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Effect of Buoyancy on Forced Convection Heat Transfer in Vertical Channels — a Literature Survey

A. Bhattacharyya

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EFFECT OF BUOYANCY ON FORCED CONVECTION HEAT TRANSFER IN VERTICAL CHANNELS - A LITERATURE SURVEY

Ajay Bhattacharyya

Abstract

This report contains a short resumé of the available information from various sources on the effect of free convection flow on forced convection heat transfer in vertical channels. Both theoretical and experimental investigations are included. Nearly all of the theoretical investigations are concerned with laminar flow with or without internal heat generation. More consistent data are available for upward flow than for downward flow. Curves are presented to determine whether free convection or forced convection mode of heat transfer is predominant for a particular Reynolds number and Rayleigh number. At $Re_b > 10^5$ free convection effects are negligible.

Downward flow through a heated channel at low Reynolds number is unstable. Under similar conditions the overall heat transfer coefficient for downward flow tends to be higher than that for upward flow.

(This report forms a part of the thesis to be submitted to the Royal Institute of Technology, Stockholm, in partial fulfillment of the requirements for the degree of Teknologie Licentiat.)

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I. Introduction

For most fluids, the density decreases with increasing temperature. The hotter fluid mass tends to rise due to an increase in the buoyant force. Colder fluid from the surroundings replaces the hotter fluid. Fluid motion caused in the above manner is called free convective flow. In general free convective flows occur due to a difference of body forces in different parts of a fluid.

If a flow field is imposed, e. g. in pumping, a convecting fluid past a heat transmitting surface, the resulting phenomena is termed as combined forced and free convection. Forced convection is a limiting phenomena in which the momentum transport rates are very large and the effects of the body forces are negligible compared with the pumping forces.

II. Theoretical investigations

All the theoretical investigations except the one described in ref. [25] are for laminar flow conditions. All the analytical solutions are based on the following assumptions:

a) The flow is fully developed

b) The only non-vanishing velocity component is the one in the vertical direction

c) The physical properties of the fluids are constant except density in the expression for body force

d) There is single phase flow

II. 1 Laminar flow

Laminar flow inside vertical channels, with or without heat generation, is a two-dimensional boundary value problem if it is based on the above assumptions.

Lu [20] considered the case of laminar flow with internal heat generation inside vertical pipes with circular sector cross sections. Finite Fourier sine transform and finite Hankel transform are used for solving the equations. The analytical solution breaks down for the following values of $(Ra)_{Lu}$: 369.7 - 4245 - 6410 - 7086 - 15440 - - 19710, and so on.

Hallman [9] and Ostroumov [25] analytically investigated the problem of laminar flow through a circular pipe with uniform heating or cooling at the wall. Solutions were obtained for cases including conditions where internal heat generation was or was not present. The problem is solved in terms of Bessel functions. Hallman [9] obtained expressions for both Nusselt number and pressure drop. The analytical functions giving the dimensionless temperature and velocity profiles have infinite discontinuities when

$$J_1(\kappa) I_0(\kappa) - I_1(\kappa) J_0(\kappa) = 0 \tag{2-1}$$

where

$$\kappa = (Ra_{mod})^{0.25} \tag{2-1-a}$$

Equation 2-1 has an infinite number of roots. Some of the corresponding values of Ra_{mod} are -452.1 and -3700.

Tao [37] and Han [14] solved the problem for laminar flow through a vertical rectangular channel. Tao's analysis is valid for conditions with or without internal heat generation. A complex function was utilised to directly relate the velocity and temperature profiles.

Ostrach [28, 29, 30] has done extensive analytical investigation of the problem of laminar flow between two parallel vertical surfaces with or without internal heat generation. Effects of aerodynamic and frictional heating is also included in the analysis. Solutions have been obtained for constant wall temperatures [29], linearly varying wall temperatures [30] and for downward increasing temperature profiles [28].

Martinelli and Boelter [23] analysed the mechanism of heat transfer in laminar flow through a vertical pipe taking into account buoyancy forces. The velocity profile is assumed to be linear near the tube wall.

II. 2 Turbulent flow

Ojalvo and Grosh [27] made an analytical study of turbulent heat transfer in a vertical circular channel under the conditions of combined forced and free convection with uniform heat flux at the wall. The eddy diffusivities of momentum and heat were assumed to be proportionately constant.

An IBM 704 digital computer was used to solve the three simultaneous equations for velocity profile, temperature profile and pressure drop. The analytical solution is valid only for upward flow. Due to reasons unclear to the authors the iteration process in the computer oscillated for the following values of Ra_{mod}:

For $Pr = 1$

$Ra_{mod} = 256, 400, 625$ or 800

For any value of Prandtl number

$Ra_{mod} = 4096, 10^4$ or 10^6

III. Experimental investigations

III. 1 Laminar flow

Kemeny and Somers [20] studied combined free and forced convective laminar flow in vertical circular channels. The flow media were water ($Pr = 3$ to 6) and oil ($Pr = 80$ to 170). Only upward flow with heating was studied. In the axial direction the wall temperature increased at the inlet to a maximum and then decreased. After reaching a minimum it again increased towards the outlet. The wall temperatures at some points in the downstream portion of the channel were found to fluctuate. The frequency of fluctuation was about 15 cycles per minute at the point of the maximum amplitude. The data for the transition region were difficult to correlate. Above a bulk Reynolds number of 200 a transition from laminar to non-laminar flow occurred. The disturbances consisted of thermally induced eddy fluctuations. It seems that wave type flow containing large cells are generated at this condition.

Experimental investigations were conducted by Hallman [8] to study laminar heat transfer in a vertical circular channel under the conditions of combined forced and free convection. It was found that the following parameter has significant effect on the measure of the influence of the free convection on the forced convection heat transfer:

$$Ra_{mod} = \frac{\rho_b^2 \beta_b \; g \; AD^4}{16 \mu_b^2} \cdot \frac{\mu_b \; Cp_b}{\lambda_b} \qquad (3-1)$$

where

$$\beta = -\frac{1}{\rho}\frac{\partial \rho}{\partial T} \quad \text{and} \quad A = \frac{\partial T}{\partial x}$$

A is positive

a) when the fluid is heated as it flows upwards, or

b) when the fluid is cooled as it flows downwards.

