^{.4} \left(\frac{T_w}{T_b} \right)^{-B} \left[1 + C \left(\frac{L}{D} \right)^{-E} \right]$$

The previous discussions in this report on entrance conditions have determined the values $C = .3$, $E = .7$.

Futhermore, it is noted that the use of a correlation of this type is considerably simplified if the fluid properties are evaluated at the bulk temperature thereby partially eliminating the need for iteration. Iteration is still required, however, to satisfy T_w/T_b .

McCarthy and Wolf⁽³⁾ recommend values for A and B depending upon the range of T_w/T_b . For T_w/T_b less than about 2.5 they recommend $A = .023$, $B = .3$ and for T_w/T_b greater than 3.5, $A = .025$, $B = .55$. However, it is entirely possible that reactor design problems will require evaluation of the film properties over a wide range of T_w/T_b . For this application, the second set of coefficients is more generally applicable. Figure 2 compares both forms of the equation against T_w/T_b for data taken from Reference 3 near the exit end of the test sections and for Reynold's numbers less than 100,000. Data values and correlating forms are both multiplied by 250 on the figure in order to bring all values within the same decade, 1 to 10. This does not effect the comparison. It appears that the second form is a better fit for use over a wide range of temperature ratios. The recommended local heat transfer correlation is, therefore:

$$Nu_b = .025 Re_b^{.8} Pr_b^{.4} \left(\frac{T_w}{T_b} \right)^{-.55} \left[1 + .3 \left(\frac{X}{D} \right)^{-.7} \right]$$

The entrance correction in the brackets should not be allowed to increase above a value of 1.5 if very small X values are used.

This recommendation should be regarded as tentative and useful until such time that the data from all applicable investigations can be examined using a uniform set of hydrogen properties. In addition, data presently being taken in laboratories may add to the range of interest.

7.0 RANGE OF APPLICATION

Most of the measurements made were carried out at temperatures above 100°R . Reference 6 reports measurements at lower temperatures in the range above and below the transposed critical temperature (where C_p reaches a maximum). Indications are that in the temperature range below 90°R the use of standard correlations such as the one recommended in this report could lead to a serious underestimate of the heat transfer coefficient, perhaps by a factor of 2 or 3. In certain cases where it is important to prevent flow choking due to excessive heat transfer, it is not conservative to underestimate the heat transfer coefficient. It is therefore recommended that the proposed correlation be used with caution below 90°R .

8.0 REFERENCES

1. F. P. Durham, R. C. Neal and H. J. Newman, "High Temperature Heat Transfer to a Gas in Heat Generating Tubes with High Heat Flux," (November, 1956) (Also, TID-7529 pt. 1 Bk. 2 p. 502).
2. M. F. Taylor and T. A. Kirchgessner, "Measurements of Heat Transfer and Friction Coefficients for Helium Flowing in a Tube at Surface Temperatures Up to 5900°R," NASA TND-133 (October, 1959).
3. J. R. McCarthy and H. Wolf, "The Heat Transfer Characteristics of Gaseous Hydrogen and Helium," RR-60-12 (December, 1960).
4. J. M. Fowler and C. F. Warner, "Measurements of the Heat Transfer Coefficients for Hydrogen Flowing in a Heated Tube," ARS Journal (March, 1960).
5. R. C. Hendricks, R. W. Graham, Y. Y. Hsu and R. Friedman, "Experimental Heat Transfer and Pressure Drop of Liquid Hydrogen Flowing Through a Heated Tube," NASA TND-765 (May, 1961).
6. R. C. Hendricks, R. W. Graham, Y. Y. Hsu and R. Friedman, "Correlation of Hydrogen Heat Transfer in Boiling and Supercritical Pressure States," ARS Journal (February, 1962).
7. C. C. Wright and H. H. Walton, "Single Tube Heat Transfer Tests - Gaseous and Liquid Hydrogen," WADC 59-423 (August, 1959).
8. J. R. McCarthy and H. Wolf, "Forced Convection Heat Transfer to Gaseous Hydrogen at High Heat Flux and High Pressure in a Smooth, Round, Electrically Heated Tank," ARS Journal p. 43 (April, 1960).
10. W. R. Thompson and E. L. Geery, "Heat Transfer to Cryogenic Hydrogen at Supercritical Pressures," Aerojet Rept. 1842 (July, 1960).
11. R. G. Deissler, "Analytical Investigation of Turbulent Flow in Smooth Tubes with Heat Transfer with Variable Properties for Prandtl Number of 1," NACA TN-2242 (December, 1950).
12. R. C. Martinelli, et. al., "Isothermal Pressure Drop for Two Phase, Two Component Flow in a Horizontal Pipe," Trans. ASME, Vol. 66 No. 2 pp. 139-151 (February, 1944).
13. Helmut Wolf, "Heating and Cooling Air and Carbon Dioxide in the Thermal Entrance Region of a Circular Duct with Large Gas to Wall Temperature Differences," ASME Paper 59-SA-15 - Semi-Annual Meeting ASME, St. Louis, Missouri (June, 1959).
14. M. D. Woods, B. L. Pierce and S. Cerni, "Hydrogen Properties for Project NERVA," WANL-TNR-043 (February, 1962).

