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SIMULATION OF THE HEAT TRANSFER CHARACTERISTICS OF LOX

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ABSTRACT

While the literature abounds with sources for either near critical or high pressure heat transfer data, aside from fluid hydrogen, a dearth of information exists on a unified experiment over a wide range of reduced temperature and reduced pressure. Forced convection heat transfer data for fluid nitrogen flowing through a vertical tube were acquired for $0.87 < T_r < 1.5$ and $1.2 < P_r < 5$, ($P_c = 3.42$ MPa, $T_c = 126.3$ K). For design purposes, these data were assumed to simulate the heat transfer characteristics of LOX ($P_c = 5.08$ MPa, $T_c = 154.8$ K). Comparisons between LN_2 and LOX data over the pressure range for $T_r < 1$ using a modified form of Petukhov's correlation factor was shown, qualitatively, to substantiate the simulation. Other parameters (buoyancy, Stanton number, and relative velocity), were found to group those data; assessment of these parametric interrelations must be made before the simulation can be termed quantitative.

NOMENCLATURE

C_p	specific heat, J/g-K
D	diameter, cm
F	thermophysical properties parameter, eq. (2)
Fr	Froude number
f_1-f_4	function forms - see text for definition
G	mass flux, g/cm^2-sec
g	body force, N
H	enthalpy, J/g
h	heat transfer coefficient, W/cm^2-K
k	thermal conductivity, W/cm-K
L	reference length, cm
Nu	Nusselt number
Nu_r	reduced Nusselt number, Nu_{exp}/Nu_{calc}
P	pressure
Pr	Prandtl number
q	heat flux, W/cm^2
R	gas constant, $(MPa)(cm^3)/(g)(K)$
Ra	Rayleigh number
Re	Reynolds number, Gd/μ
Sr	Stermann Parameter
T	temperature, K
T^*	transposed critical temperature, K
V	specific volume, cm^3/g
$\dot{W}$	mass flux, g/sec
X	axial position, cm
α	thermal diffusivity, cm^2/sec
β	volume expansivity, $(\partial \ln V/\partial T)_P$, K^{-1}
λ	latent heat of vaporization, J/g
ϕ	Dittus-Boelter properties parameter, $C_p^{0.4}k^{0.6}/\mu^{0.4}$
ρ	density, g/cm^3
μ	viscosity, g/cm-sec

Subscripts

B	bulk
c	critical
calc	calculated
exp	experimental
r	reduced parameter (eg. $T_r = T/T_c$)
w	wall
1	heavy component
2	light component

Superscript

*	wall to bulk property ratio

INTRODUCTION

One of the proposals for a second generation shuttle vehicle suggests that the engine regenerative coolant be the oxidizer rather than a fuel as is usually the case (1). The feasibility of such a proposal depends heavily on the ability of oxygen to function as a coolant. While there exists a wealth of heating and cooling data in the literature, there exists a dearth of information on the heat transfer characteristics of liquid oxygen (LOX) in the near critical region at elevated pressures (proposed engine operating pressures, 20 to 50 MPa). In this paper we propose to make use of data from similar fluids, thus tapping this source of information and obviating many of the safety problems associated with a heat transfer test of fluid oxygen at high pressure.

Recently, Hendricks and Simoneau (2) proposed and

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demonstrated that two phase choked flow of fluid oxygen could be accurately simulated using fluid nitrogen. The principle of corresponding states was successfully applied to two phase choked flows of simple fluids over a broad range in reduced temperature and pressure as well as for a variety of nozzles, orifices, and slits.

This same concept was assumed to apply to the heat transfer characteristics of liquid oxygen. As a result, two experimental heated tube programs were initiated, one at Lewis Research Center using fluid nitrogen to simulate LOX heat transfer and the other at Aerojet General using LOX to simulate actual engine operating conditions.

The initial phase of the latter study was reported in reference 3. Rousar and Miller (3) presented an equation for the cooling characteristics of fluid oxygen based on the modified property ratio parameters correlation of Petukhov (4) for pressures to 34.51 MPa over a range of experimental conditions simulating engine coolant requirements.

The purpose of this paper is to consider similarities and data to support the thesis that fluid nitrogen simulation of fluid oxygen heat transfer characteristics is proper and can be justified.