A is negative

a) when the fluid is cooled as it flows upwards, or

b) when the fluid is heated as it flows downwards.

If the coefficient of volumetric expansion, β , is positive then Ra_{mod} has the same sign as A. In most of the cases encountered in common engineering practice β has a positive sign.

For positive Ra_{mod}, i. e. upwards flow with heating without internal heat generation, Hallman's data are correlated by the following equation which is valid in the region

$$10^2 < Ra_{mod} < 10^4$$

$$Nu_{bD} = 1.40\ Ra_{mod}^{0.28} \tag{3-2}$$

With positive Rayleigh numbers a transition to a fluctuating flow condition was observed for values given by the following equation valid in the region (see Fig. 3)

$$1 < \frac{Re_b\ Pr_b}{2\frac{x}{D}} < 20$$

$$Ra_{bD} = 9470\ \left(\frac{Re_b \cdot Pr_b}{\frac{2x}{D}}\right)^{1.83} \tag{3-3}$$

where

$$Ra_{bD} = \frac{\rho_b^2 \beta_b\ g D^3 (t_w - t_b)}{\mu_b^2} \cdot \frac{\mu_b\ Cp_b}{\lambda_b}$$

Data with downwards flow, i. e. negative Ra_{mod}, indicated the following:

a) The wall temperature was axially assymetric.

b) With higher heating rates the wall temperature at the lower portion of the vertical tube was found to be unsteady. The variations were periodic in nature. Records of the fluctuations indicated that the frequency of the fluctuation was independent of axial location but the amplitudes of the fluctuations were different at different axial locations.

c) The Nusselt numbers were below the pure forced convection value of 4.36 and considerably below the data which was obtained for the same heating value and flow conditions but for reversed flow directions.

Guerrieri and Hanna [7] used optical methods to study downwards flow of air through a narrow rectangular duct. Only two opposed parallel sides of the duct were heated. The flow rate ranged up to a maximum Reynolds number of 4900. Fig. 5 shows an example of how the local Nusselt number varied downwards along the length of the test section. In the upper part of the test section the heat transfer coefficient decreased because of stagnation of the flow near the heated walls. Further downstream the buoyancy forces become more predominant and cause local disturbances near the wall. Local upwards flow near the walls increases mixing and as a result the heat transfer coefficient increases. Still further downstream, the temperature gradient near the wall decreases due to improved mixing and as a result upward flow due to buoyancy forces decreases near the heated walls. From Fig. 6 it can be seen that with higher bulk Reynolds number the regions described above are longer. This agrees with the idea that at very high bulk Reynolds numbers, the effect of the free convective flow on the forced convection heat transfer should be negligible. No observation of instabilities or asymmetries in wall temperatures are mentioned by Guerrieri and Hanna [7].

III. 2 Turbulent flow

Eckert, Diaguila and Curren [3] studied mixed free and forced convective heat transfer connected with turbulent flow of air through a short duct. The Reynolds number range covered in the experiment was $3.6 \cdot 10^4$ to $3.77 \cdot 10^5$. Both upwards and downwards flow were studied. On the basis of the experimental results the heat transfer phenomena was divided into three groups:

a) pure free convective

b) mixed forced and free convective

c) pure forced convective

The three regimes were established in terms of the local heat transfer coefficient. For a particular Reynolds number = Re_{bx} the limit between free convective and mixed forced and free convective heat transfer was defined as the value of $Gr_{bx} \cdot Pr_b$ for which $(Nu_{bx})_{exp}$ had values 10 % above the dashed line representing the free convection heat transfer (Fig. 7 and Fig. 8). The forced convection limit was determined in a similar way from Fig. 7. Fig. 8 shows the resultant plot between Re_{bx} and $Gr_{bx} \cdot Pr_b$ for the two limits. For parallel or upwards flow the limiting line between the free and mixed flow regime is given by

$$Re_{bx} = 8.25 \, (Gr_{bx} \cdot Pr_b)^{0.40} \qquad (3\text{-}4)$$

The limiting line between the forced and mixed flow regimes is given as

$$Re_{bx} = 15.0 \, (Gr_{bx} \cdot Pr_b)^{0.40} \qquad (3\text{-}5)$$

With counterflow the limiting line between free and mixed flow is given by

$$Re_{bx} = 18.15 \, (Gr_{bx} \cdot Pr_b)^{0.33} \qquad (3\text{-}6)$$

It should be mentioned here that with counterflow x still denotes the distance of the measuring point from the bottom of the test section. Fig. 9 shows a plot in which the dimensionless numbers are recalculated by substituting $\xi = L - x$ in the place of x. L = total length of the test section.

The limit between forced convective flow and mixed forced and free convective flow was difficult to determine because the mixed flow regime approached the pure forced flow conditions much more gradually for counterflow than for parallel flow.

An important observation in connection with counterflow was that the heat transfer coefficients were nearly two times greater than those calculated for pure free or forced convection flow. The tendency is opposite to what was observed and analytically predicted by Hallman for laminar flow.

Watzinger and Johnson [39] investigated flow of hot water through a vertical pipe with cooled walls. Downwards flow in this case corresponds to a positive Ra_{mod}. The limiting line between the free and mixed flow is given by

$$(Re)_b = 7.39\ (Gr_{bD})^{0.35} \tag{3-7}$$

The limiting line between forced and mixed flow regime is given by

$$Re_b = 19.64\ (Gr_{bD})^{0.35} \tag{3-8}$$

Some data were obtained for negative Ra_{mod}. It appears that the heat transfer coefficients for negative $(Ra)_{mod}$ are 6 to 20 percent higher than the coefficients obtained from corresponding positive $(Ra)_{mod}$ runs with equal Δt_j. Fig. 10 shows a plot of Watzinger and Johnson relations reproduced from [3].