9.0 NOMENCLATURE

A	- a constant
B	- a constant
C	- a constant
D	- diameter of channel
E	- a constant
k	- thermal conductivity
L	- total channel length
Nu	- Nusselt number
Pr	- Prandtl number
Re	- Reynolds number
T _b	- temperature of the gas (absolute)
T _w	- temperature of the wall (absolute)
x	- distance from heated entrance
ρ	- gas density
μ	- gas viscosity

SUBSCRIPTS

b	- bulk
f	- film
w	- wall
x	- local

LEGEND

- x air $Re \sim 50,000$
- + air $Re \sim 100,000$
- * air $Re \sim 150,000$
- Δ CO_2 $Re \sim 100,000$

FIGURE 1.

FIGURE 2.

SURVEY OF HEAT TRANSFER COEFFICIENTS MEASUREMENTS FOR LIGHT GASES - SINGLE PHASE

AUTHORS	REFERENCE	COOLANT	CORRELATIONS RECOMMENDED	RANGE OF CONDITIONS							Remarks
				L/D	T _w /T _b	T _b - °R	T _w - °R	Pressure-ps.	Reynolds Number	q"	
Durnam, F. P., Neal, R. C. and Newman, H. J. (1)	High Temp. Heat Transfer to a Gas in Heat Generating Tubes with High Heat Flux Nov. 1956) Iso, TID-7327 at. 1Bk 2 P. 302)	Helium	$\left(\frac{hD}{K_g}\right)_x = .036 \left(\frac{\rho_g D V}{\mu_g}\right)^{.8} \left(\frac{C_p \mu_g}{K_g}\right)^{.4} \left(\frac{x}{D}\right)^{-.1}$ $\left(\frac{hD}{K_g}\right)_{av} = .034 \left(\frac{\rho_g D V}{\mu_g}\right)^{.8} \left(\frac{C_p \mu_g}{K_g}\right)^{.4} \left(\frac{L}{D}\right)^{-.1}$	368 (16-368)		3675-4640	1800-504C	506-1511	1.0 x 10 ⁴ - 1.36 x 10 ⁵	7.0 x 10 ⁵ 3.9 x 10 ⁶	
Taylor, A. F. and Kirchengessner, T. A. (2)	NASA TND-133- Measurements of Heat Transfer and Friction Coefficients for Helium Flowing in a Tube at Surface Temperatures up to 5900°R (Oct. 1959)	Helium	$\left(\frac{hD}{K_g}\right)_x = .021 \left(\frac{\rho_g D V}{\mu_g}\right)^{.8} \left(\frac{C_p \mu_g}{K_g}\right)^{.4}$ $\left(\frac{hD}{K_g}\right)_{av} = .021 \left(\frac{\rho_g D V}{\mu_g}\right)^{.8} \left(\frac{C_p \mu_g}{K_g}\right)^{.4} \left[1 + \left(\frac{x}{D}\right)^{-.77}\right]$	60 9C	1.8 - 3.9		T _w : 1457 - 5433		3.2 x 10 ³ - 6 x 10 ⁴	71,000 - 345,000	for helium K values, at high temp. con- siderably lower than used in 1) and 3
McCarthy, J. R. and Wolf, H. (3)	RR-60-12 The Heat Transfer Characteristics of Gaseous Hydrogen and Helium (Dec. 196C)	Helium & Hydrogen	Phase I $\left(\frac{hD}{K_{b,av}}\right) = .023 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_p \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.5}$ $\left(\frac{hD}{K_{f,av}}\right) = .025 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_p \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.5}$ $\left(\frac{hD}{K_{w,av}}\right) = .028 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_p \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.76}$ Phase II $\left(\frac{hD}{K_{b,av}}\right) = .046 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_p \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.55} \left(\frac{L}{D}\right)^{-.15}$ $\left(\frac{hD}{K_{f,av}}\right) = .046 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_p \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.55} \left(\frac{L}{D}\right)^{-.15}$ $\left(\frac{hD}{K_{w,av}}\right) = .046 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_p \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.55} \left(\frac{L}{D}\right)^{-.15}$ (cont'd. next page)	32.8 - 51.6	2.3 - 11.1	135 (min) T: 559-729	T: 860-1640	64-1354	4000 - 1.5 x 10 ⁶	19,000 7.7 x 10 ⁶	