LIQUID NITROGEN APPARATUS AND INSTRUMENTATION

The experimental test facility and apparatus is essentially that reported in reference 7 except that the working fluid is nitrogen. The joule heated test section is a 0.635 cm o.d. by 0.050 cm wall Inconel tube 43 cm long (L/D = 81). The surface temperatures were measured and recorded at 19 stations along the tube. Three pressure taps in addition to the mixing chamber conditions provided for pressure measurements. The accuracy of the recording system and transducers is discussed in reference 7. The primary measurements are heat flux, mass flow rate, surface temperature, and (inlet/outlet) conditions (i.e., the standard $q-\dot{W}-\Delta T$ type experiment). For most of the data herein, the system heat balances are within ±5 percent and redundant flow measurements compare within ±2 percent.

EXPERIMENTAL TEST CONDITIONS

While the concept was to simulate fluid oxygen heat transfer at pressure levels characteristic of engine operating conditions, fluid nitrogen operations were limited by the facility to 17.25 MPa. At the same reduced pressure, this is equivalent to fluid oxygen operation at 26 MPa, or about half of the upper bound but well within the proposed operating pressures. Some thermodynamic critical parameters for fluid oxygen and nitrogen are given in table I.

The range of experimental parameters are

Heat flux to 750 W/cm^2
Pressure to 17 MPa ($1.2 < P_B/P_c < 5$)
Mass flow rate to 840 g/sec
Wall temperature to 650 K
Bulk temperature 110 to 200 K ($0.87 < T_B/T_c < 1.6$)

DISCUSSION AND RESULTS

In 1957, Powell (5) reported the results of a heated tube experiment with liquid oxygen in the near critical region. In 1961 Petukhov (4) presented a set of empirical property ratio parameters which appeared useful in correlating near critical heat transfer data. These and many other techniques both theoretical and empirical for evaluating the heat and momentum transfer characteristics of near critical fluids are presented in a survey article by Hendricks, Simoneau, and Smith (6).

From the literature survey (6) it is quite apparent that we neither understand the fundamentals of heat and mass transfer in the near critical region nor can we recommend a universally empirical correlation for existing forced convection data. However, we can readily summarize some of the qualitative concepts relating to the heat transfer in the near critical region (6). For example, the modified Petukhov parameter (4) and the Dittus-Boelter property parameter $\phi = C_p^{0.4}k^{0.6}/\mu^{0.4}$ evaluated at some reference temperature are useful in grouping near critical data. (Both will be used herein.)

We know there exist rather large (L/D) effects implying thermodynamic nonequilibrium and in some cases large volumetric expansion effects which imply local and/or global instabilities. We also know that near critical p-hydrogen data can be correlated by a modified Dittus-Boelter type equation over a narrow range of reduced temperatures (0.8 to 1.5) at reduced pressures of 10 to 13. Furthermore, the fluid behavior of liquid and gaslike flows on either side of the critical region can be correlated using a Dittus-Boelter equation modified by some form of a (T_w/T_B) correction (6).

With these concepts in mind, we elected to examine several correlating parameters which afforded some degree of success in grouping near critical heat transfer data. One of these parameters was of the modified Petukhov type (4,6), and quite similar to that presented by Rousar and Miller (3). With some adjustments of the exponents, this correlation group could serve as a common technique to examine the thesis that the heat transfer characteristics of fluid oxygen can be simulated using fluid nitrogen; this is more important than offering still another correlation technique, although some alternate parameters are discussed in appendix A.

Electing to leave the equation in a grouped format to illustrate the significance of each, the form chosen for comparison becomes

$$Y = \left(\frac{hd^{0.2}}{0.023\ G^{0.8}}\right)\left(\frac{1}{\phi F}\right) f_1\left(\frac{L}{D}\right) f_2\left(\frac{P_B}{P_c}\right) f_3\left(\frac{T_w}{T_B}\right) f_4(\mathrm{Re}) \tag{1}$$

or

$$Y = Nu_r f_1 f_2 f_3 f_4 F^{-1} \tag{1a}$$

where

$$\left.\begin{aligned} \phi &= \left(\frac{C_p^{0.4}k^{0.6}}{\mu^{0.4}}\right)_{bulk} \\ F &= \rho^{*3/5}k^{*3/4}\mu^{*-6/5}C_p^{*1/2} \\ Nu_r &= \frac{Nu_{exp}}{Nu_{calc}} \end{aligned}\right\} \tag{2}$$

and the * simply refers to the wall-to-bulk value, e.g.,

$$\rho^* = \frac{\rho_w}{\rho_B}$$

and

$$C_p^* = \left[\frac{H_w - H_B}{C_{p,B}(T_w - T_B)}\right]$$

The first parameter set of equation (1) essentially includes all of the variables in the heated tube experiment (experimental control group). The second parameter set represents thermophysical property variations in response to the system operating conditions. The thermophysical property data were calculated using Subroutine GASP (7).