IV. Discussion

A general examination of the theoretical and experimental investigations reported in the published literature indicates the following:

IV.1 Laminar flow

a) For upward flow with heating under laminar flow conditions there is a fairly good agreement between the theoretical and the experimental investigations.

b) For downward flow with heating under laminar flow conditions local heat transfer coefficients vary with time. The variation is caused by instabilities due to local cell formation. Overall time-average heat transfer coefficients are difficult to predict.

IV.2 Turbulent flow

a) For upward flow with heating under turbulent flow conditions all the data are for round pipes. No reliable correlations are available for predicting the heat transfer coefficient in the mixed flow region. For Reynolds number greater than 10^5 effects of free convective flow on forced convection heat transfer are negligible for cases encountered in common engineering practices.

b) In the case of turbulent counterflow the highest Reynolds number for which data is available is $3.77 \cdot 10^5$. Effects of free convection are not negligible at this Reynolds number if the Grashif number is of the order 10^{12}. No instabilities or asymmetries in the wall temperatures are reported. The heat transfer coefficients for counterflow are higher than those for parallel flow under similar conditions. The quantitative agreement between the data from different sources is poor. The increase in the heat transfer coefficient varies from 6 to 200 percent.

V. Recommendations

V.1 Upward flow

a) Under laminar flow conditions equation (3-2) can be used for calculating heat transfer coefficients and equation (3-3) for estimating transition to fluctuating flow.

b) Under turbulent flow conditions the following equation can be used for estimating the local heat transfer coefficient.

$$Nu_{bx} = 0.116 \left[\left(Re_{bx} \frac{D}{x} \right)^{2/3} - 125 \right] (Pr)^{1/3} \left(\frac{x}{D} \right) \left[1 + 1/3 \left(\frac{D}{x} \right)^{2/3} \right] \qquad (5\text{-}1)$$

V.2 Downward flow

a) From the existing experimental data for laminar flow it is not possible to predict the local heat transfer coefficients. Hallman's (9) theoretical analysis for laminar flow can be used for predicting the local heat transfer coefficients at very low values of Ra_{mod}. At higher Ra_{mod} under laminar flow conditions inversions in the flow directions makes it difficult to correlate the available experimental data.

b) No satisfactory correlations were obtained for the experimental data for counterflow under turbulent flow conditions. The curves in the Fig. 9 can be used for estimating the local heat transfer coefficients for counterflow.

References

1. BROWN W G und GRASSMANN P
Der Einfluss des Auftriebs auf Wärmeübergang und Druckgefälle bei erzwungener Strömung in lotrechten Rohren. (The influence of buoyancy on heat transfer and pressure drop for forced flow in vertical tubes.)
Forsch. auf d. Geb. d. Ing. Wesen, Bd 25 (1959) No 3.

2. CLARK J A and ROHSENOW W M
Local boiling heat transfer to water at low Reynolds numbers and high pressures.
Trans. ASME, 76 (1954) 553.
(see Eckert E R G, Diaguila A J and Livingood J N B, NACA-TN--3584).

3. ECKERT E R G, DIAGUILA A J and CURREN A N
Experiments on mixed-free-and-forced convective heat transfer connected with turbulent flow through a short tube.
1953 (NACA-TN-2974).

4. ECKERT E R G, DIAGUILA A J and LIVINGOOD J N B
Free-convection effects on heat transfer for turbulent flow through a vertical tube.
1955 (NACA-TN-3584).
(see Clark J A and Rohsenow W M, Trans. ASME 76 (1954) 553).

5. FLINTA J and LARSSON S E
Värmeövergångstalet till vatten för ett vertikalt element IP.
(in Swedish) Internal report IPRV-8:58, AB Atomenergi.

6. GEBHART B
Heat transfer.
New York McGraw-Hill, 1961, 251-280.

7. GUERRIERI S A and HANNA R J
Local heat flux in a vertical duct with free convection in opposition to forced flow.
Final report 1952. (AD-36824).
(Dep. of Chem. Engin. Univ. of Delaware Newark, Delaware).

8. HALLMAN T M
Experimental study of combined forced and free-laminar convection in a vertical tube.
1961. (NASA-TN-D-1104).

9. HALLMAN T M
Combined forced, and free-laminar heat transfer in vertical tubes with uniform internal heat generation.
Trans. ASME, 78 (1956) 1831.

10. HAMILTON D C, LYNCH F E and PALMER L D
The nature of the flow of ordinary fluids in a thermal convection harp.
1954 (ORNL-1624).

11. HAMILTON D C, POPPENDIEK H F, REDMOND R F and PALMER L D
Free convection in fluids having a volume heat source. (Theoretical laminar flow analyses for pipe and parallel plate systems.)
1954 (ORNL-1769).

12. HAMILTON D C and LYNCH F E
Free convection theory and experiment in fluids having a volume heat source.
1955 (ORNL-1888).

13. HAMMITT F G, BROWER E M and CHU P T
Free convection heat transfer and fluid flow in closed vessels with internal heat source.
1959 (NP-8780).

14. HAN L S
Laminar heat transfer in rectangular channels.
Trans. ASME, 81 (1959) Ser. C, Journal of Heat Transfer, 121.

15. INMAN R M
Experimental study of temperature distribution in laminar tube flow of a fluid with internal heat generation.
Int. J. Heat Mass Transfer, 5 (1962) 1053.

16. JACKSON T W, HARRISON W B and BOTELER W C
Combined free and forced convection in a constant-temperature vertical tube.
Trans. ASME, 80 (1958) 739.

17. JACKSON T W, SPURLOCK J M and PURDY K R
Combined free and forced convection in a constant temperature horizontal tube.
AIChE Journal, 7 (1961) 38.

18. JURGENSEN D F Jr. and MONTILLON G H
Heat transfer coefficients on inclined tubes.
Ind. Eng. Chem., 27 (1935) 1466.

19. KLYACHKO L S
Relations for the critical state describing transition from laminar to turbulent flow in free convection.
Int. J. Heat Mass Transfer, 5 (1962) 763.

20. KEMENY G A and SOMERS E V
Combined free and forced-convective flow in vertical circular tubes - experiments with water and oil.
Trans. ASME, Ser. C, Journal of Heat Transfer, 83 (1962) 339.

