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MIXED CONVECTION AND HIGH-PRESSURE LOW-FLOW STEAM COOLING DATA FROM A 64-ROD BUNDLE*

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ABSTRACT

Heat transfer data were obtained from low flow steam cooling experiments in a partially uncovered 64-rod bundle. These tests indicated that free convection effects were superimposed on the laminar and turbulent forced convection heat transfer. This paper describes the influence of buoyancy on laminar and turbulent forced convection heat transfer coefficients. Mechanisms due to buoyancy which alter the local heat transfer are summarized. Criteria indicating the importance of buoyancy on laminar and turbulent upflow in a vertical pipe were developed and compared to other criteria found in the literature. These criteria were used to determine the steam cooling data with significant buoyancy influence. Data with buoyancy influence were compared to mixed convection correlations and to a numerical study for rod bundles.

1. INTRODUCTION

During a small-break loss-of-coolant accident (LOCA) in a pressurized water reactor, partial core uncovering may occur, exposing fuel rods to steam. Under high pressure low-power core uncovering conditions of such an accident, steam flow rates may decrease to such a degree that large wall-to-bulk temperature ratios exist, blanketing fuel rod surfaces with steam of lighter density than that in the fluid core. Under these conditions, density variations across the flow cross sectional area may reach such levels that buoyancy forces become comparable to inertial and viscous forces.

Buoyancy forces resulting from the density difference between a heated wall and bulk fluid cause the relatively light fluid layer near the heated wall to speed up and increase heat transfer coefficients in upward heated laminar flow (1-7). Conversely, in upward heated turbulent flow, a deterioration of heat transfer coefficients occurs because of the reduction in turbulence production (8). The combination of forced and free convection regimes are normally called mixed or combined convection.

Oak Ridge National Laboratory experimentally investigated uncovered core heat transfer performance (9). Heat transfer data obtained from these experiments indicated that free convection effects were superimposed on forced convection heat transfer coefficients. Criteria indicating the importance of buoyancy on laminar and turbulent upflow in a heated vertical pipe were derived from the momentum equation. These criteria and the others found in the open literature are used to determine the steam cooling data with significant buoyancy influence. The data with buoyancy influence are compared to mixed convection correlations and a numerical study for rod bundles.

II. THEORETICAL BACKGROUND

In laminar flow, when buoyancy is not negligible, higher heat transfer coefficients than those for pure laminar flow values are obtained mainly due to an increase in velocity near the heated wall. Mass conservation requires that center-line velocities therefore decrease. As buoyancy becomes more dominant, this can lead to an unstable (turbulent) flow regime (2,10-12). Unstable flow conditions also increase heat transfer coefficients over pure laminar flow values (3).

When buoyancy forces are significant, heat transfer coefficients deteriorate in turbulent flow due to a change in the total shear stress distribution over the flow cross sectional area (Hall's hypothesis) (8,13).

For an isothermal turbulent flow in a pipe, the shear stress is given by (21):

$$\tau = \tau_w (1 - y/R) ,$$

and for a very short distance from the wall (y), the shear stress may be approximated by:

$$\tau = \tau_w .$$

When the buoyancy force acts in the opposite direction of shear stress (as in heated upflow), it will decrease the magnitude of shear stress in the wall layer ($y^+ \leqslant 30$). In this case, τ may be approximated by:

$$\tau \approx \tau_w - gy (\rho_b - \rho_w) ,$$

where $gy (\rho_b - \rho_w)$ is the buoyancy term. Following the assumption that turbulence production depends on the magnitude of shear stress in the wall layer, Hall predicts considerable reductions in heat transfer as τ approaches zero (8).

Experimentally measured velocity and total shear stress profiles for air flow in a heated vertical pipe support this conclusion (14). Hall's analysis is also in good agreement with buoyancy influenced turbulent upflow experiments (13).