While we have investigated to a limited extent, the influence of the functional forms f_1, f_2, f_3, and f_4, the most significant is the ϕF group.

In order to compare the fluid nitrogen data with the fluid oxygen data of Rousar and Miller (6) which covered a large range of heat transfer conditions as well as the data of Powell (5), the functional forms $f_1 - f_4$ have to be modified as follows:

$$\left.\begin{aligned} f_1 &= f_3 = 1 \\ f_2 &= \begin{cases} 1 & \text{for } \dfrac{P_B}{P_c} \leq \dfrac{13}{3} \\ \dfrac{\left(\dfrac{P_B}{P_c}\right)^{1.06}}{4.66} & \text{for } \left.\dfrac{P_B}{P_c}\right) > \dfrac{13}{3} \end{cases} \\ f_4 &= \frac{17}{4} Re^{-0.15} \end{aligned}\right\} \qquad (3)$$

Under these conditions, the fluid oxygen data of Powell (5) are presented in figure 1 as a function of reduced enthalpy. The value of Y for these data group between 0.8 and 1.3. An inspection of the data presented by Rousar and Miller (3) indicates that the value of Y for most of their data fall between 0.7 and 1.3. The ±30 percent scatter bands on these and subsequent figures aid in comparison of the nitrogen and oxygen data sets. Considering the large range of parameters covered by the experiment of reference 3, the agreement with the Powell data is quite good. Using these same parameters, the fluid nitrogen data are plotted in figure 2. The value of Y for these data is between 0.4 and 0.8, which is qualitatively quite similar to that of oxygen.

In order to determine if the increase in Reynolds number exponent from 0.8 to 0.95 (combining f_4 of equation (3) with equation (2)) suppresses other effects such as (L/D) we assigned the f_1 to f_4 functions as:

$$\left.\begin{aligned} f_1^{-1} &= 1 + 2\frac{D}{X} \\ f_2^{-1} &= 1 + \frac{2P_c}{3P_B} \\ f_3 &= 1 = f_4 \end{aligned}\right\} \qquad (4)$$

For the fluid nitrogen data the value of Y grouped primarily between 0.65 and 1.15 with a possible trend to lower values at low reduced enthalpy and higher at the higher reduced enthalpy. The fluid oxygen data of Powell (5) showed similar trends but group between 0.9 to 1.4 with a little more scatter. As the grouping of Y was similar to that of figures 1 and 2, one can deduce the data can be grouped in a similar way without altering the Reynolds number exponent.

From figures 1 and 2 and the above discussion, one may conclude that the modified Petukhov parameter (eq. (2)) is effective in qualitatively grouping the experimental heat transfer data for fluids oxygen and nitrogen in a similar manner as proposed; however, there is considerable scatter in these results.

Quantitatively, however, the oxygen and nitrogen Nusselt numbers are at different levels. The Nusselt number levels appear to be related through their T^* ratios

$$\frac{Nu_{oxygen}}{Nu_{nitrogen}} \sim \left(\frac{T^*_{oxygen}}{T^*_{nitrogen}}\right)^p \approx (1.22)^p$$

where T^* is given in appendix A, and $p \approx 2$ for equation (3) and $p \approx 1$ for equation (4).

OTHER PARAMETERS

Other parameters related to a rapid change in fluid properties that can influence heat transfer such as Grashof number, penetration length (Stanton number) and relative velocity effects were examined for similarities when applied to fluids oxygen and nitrogen. Discussion of these parameters is presented in appendix A. In presenting the figures of this section it is useful to use reduced Nusselt number, equations (1a) and (2).

To determine if the influence of body forces (volumetric expansion effects) is the same for fluids nitrogen and oxygen, the reduced Nusselt number was plotted as a function of the parameter $\beta\ \Delta T/\alpha^2$. Comparing figures 3(a) and (b) indicates a decrease in heat transfer as the parameter (Grashof effects) increases for both fluid oxygen and nitrogen. There also appears to be a threshold value below which the parameter has little effect on Nu_r or the liquid data simply group at large values of the parameter.