21. LU PAU-CHANG
Combined free and forced-convection heat-generating laminar flow inside vertical pipes with circular sector cross sections.
Trans. ASME, Ser. C, Journal of Heat Transfer, 82 (1960) 227.

22. MARTIN B W
Free convection in an open thermosyphon, with special reference to turbulent flow.
Proc. Roy. Soc. (London). A 230 (1955) 502.

23. MARTINELLI R C and BOELTER L M K
The analytical prediction of superposed free and forced viscous convection in a vertical pipe.
Univ. of Calif. Publ. in Eng. 5 (1942) No. 2, 23.

24. METAIS B and ECKERT E R G
Forced, mixed, and free convection regimes.
Trans. ASME, Ser. C, Journal of Heat Transfer, 86 (1964) 295.

25. MORTON B R
Laminar convection in uniformly heated pipes.
J. Fluid Mechanics, 8 (1960) p. 2, 227.

26. OSTROUMOV G A
Free convection under the conditions of the internal problem.
1958 (NACA-TM-1707).

27. OJALVO M S and GROSH R J
Combined forced and free turbulent convection in a vertical tube.
1962 (ANL-6528).

28. OSTRACH S
Unstable convection in vertical channels with heating from below including effects of heat sources and frictional heating.
1955 (NACA-TN-3458).

29. OSTRACH S
Laminar natural-convection flow and heat transfer of fluids with and without heat sources in channels with constant wall temperatures.
1952 (NACA-TN-2863).

30. OSTRACH S
Combined natural-and forced-convection laminar flow and heat transfer of fluids with and without heat sources in channels with linearly varying wall temperatures.
1954 (NACA-TN-3141).

31. ROSEN E M and HANRATTY T J
Use of boundary-layer theory to predict the effect of heat transfer on the laminar-flow field in a vertical tube with a constant temperature wall.
AIChE Journal, 7 (1961) 112.

32. Von STENDER W
Die Abhängigkeit der mittleren Wärmeübergangszahl von der Rohrlänge.
Siemens-Konzern (Siemensstadt b. Berlin) Wiss. Veröffentlich. 9 (1930) 88.

33. SPARROW E M, EICHHORN R and GREGG J L
Combined forced and free convection in a boundary layer flow.
Phys. of Fluids, 2 (1959) 319.

34. SPARROW E M, LOEFFLER Jr A L and HUBBARD H A
Heat transfer to longitudinal laminar flow between cylinders.
Trans. ASME, Ser. C, Journal of Heat Transfer, 83 (1961) 415.

35. SCHEELE G F, ROSEN E M and HANRATTY T J
Effect of natural convection on transition to turbulence in vertical pipes.
Can. J. Chem. Eng. 38 (1960) 67.

36. TOULOUKIAN Y S, HAWKINGS G A and JAKOB M
Heat transfer by free convection from heated vertical surfaces to liquids.
Trans. ASME, 70 (1948) 13.

37. TAO L N
On combined free and forced convection in channels.
Trans. ASME, Ser C, Journal of Heat Transfer, 82 (1960) 233.

38. TAO L N
On some laminar forced-convection problems.
Trans. ASME, Ser. C, Journal of Heat Transfer, 83 (1961) 466.

39. WATZINGER A und JOHNSON DAG G
Wärmeübertragung von Wasser an Rohrwand bei senkrechter Strömung in Übergangsgebiet zwischen laminarer und turbulenter Strömung.
Forsch. auf d. Geb. d. Ing. Wesen, Bd 10 (1939) H 4, 182.

NOMENCLATURE

A	temperature gradient in the axial direction (along the x axis) = $= \frac{\partial T}{\partial x}$ - ^{o}C/meter
C_p	specific heat at constant pressure - J/kg ^{o}C
D	diameter - meter
D_e	equivalent diameter - meter
I_0	modified Bessel function of the zeroeth order
I_1	modified Bessel function of the first order
J_0	Bessel function of the zeroeth order
J_1	Bessel function of the first order
L	total length of a vertical channel - meter
T	temperature - ^{o}C
g	acceleration due to gravity - meter/sec^2
t	temperature in ^{o}C when not defined otherwise
x	longitudinal or axial coordinate (see fig. 1)
y	transverse coordinate (see fig. 1)
Gr_{bD}	Grashof number $= \frac{\rho_b \beta_b g D^3 (t_w - t_b)}{\mu_b^2} \cdot \frac{\mu_b C p_b}{\lambda_b}$
Gr_{bx}	Grashof number $= \frac{\rho_b \beta_b g x^3 (t_w - t_b)}{\mu_b^2} \cdot \frac{\mu_b C p_b}{\lambda_b}$
Nu_{bD}	Nusselt number $= \frac{\alpha D}{\lambda_b}$
Nu_{bx}	Nussel number $= \frac{\alpha x}{\lambda_b}$
$Nu_{b\xi}$	Nusselt number $= \frac{\alpha \xi}{\lambda_b}$

Pr_b	Prandtl number $= \dfrac{\mu_b \, Cp_b}{\lambda_b}$
Ra_{mod}	modified Rayleigh number $= \dfrac{\rho_b{}^2 \beta_b \, g A D^4}{16 \mu b^2} \cdot \dfrac{\mu_b \, Cp_b}{\lambda_b}$
Ra_{bD}	Rayleigh number $= Gr_{bD} \cdot Pr_b$
Ra_{Lu}	modified Rayleigh number of Lu (20) $= \dfrac{\rho^2 \cdot \beta \cdot g A D^4}{\mu^2} \cdot \dfrac{\mu \, Cp}{\lambda} \cdot \dfrac{1}{\gamma}$
Re_b	Reynolds number $= \dfrac{\rho_b \, w_b \, D}{\mu_b}$
Re_{bx}	Reynolds number $= \dfrac{\rho_b \, w_b \, x}{\mu_b}$
$Re_{b\xi}$	Reynolds number $= \dfrac{\rho_b \, w_b \, \xi}{\mu_b}$
α	coefficient of heat transfer $W/m^2 \, {}^oC$
β	volumetric expansion coefficient $= -\dfrac{1}{\rho} \dfrac{\partial p}{\partial T}$; $1/{}^oC$
γ	ratio of specific heats
μ	dynamic viscosity - kg/m s
λ	thermal conductivity - $W/m \, {}^oC$
κ	as defined in eq (2-1-a)
ξ	longitudinal or axial coordinate (see fig. 1) - meters