II.1 Criteria for the Importance of Buoyancy

Estimates of the approapriate values for the importance of buoyancy may be obtained from the momentum equation in the flow direction for flow in a vertical pipe:

$$\rho \left(v\frac{\partial u}{\partial r} + u\frac{\partial u}{\partial z} \right) = - \frac{\partial p}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}\left(\mu r \frac{\partial u}{\partial r} \right) - \rho g \ ,$$

with the assumptions that the angular velocity is zero and that properties are constant. (Density is assumed variable only in the buoyancy term.) For approximately fully developed conditions, the pressure gradient can be substituted into the equation in terms of wall shear and gravitational force. (Bulk fluid acceleration forces are negligible compared to buoyancy forces in the ORNL tests.) Then in dimensionless form, the equation becomes:

$$\frac{Gr}{Re^2} \frac{T - T_b}{T_w - T_b} + 4\bar{\tau}_w - \frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}(\overline{r\tau}) = 0 \ .$$

The dimensionless forms are $\bar{v} = v/u_r$, $\bar{u} = u/u_r$, $\bar{r} = r/D$, $\bar{\tau} = \tau/\rho_r u_r^2$, and $\bar{\tau}_w = \tau_w/\rho_r u_r^2$.

The significance of the ouoyancy term may be obtained by comparing it with $4\overline{\tau}_w$:

$$\frac{Gr}{Re^2} \frac{T - T_b}{T_w - T_b} \sim 4\overline{\tau}_w .$$

The local friction factor is defined as $f = 2\tau_w/\rho_r u_r^2$ and, in terms of dimensionless wall shear stress, as $f = 2\overline{\tau}_w$. For laminar and turbulent flows in smooth pipes, the local friction factor is given, respectively, by:

$$f = \frac{16}{Re}$$

and

$$f = 0.046 \, Re^{-0.2} .$$

Then, if a maximum of $(T - T_b)/(T_w - T_b) = 1$ near the heated wall is used:

$$\frac{Gr}{Re^2} \sim 2f .$$

Therefore, buoyancy will affect laminar and turbulent flow, respectively, when:

$$\frac{Gr}{Re} \approx 32 . \qquad (1)$$

and

$$\frac{Gr}{Re^{1.8}} \approx 0.092 . \qquad (2)$$

Jackson and Hall (13) developed a cheoretical criteria for the importance of buoyancy in turbulent flow:

$$\overline{Gr}_b/Re_b^{2.7} > 10^{-5} \qquad (3)$$

This criteria was developed from turbulent flow shear stress redistribution considerations. Equation (2) yields similiar Gr numbers to those calculated from inequality (3) in the Re number range $10^4<Re<10^5$.

III. FACILITY DESCRIPTION AND EXPERIMENTS

Uncovered bundle steam cooling experiments were performed in the Thermal Hydraulic Test Facility at Oak Ridge National Laboratory. The test facility has an electrically heated 64-rod bundle and is configured to provide conditions similiar to those which would occur during a small break loss of coolant accident. The system configuration is shown in Fig. 1.

Figure 2 is a cross section of the rod bundle. The bundle has rod diameter and pitch typical of a 17 x 17 PWR fuel assembly (P/D = 1.33, D = 9.5 mm). The bundle is heavily instrumented to provide accurate fuel rod simulator, fluid and bundle shroud temperature measurements. Axial and radial power profiles are uniform. A detailed description of the test facility is presented in Ref. 9.

In this facility, a series of high pressure (600-1050 psia) and low flow ($0.23\ 10^4$ - $2.19 \cdot 10^4$ lb_m/ft^2h) steam cooling experiments were performed (9). The purpose of the experiments were to acquire heat transfer coefficients and fluid flow conditions in a partially uncovered bundle under steady state conditions. During the experiments 30 to 40% of the heated core was uncovered. A summary of uncovered bundle heat transfer test conditions are depicted in Table 1.

In the uncovered portion where rod surfaces are covered with steam, a range of wall-to-bulk temperature ratios up to 1.58, Grashof numbers up to 7.6×10^6, and bulk Reynolds numbers between 1500 and 17,700 are covered. More detailed information about the test procedures, the calculation of heat transfer parameters and related uncertainties can be found in Ref. 9.