To determine if the Stanton number (penetration length) influences heat transfer to fluid oxygen and nitrogen in a similar manner, the reduced Nusselt number was plotted as a function of $(q/G(H_w - H_B))$. The resulting plot showed trends which were similar for fluids oxygen and nitrogen and, furthermore, similar to the hydrogen data of reference 8. These data were found to be nearly dependent on the square root of the reduced Nusselt number and to have a greater dependence on Prandtl number.

$$Nu_r = \frac{Nu_{exp}}{Nu_{calc}} \sim St^{3/2} \quad \text{or} \quad \frac{\sqrt{Nu_r}}{Pr^{0.7}} \qquad (5)$$

Using equation (5), the oxygen data of Powell and nitrogen data are plotted as figures 4(a) and (b), respectively. At low values of reduced enthalpy, the trends are similar, while at elevated values no comparison can be made although the oxygen data do appear to have a wavelike form.

The final parameter investigated $(1 + (\partial \ln V/\partial H)\Delta H)$ indicates that reduced Nusselt number decreases as the relative (slip) velocity increases, see figures 5(a) and (b) for fluids oxygen and nitrogen, respectively. Such behavior is indicative of an increased boundary layer thickness similar to that associated with film cooling.

For each of the above parameters tested, fluid nitrogen and fluid oxygen behave in a somewhat similar manner; however, there are several issues to be resolved before the heat transfer behavior can be predicted quantitatively.

CONCLUSIONS

Figures 1 and 2, and the agreement with the large data set of reference 3, demonstrate that experimental heat transfer results for fluid nitrogen can be used qualitatively to simulate heat transfer to liquid oxygen. Quantitative agreement appears satisfactory provided the proper level or adjusting constant can be determined. This constant may be related to the ratio of transposed critical temperatures.

Figures 3 to 5 further demonstrate the qualitative agreement in the heat transfer behavior of fluids oxygen and nitrogen; however, the parameters tested indicate dependence on terms such as buoyancy, Stanton number and relative velocity which are not part of the correlation used to produce figures 1 and 2. Answers to such interrelations must be determined before the simulation can be termed quantitative.

It is suggested that heat transfer tests be conducted on fluids nitrogen and oxygen in the same facility with the same test apparatus with test parameters spanning the same range of reduced conditions. Such a procedure which was so successful in the work of reference 2, should also prove productive here.

APPENDIX A

Near Critical Convection

Many authors have proposed and found that deterioration of heat transfer in the critical region is body force dependent. However, in the case of hydrogen, the temperature profiles remained unaltered for vertical up or down flow in a 0.851 cm (0.335 in.) diameter tube at Reynolds numbers ranging from 1 to 5 M. At these Reynolds numbers, the inertial forces are quite large and deterioration appeared to have an analogy to the transition from nucleate to film boiling. The nature of the axial temperature profile appears to be a significant factor, in determining whether or not body forces are important. In any case, the relative magnitude of the forces involved should be considered as the hydrogen data of reference 7 are clearly separated into two bands. In the first band, are data from two larger diameter tubes, 1.113 and 1.28 cm (0.438 and 0.507 in.) and in the second band are the data of three smaller tubes 0.478, 0.559, and 0.851 cm (0.188, 0.22, and 0.335 in.) diameter. A Froude number effect was used to combine these bands. Boussinesq (9) pointed out that for highly turbulent flows in natural convection, the Nusselt number should be related to the product Rayleigh x Prandtl:

$$Nu = RaPr = \frac{L^3 g}{\alpha^2} \beta \, \Delta T \qquad \text{(A1)}$$

Here, the significant parameter is $\beta \, \Delta T/\alpha^2$ as the test section of references 3, 5, and herein are nearly the same diameter with vertical upward flow.

$\beta \, \Delta T$ represents the body force (or volume expansion) potential and α is the molecular diffusivity which is related to the periodic behavior of energy transport in the vicinity of the wall. In the near critical region, β is large, α is small, and in our case ΔT is large; consequently the parameter can be quite large.