<u>Suffixes</u>

b	bulk
x	at a distance x
ξ	at a distance ξ

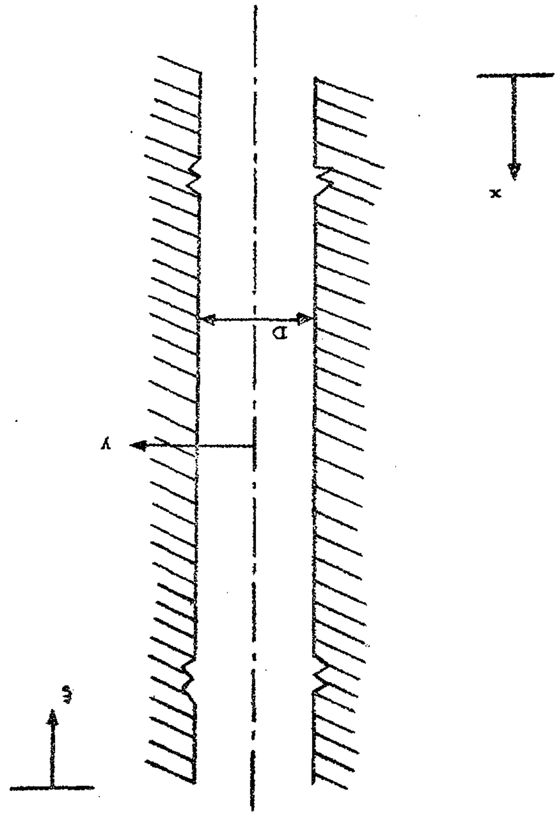

Fig. 1. Schematic sketch of configuration.
x = distance from the bottom of a test section
ξ = " " " top " " "

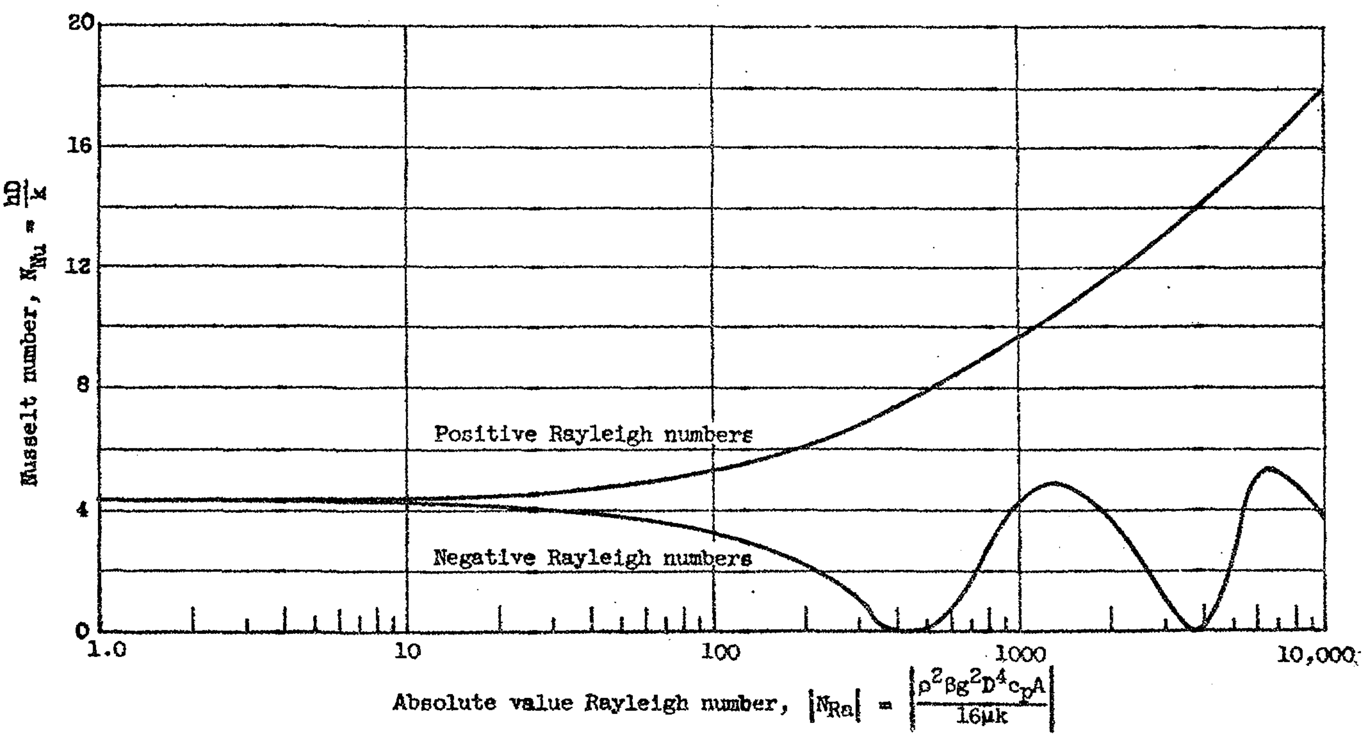

Fig. 2. Nusselt number versus absolute value of Ra_{mod} for positive and negative Rayleigh numbers (ref. 9) Abscissa $|Ra_{mod}|$ Ordinate Nu_{bD}