IV. ANALYSIS OF STEAM COOLING DATA

A summary of the significant heat transfer parameters for five tests are presented in Table 2, where maximum and minimum values of each parameter for each test are depicted.

The convective heat transfer data obtained from these experiments were compared to pure forced convection values. Nearly 100% of the convective heat transfer data with $Re_b > 2700$ were overpredicted by the Dittus-Boelter correlation ($Nu_b = 0.023\ Re_b^{0.8}\ Pr_b^{0.4}$). Below $Re_b = 2700$, considerable enhancement of the experimental heat transfer over pure forced convection values were obtained.

Comparisons to Eqs. (1) and (2) indicate a possible transition to mixed or free convection dominated flow regime. Comparison to the flow regime map of Metais and Eckert (15) indicated that tests J, M and N are in mixed convection regimes (9). (The flow regime map was developed from the single tube flow experiments.)

IV.1 Turbulent and Transitional Flow Data

The ratio of experimentally measured Nusselt numbers to those predicted by the Dittus-Boelter correlation is plotted against $\overline{Gr}_h/Re_b^{2.7}$ in Fig 3. This ratio was used by Hall and Jackson (13) and a modified version including the Prandtl number was used by Watson and Chou (16). As mentioned earlier, Hall and Jackson indicate the buoyancy importance in turbulent flow with inequality (3) and present a correlation for the minimum heat transfer coefficients,

$$Nu/Nu_T = 15\ (\bar{Gr}_b/Re_b^{2.7})^{0.4}\ . \qquad (4)$$

This correlation along with data reported in Ref. (13) (shaded area) is presented in the figure. The data were for water and carbon dioxide. The data of tests J, L, M and N appear in the mixed convection regime and follow the general trend of the data distribution. The two data points shown for test N are in the forced convection transition region while all other data shown in Fig. 3 are within the turbulent flow regime. The data were also compared to Eq. (2). All tests except test I have ratios above 0.092 indicating considerable buoyancy influence.

Alferov (16) and Petukhov (17) reported a similiar variation of Nu/Nu_T with a Ra_A/Re^2 ratio. Alferov indicated the mixed convection regime if

$$1 > Ra_A/Re^2 > 3 \times 10^{-6}\ .$$

According to this criteria, all experimental data reported here appear in the mixed convection regime. Petukhov correlated his mixed convection data for water with the following equations,

$$\frac{Nu}{Nu_T} = \frac{1}{1 + B\,\dfrac{Ra_A}{Re^2}} \qquad (5)$$

$B = 1.15 \times 10^4$ for $Ra_A/Re^2 < 10^{-4}$ with calming section.

$B = 1.5 \times 10^3$ for $Ra_A/Re^2 < 3 \times 10^{-4}$ without a calming section.

$$\frac{Nu}{Nu_T} = 10 \left(\frac{Ra_A}{Re^2}\right)^{0.33} \quad (6)$$

$10^{-4} < Ra_A/Re^2 < 1$ with calming section,

$3 \times 10^{-4} < Ra_A/Re^2 < 1$ without calming section.

Connor and Carr (14) reported a slightly different form of Eq. (6). Their equation was developed using fluids of various Pr numbers for $Gr_A/Re^2 > 1.2 \times 10^{-5}$,

$$\frac{Nu}{Nu_T} = 8.84 \left(\frac{Gr_A}{Re^2}\right)^{0.263} \quad Gr_A = \frac{Gr\ Nu}{4\ Pr\ Re} \quad (7)$$

When Nu_T is calculated from the Dittus-Boelter correlation, the ORNL data follow the trends of these correlations; however, the maximum deviation for the Petukhov's equations is about 40% and for Eq. (7) is about 20%.