It should also be pointed out that the Froude number relates to the body force potential, relative or slip velocity and penetration length when using the Boussinesq formalation (eq. (A1)),

$$\frac{Fr}{Nu} = \left(\frac{\frac{U^2}{Lg}}{Nu}\right) = \frac{St^{-2}Nu}{RaPr} \beta \, \Delta T = \left(\frac{U_2}{U_1}\right)^{-2} \beta \, \Delta T \qquad \text{(A2)}$$

Stanton Number or Dimensionless Penetration Length

The interchange of light and heavy components in the vicinity of the wall is analogous to a jet of fluid moving toward and away from the wall (8). A ratio of the normal velocity to the free stream velocity can be considered to be a dimensionless penetration distance. The Stanton number can be interpreted to be a dimensionless penetration parameter. Stermann (10) defined a pseudo-Stanton number for two-phase flow as

$$S_r = \frac{q}{\lambda \rho U} \sim \frac{q}{G \, \Delta H} \approx St = \frac{Nu}{RePr} \sim \frac{U_2}{U_1} \qquad \text{(A3)}$$

Relative Velocity

A form for the relative velocity, which may be viewed as a slip condition, can be postulated using the concept that the mass influx equals mass outflux of a control volume in the boundary layer or

$$1 = \frac{(\rho UA)_{influx}}{(\rho UA)_{outflux}} = \frac{V_2 U_1 A_1}{V_1 U_2 A_2} \qquad \text{(A4)}$$

$A_1/A_2 = (V_1/V_2)^{2/3}$ is given in reference 8, and V_2/V_1 may be determined from a truncated series relating volume and energy across the boundary layer as

$$\frac{V_2}{V_1} = 1 + \frac{1}{V_1} \left.\frac{\partial V}{\partial H}\right)_p \Delta H \qquad \text{(A5)}$$

and the relative velocity becomes

$$\frac{U_2}{U_1} = \left(\frac{V_2}{V_1}\right)^{1/3} \qquad \text{(A6)}$$

A large value of this ratio would imply small volume toward the wall and large volume away from the wall.

Transposed Critical Temperature

While not precisely correct, the transposed critical temperature for fluids nitrogen and oxygen may be represented by

$$T^{*} \approx -3.5\left(\frac{P_B}{P_c}\right)^{2} + 28\left(\frac{P_B}{P_c}\right) + (T - 23.5) \qquad \text{(A7)}$$

for $1 < (P_B/P_c) < 4$ and constant at $(P_B/P_c) = 4$ for higher pressures to perhaps 6Pc (6).

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TABLE I. - CRITICAL CONSTANTS FOR FLUID OXYGEN AND NITROGEN

Fluid	Pressure, MPa	Temperature, K	Density, g/cm^3	Compressibility
Nitrogen	3.417	126.3	0.3105	0.294
Oxygen	5.082	154.8	.4325	.292

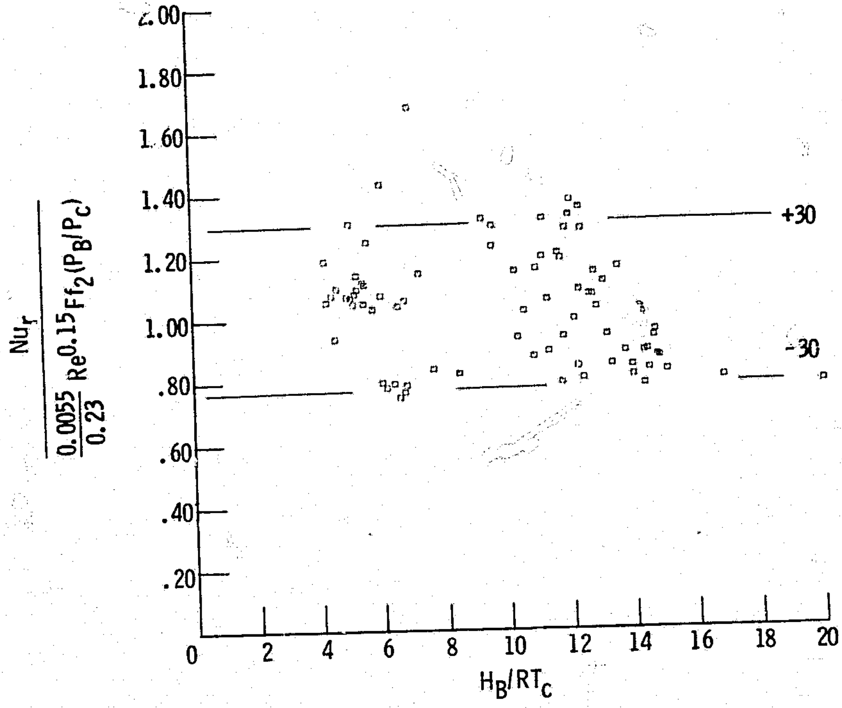

Fig. 1 Influence of the functional group of equation (3) on the fluid oxygen heat transfer data of Powell (ref. 5) as a function of reduced enthalpy.