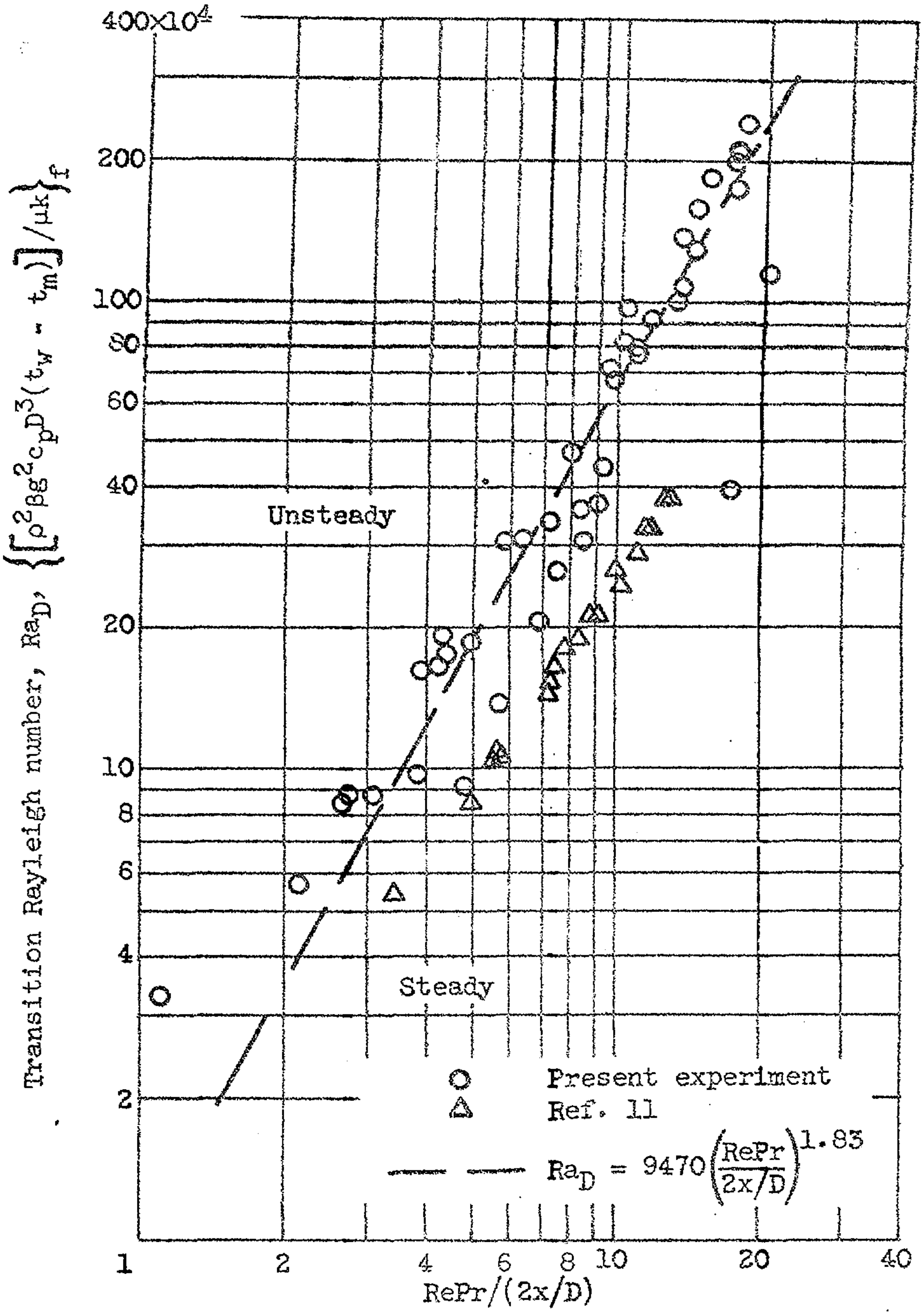

Fig. 3. Correlation of data for transition in upflow with heating (ref. 9) Abscissa $\dfrac{Re_b \cdot Pr_b}{2\frac{x}{D}}$ Ordinate Ra_{bD}