IV.2 Laminar Flow Data

Test N has data in laminar and transition flow regimes ($1500<Re_b<2700$). The transition data was included in the previous section. In Fig. 4, test N data are compared to the numerical results of Yang (18) for buoyancy influenced laminar flow in infinite rod arrays, the correlations of Gruszczynski and Viskanta (19), and to Nu ≈ 7.5. (Nu ≈ 7.5 is generally expected to be the lowest Nu number for standard rod bundles.) The correlations of Gruszczynski were developed from buoyancy induced water flow experiments in a rod bundle with P/D = 1.25. Within the recommended limits of the correlations, the data are reasonably predicted by one of these correlations. The trends of the data and numerical results appear to coincide. Minimum Gr_f/Re_f ratios of test N are about 190 which is far above the value indicated by Eq. (1). This implied significant buoyancy influence on test N data.

A note of caution is needed when interpreting the laminar flow data. Portions of this data were obtained from measurement sites downstream of grid spacers. The axial profile of the Nu number along the bundle shows little variation around the spacer grids; however, high Nu numbers could be due to a combination of free convection and spacer grid effects.

V. CONCLUSIONS

Heat transfer data obtained from low flow steam cooling experiments in a partially uncovered 64-rod bundle are analyzed. Buoyancy criteria found in the literature and developed in this paper indicate that most of the laminar and turbulent flow data are influenced by free convection forces. There is a scarcity of rod bundle mixed convection data; therefore, the laminar and turbulent data should be of value in development of transition criteria between forced, mixed and free convection regimes and in development of heat transfer correlations for rod bundles.

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NOTATION

D, D_h = diameter and hydraulic equivalent diameter

f = friction factor

g = gravitational acceleration

$\bar{G}r_b$ = Grashof number = $\rho_b \ (\rho_w - \bar{\rho}) g D_h^3 / \mu^2$

Gr_f = Grashof number = $\rho_f^2 \ B_f g \ D_h^3 \ (T_w - T_b) / \mu_f^2$

h = heat transfer coefficient

k = thermal conductivity

Nu = Nusselt number = $h \ D_h / k$

P = distance between the centers of two neighboring rods

P/D = pitch to diameter ratio

Pr = Prandtl number = $C_p \ \mu / k$

r = radial distance

R = radius of flow channel

Ra_A = Rayleigh number = Gr Nu/4Re

Re = Reynolds number = $\rho u \ D_h / \mu$

T = temperature

u,v = velocities in axial and radial directions, respectively

y^+ = nondimensional distance = $\frac{y}{\nu} (g_c \tau / \rho)^{0.5}$

Z = axial distance

β = temperature coefficient of volume expansion

μ = viscosity

ν = kinematic viscosity = μ / ρ

ρ = density

τ = shear stress

SUBSCRIPTS

b = evaluated at bulk fluid temperature

f = evaluated at film temperature = $(T_w + T_b)/2$

r = reference value

T = turbulent

w = evaluated at wall temperature or at the wall

Table 1. Summary of uncovered-bundle heat transfer test conditions

Test	System pressure [MPa (psia)]	Linear power/rod [kw/m (kw/ft)]	Mass flux [$kg/m^2 \cdot s$ ($lb_m/h \cdot ft^2$) x 10^{-4}]	Mixture level [m (ft)]	Steam cooling region [m (ft)]	Fractional heat loss
3.09.10I	4.5 (650)	2.2 (0.68)	29.7 (2.19)	2.62 (8.6)	3.02-3.62 (9.91-11.88)	0.018
3.09.10J	4.2 (610)	1.07 (0.33)	12.7 (0.94)	2.47 (8.1)	3.02-3.62 (9.91-11.88)	0.052
3.09.10L	7.5 (1090)	2.17 (0.66)	29.1 (2.15)	2.75 (9.0)	3.02-3.62 (9.91-11.88)	0.017
3.09.10M	7.0 (1010)	1.02 (0.31)	12.6 (0.93)	2.62 (8.6)	3.02-3.62 (9.91-11.88)	0.042
3.09.10N	7.1 (1030)	0.47 (0.14)	4.6 (0.34)	2.13 (7.0)	2.42-3.62 (7.94-11.88)	0.162