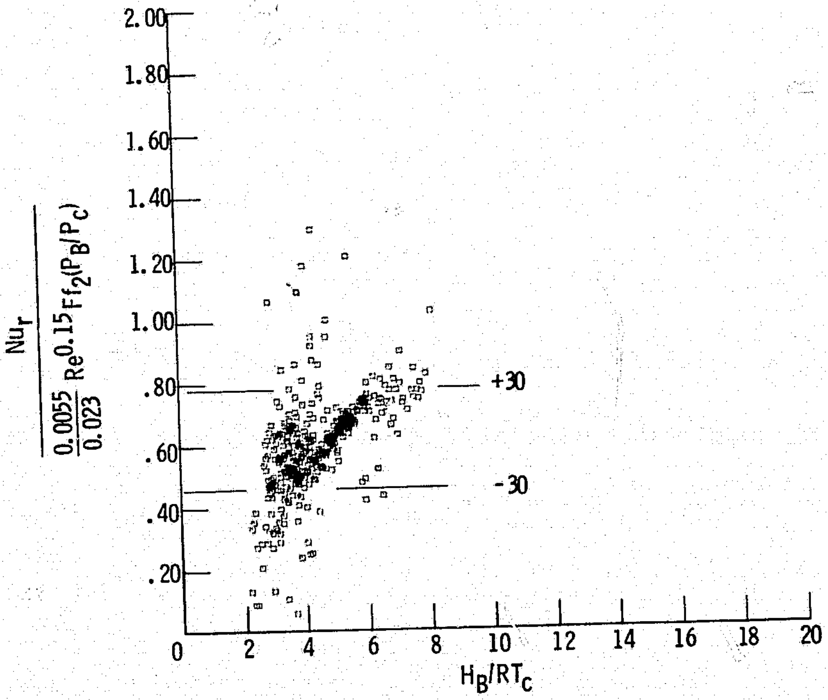

Fig. 2 Influence of the functional group of equation (3) on the fluid nitrogen data as a function of reduced enthalpy.