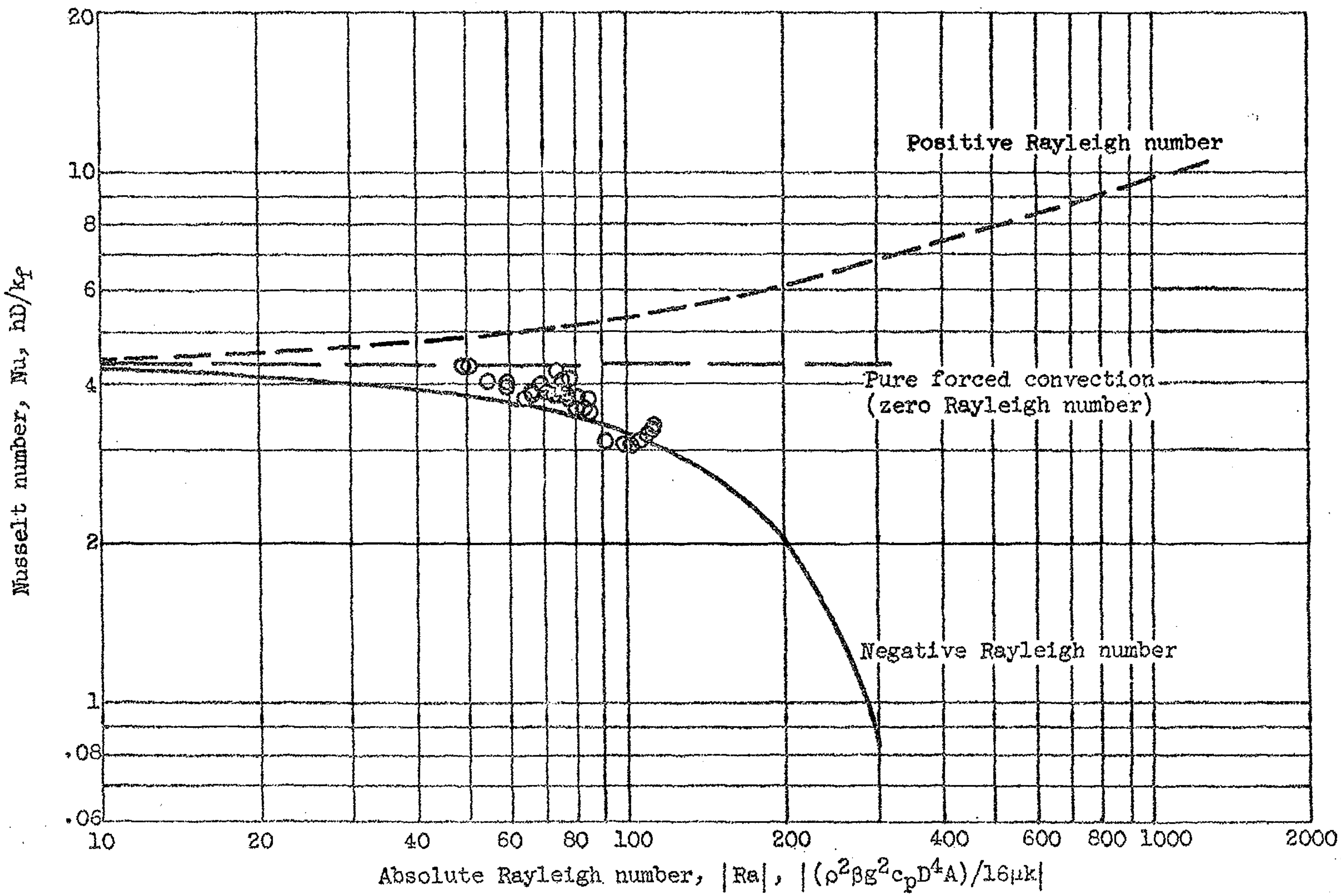

Fig. 4. Comparasion of fully developed Nusselt numbers with analysis for downflow with heating (ref. 9) Abscissa $|Ra_{mod}|$ Ordinate Nu_{bD}