Table 2. Summary of heat transfer parameters[a]

Test	T_b [K (°F)]	T_w [K (°F)]	$Re_b \times 10^{-3}$	$Gr_f \times 10^{-6}$	h [W/m^2K (Btu/ft^2°F)]
I	606 (630) 790 (970)	930 (1220) 1060 (1450)	12.2-16.6	1.8-0.5	200 (36) 230 (40)
J	630 (670) 830 (1030)	930 (1220) 1030 91390)	5.0-6.7	1.3-0.3	81 (14) 120 (21)
L	570 (580) 720 9840)	910 (1180) 1000 (1340)	13.0-17.7	7.6-2.5	150 (27) 210 (37)
M	630 (670) 790 (970)	850 (1070) 1020 (1370)	5.1-6.5	4.2-1.2	90 (16) 126 (22)
N	590 (600) 950 (1250)	770 (840) 1030 (1400)	1.6-3.0	6.7-0.3	90 (16) 110 (20)

[a] Pr_f values mainly varied between 0.9 and 1.0.

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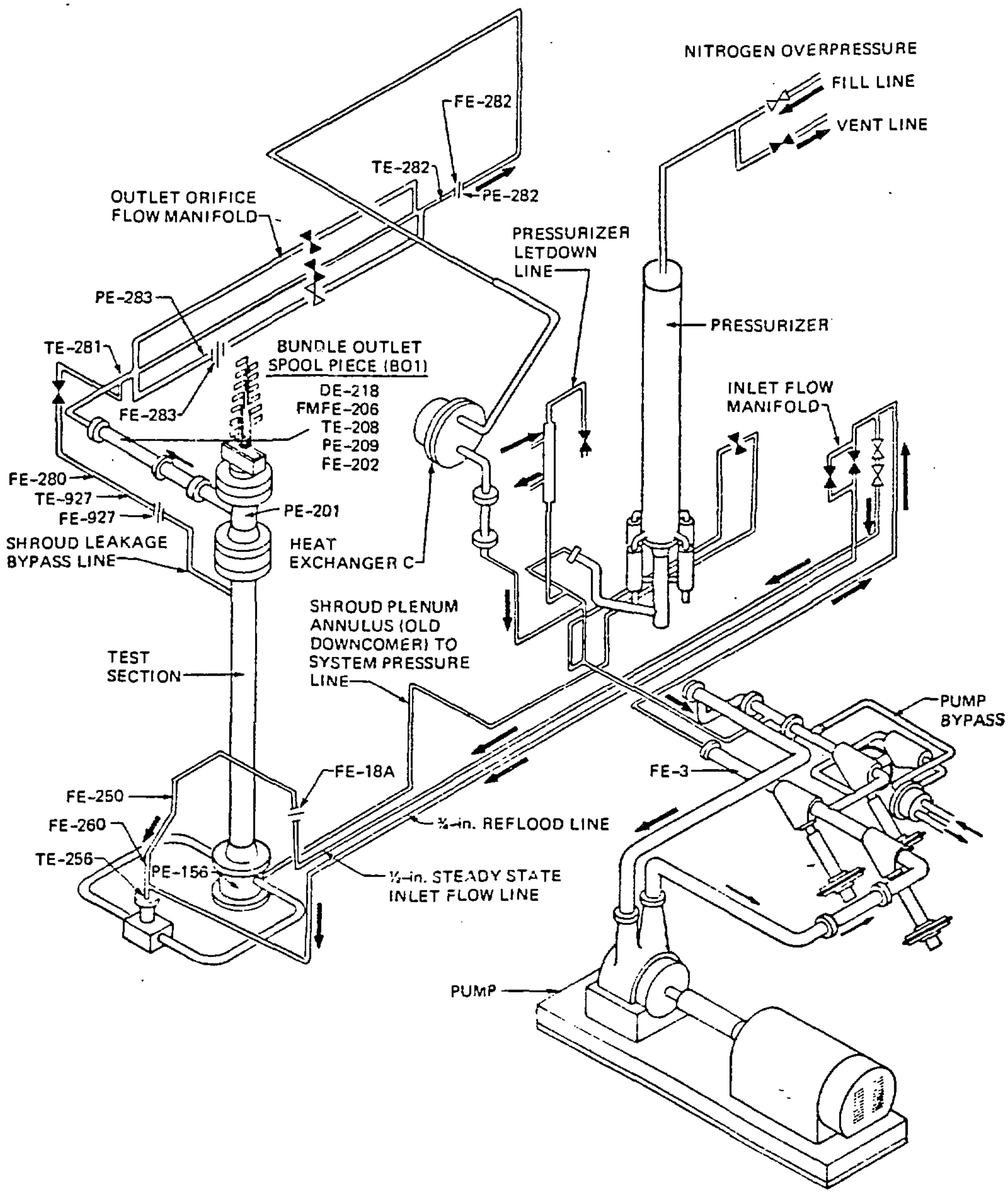