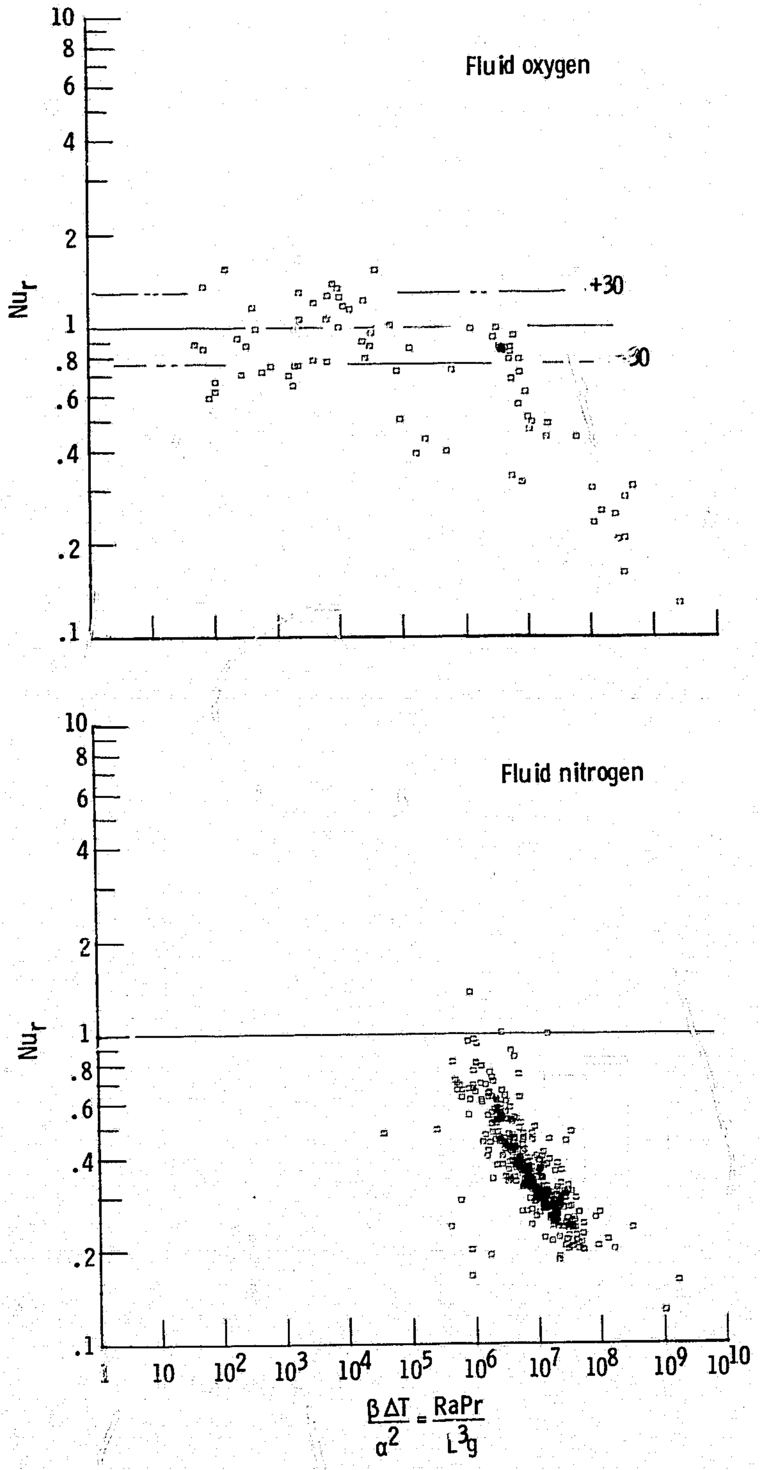

Fig. 3 Influence of buoyancy to thermal diffusivity ratio
(a) Fluid oxygen
(b) Fluid nitrogen