AUTHORS	REFERENCE	COOLANT	CORRELATIONS RECOMMENDED	RANGE OF CONDITIONS							Remarks
				L/D	T _w /T _b	T _b	T _w	Pressure-psi	Reynolds Number	q"	
Ref. 3, Con't			$\left(\frac{hD}{K_b}\right)_{\infty} = .025 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_{p,b} \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.55}$ $\left(\frac{hD}{K_w}\right)_{\infty} = .025 \left(\frac{\rho_w D V}{\mu_w}\right)^{.8} \left(\frac{C_{p,w} \mu_w}{K_w}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.80}$								
Fowler, J. M. and Warner, C. F. (4)	ARS Journal - Mar, 1960 "Measurements of the Heat Transfer Coefficients for Hydrogen Flowing in a Heated Tube"	Hydrogen	$\left(\frac{hD}{K_f}\right)_{av} = .023 \left(\frac{\rho_f D V}{\mu_f}\right)^{.8} \left(\frac{C_{p,f} \mu_f}{K_f}\right)^{.4}$ $\left(\frac{hD}{K_f}\right)_{av} = .021 \left(\frac{\rho_f D V}{\mu_f}\right)^{.8} \left(\frac{C_{p,f} \mu_f}{K_f}\right)^{.4} \left[1 + \left(\frac{L}{D}\right)^{-.77}\right]$	130	avg-1.17 - 2.47			40-100	3670- 62,200		
Hendricks, R. C.; Graham, R. W.; Hsu, Y. Y.; and Friedman, R. (5) and (6)	NASA TN D-765 Experimental Heat Transfer and Pressure Drop of Liquid Hydrogen Flowing Through a Heated Tube. May, 1961 ARS Journal - Correla- tion of Hydrogen Heat Transfer in Boiling and Supercritical Pressure States	Hydrogen Hydrogen	$\left(\frac{hD}{K_f}\right)_{\infty} = .023 \left(\frac{\rho_f D V}{\mu_f}\right)^{.8} \left(\frac{C_{p,f} \mu_f}{K_f}\right)^{.4}$								No actual single phase work indicated.
Wright, C. C. and Walters, H. H. (7)	WADC 59-423 Single Tube Heat Transfer Tests - Gaseous and Liquid Hydrogen Aug. 1959	Hydrogen	$\left(\frac{hD}{K_b}\right)_{av} = .021 \left(\frac{\rho_b D V}{\mu_b}\right)^{.8} \left(\frac{C_{p,b} \mu_b}{K_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.575} \left[1 + \left(\frac{L}{D}\right)^{-.77}\right]$	24	1.77 -2.95	95-134	229 - 309	690-700	85,000 - 2 x 10 ⁶	210,000 - 450,000	

AUTHOR	REFERENCE	COOLANT	CORRELATIONS RECOMMENDED	RANGE OF CONDITIONS							Remarks
				L/D	T _w /T _b	T _b	T _w	pressure-psi	Reynolds Number	q"	
Mc Carthy, J. R.; and Wolf, H. (8)	ARS Journal Apr-196C p.43 - Forced Convection Heat Transfer to Gaseous Hydrogen at High Heat Flux and High Pressure in a Smooth, Round, Electrically Heated Tank.	Hydrogen and Helium	$\left(\frac{hD}{k_b}\right) = .023 \left(\frac{\rho D V}{\mu_b}\right)^{.8} \left(\frac{c_p \mu_b}{k_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.3}$	67 42.6	Avg. 1.5 - 2.8	inlet 360-560 Avg. 559-729	avg. 860-1640	inlet 64 - 1354	7,800 - 1.5 x 10 ⁶		May be good for low T _w /T _b values
	(9) Heat Transfer to Hydrogen and Helium with Wall to Fluid Temp. Ratios to 11.09 AIChE Annual Meeting Dec., 1960	Hydrogen and Helium	See Ref. (3)								Essentially same as Ref (3)
Thompson, W. R. and Geery, E. L. (10)	Heat Transfer to Cryogenic Hydrogen at Supercritical Pressures Aerojet Rept. 1842 July, 1960	Hydrogen	"A" Regime: $\left(\frac{hD}{k_b}\right) = .000534 \left(\frac{\rho D V}{\mu_b}\right)^{.41} \left(\frac{c_p \mu_b}{k_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.64}$ "B" Regime: $\left(\frac{hD}{k_b}\right) = .0217 \left(\frac{\rho D V}{\mu_b}\right)^{.3} \left(\frac{c_p \mu_b}{k_b}\right)^{.4} \left(\frac{T_w}{T_b}\right)^{-.34}$	41	1.36-16.5	inlet 55-102 max 238	max 1594	inlet 1289-1392			