Fig. 1. Thermal Hydraulic Test Facility

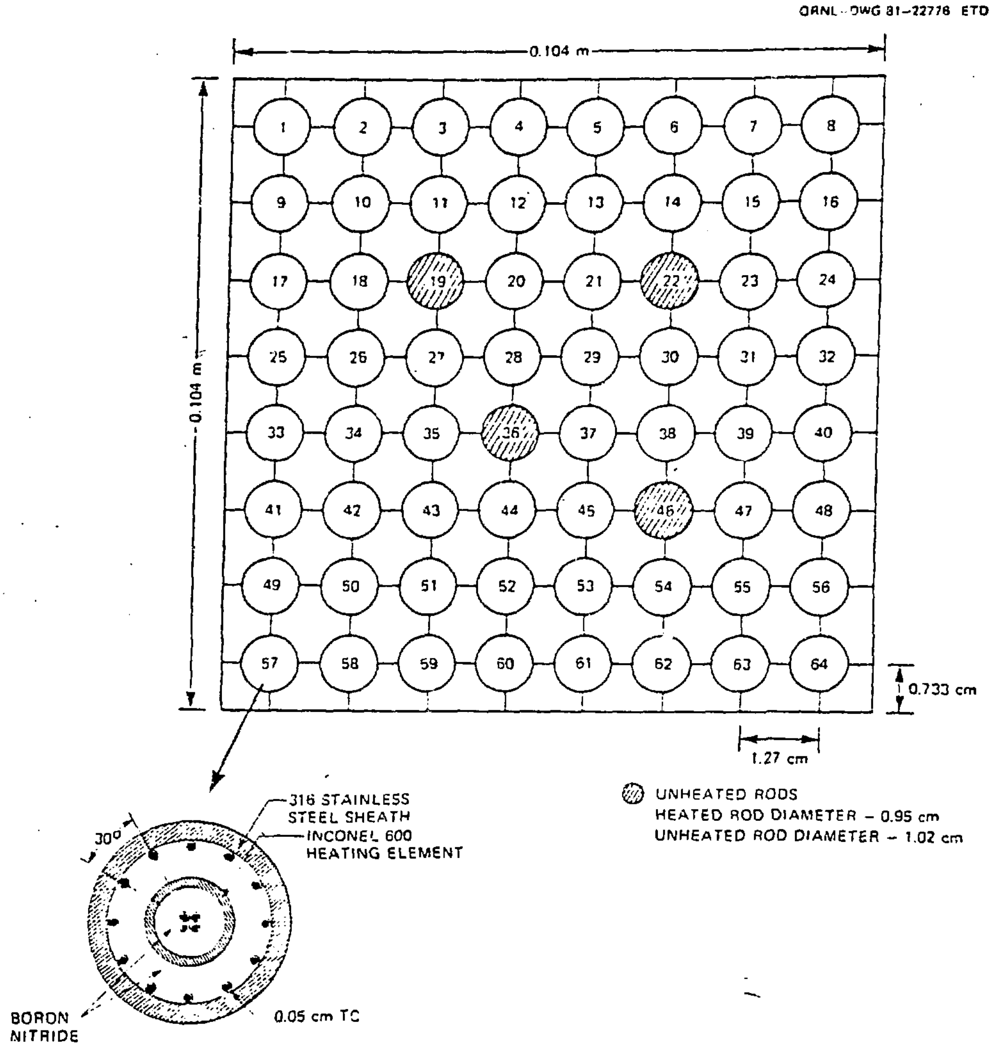

Fig. 2. Cross Sections of the Rod Bundle and Fuel Rod Simulators.

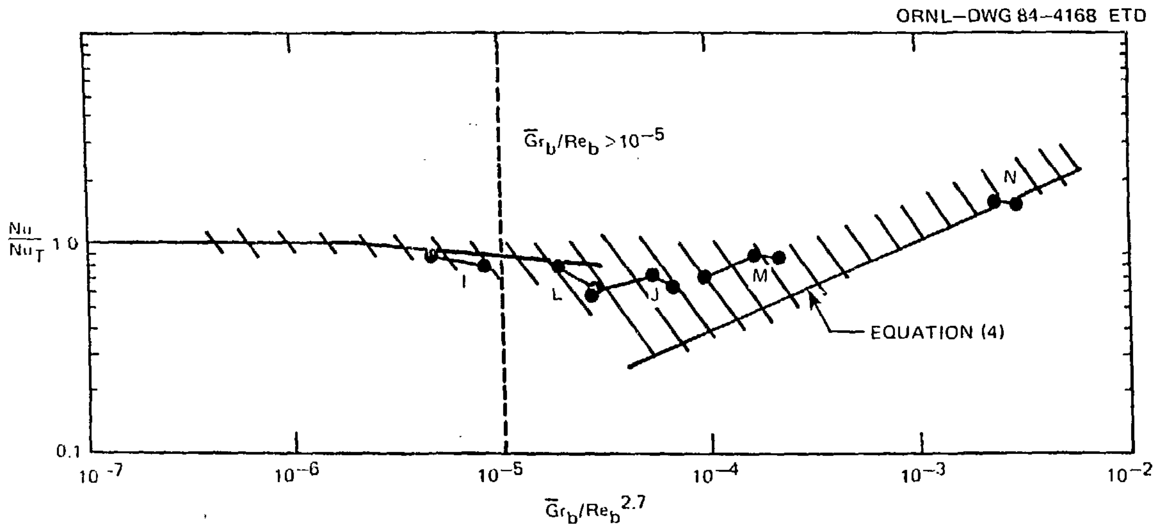

Fig. 3. ORNL Turbulent and Transitional Data (shaded area is the distribution of the mixed convection data reported in Ref. 13).

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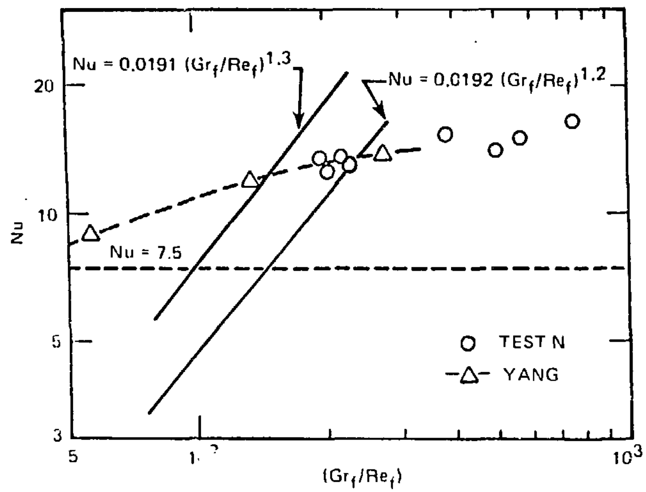

Fig. 4. Comparison of ORNL Laminar Flow Data to Numerical Results of Ref. 18 and Correlations of Ref. 19.