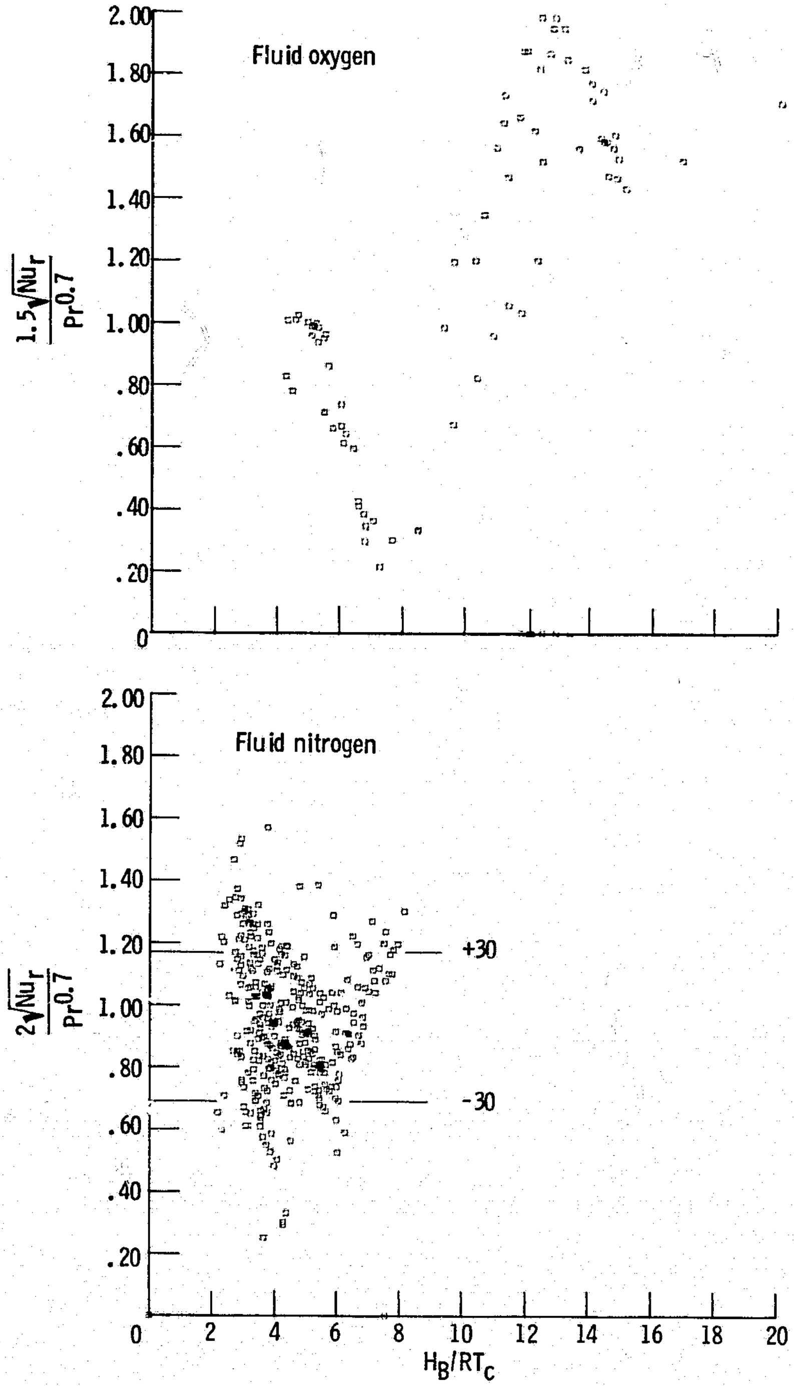

Fig. 4 Influence of Stanton number (dimensionless penetration length)
(a) Fluid oxygen
(b) Fluid nitrogen

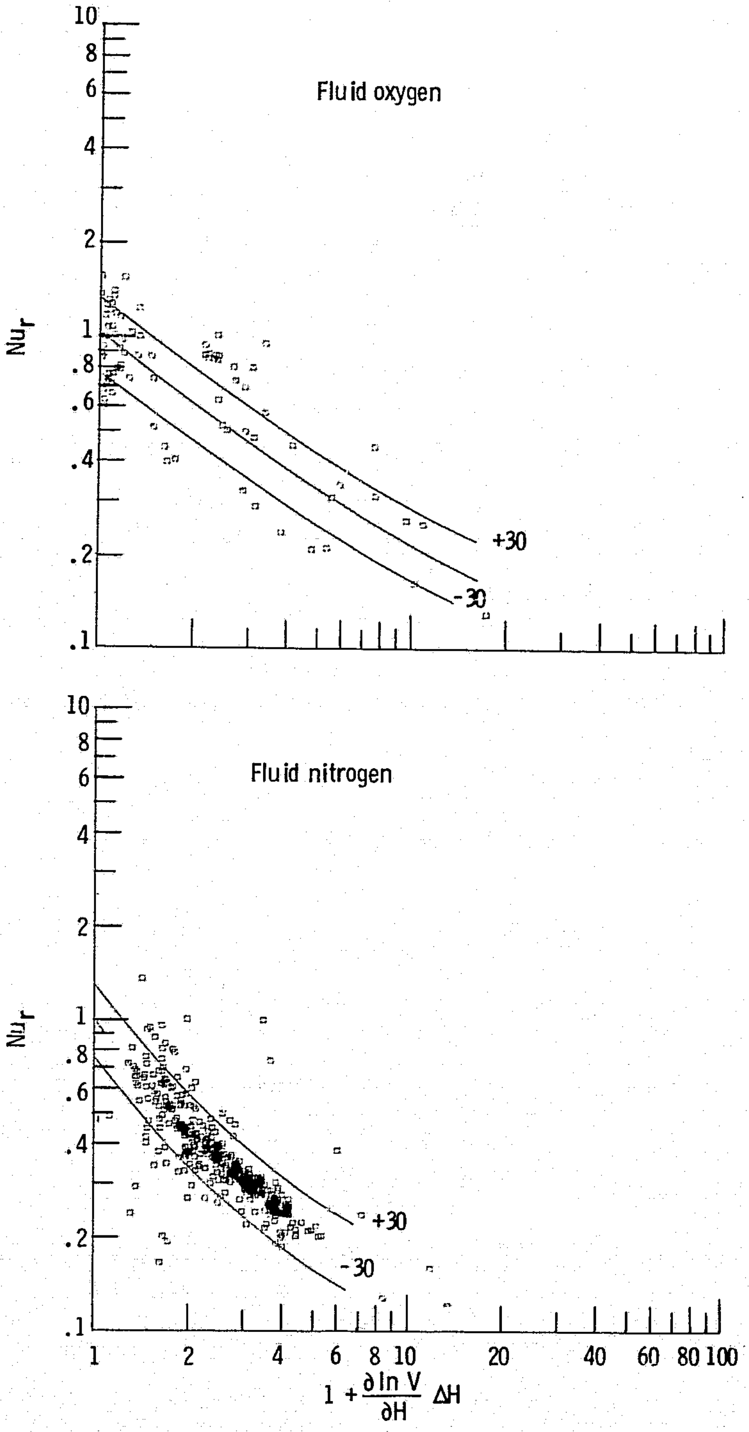

Fig. 5 Influence of relative velocity (slip)
(a) Fluid oxygen
(b) Fluid nitrogen

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