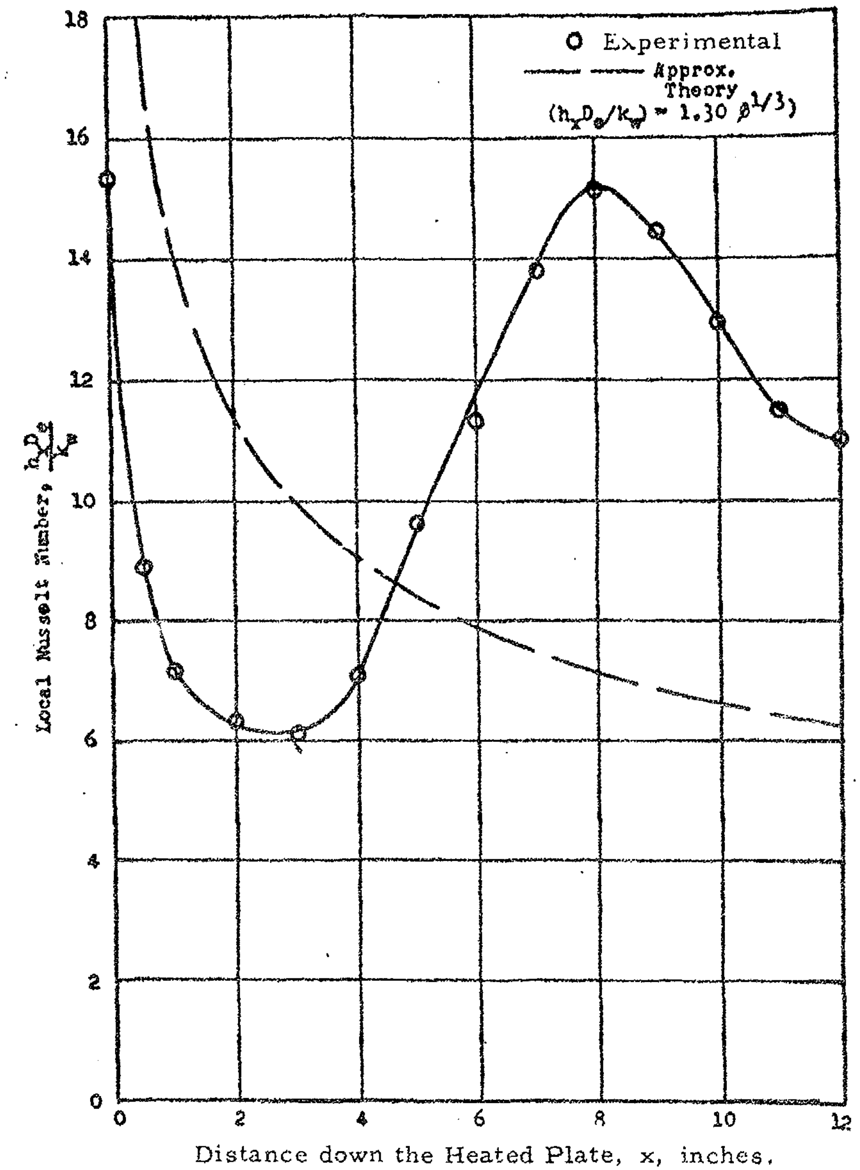

Fig. 5. **Variation of Nusselt number in the downward direction (ref. 7)**

Abscissa ξ in inches Ordinate $\frac{\alpha_\xi D_e}{\lambda_w}$

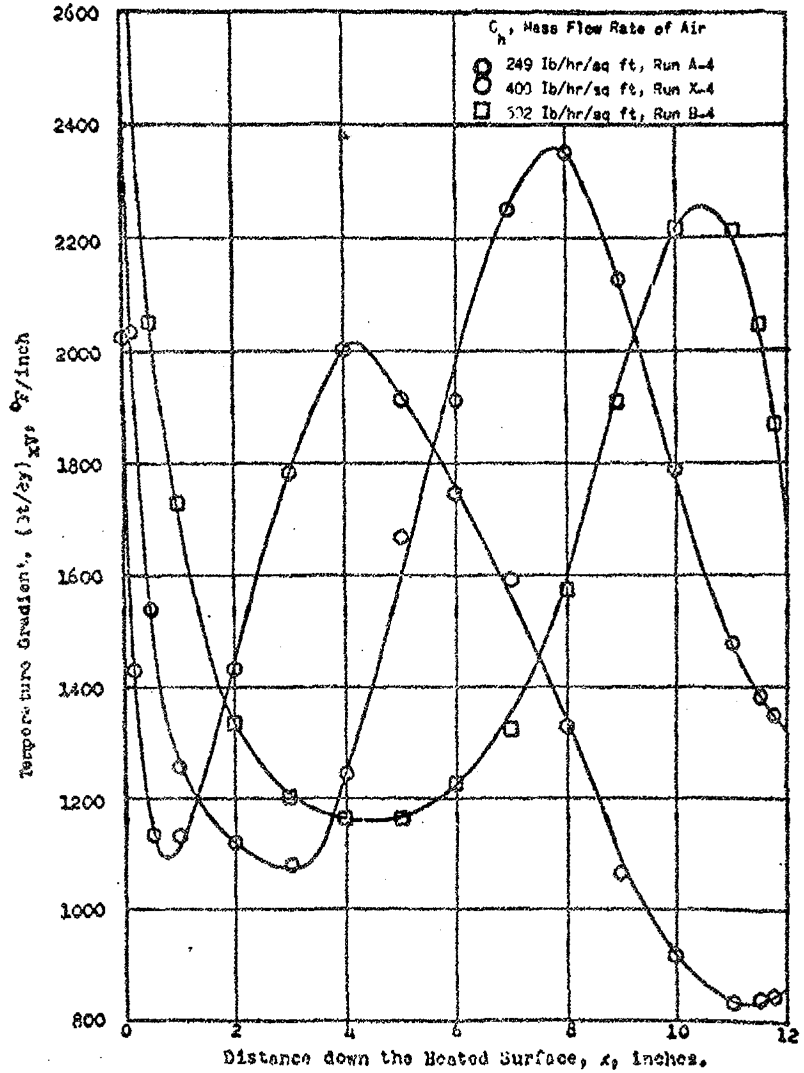

Fig. 6 Variation of air temperature gradient at the wall versus distance down the heated surface at various flow rates and constant average wall temperature (ref. 7).

Abscissa ξ in inches Ordinate $(\frac{\delta t}{\delta y})_\xi$, in °F/inch.

Run. nr	Re_b
A-4	900
x-4	1440

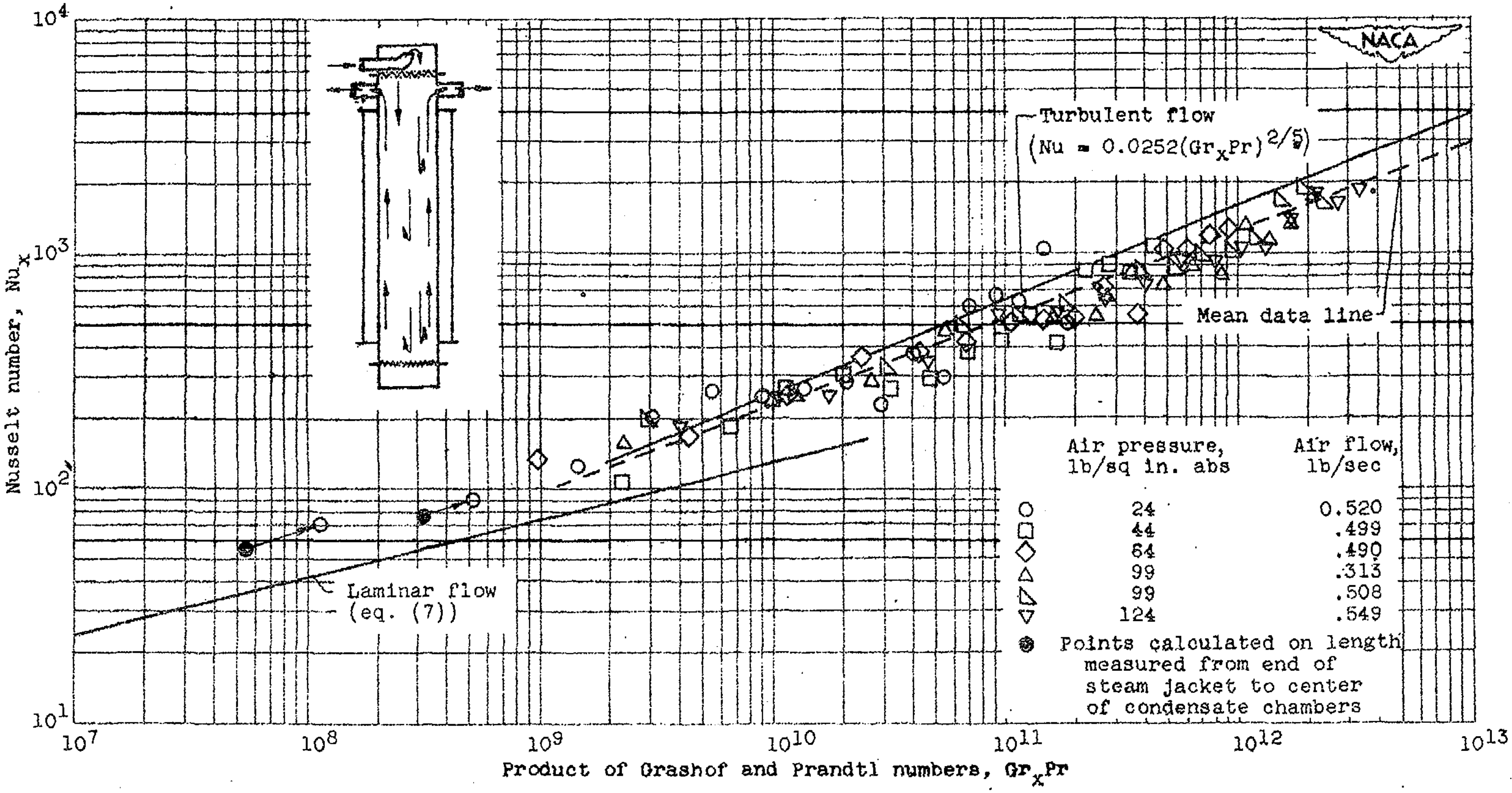

Fig. 7. Dimensionless correlation of local mixed-free-and forced-convection heat transfer coefficients for turbulent parallel flow (ref. 3).

Abscissa $Gr_{bx} \cdot Pr_b = Ra_{bx}$ Ordinate Nu_{bx}

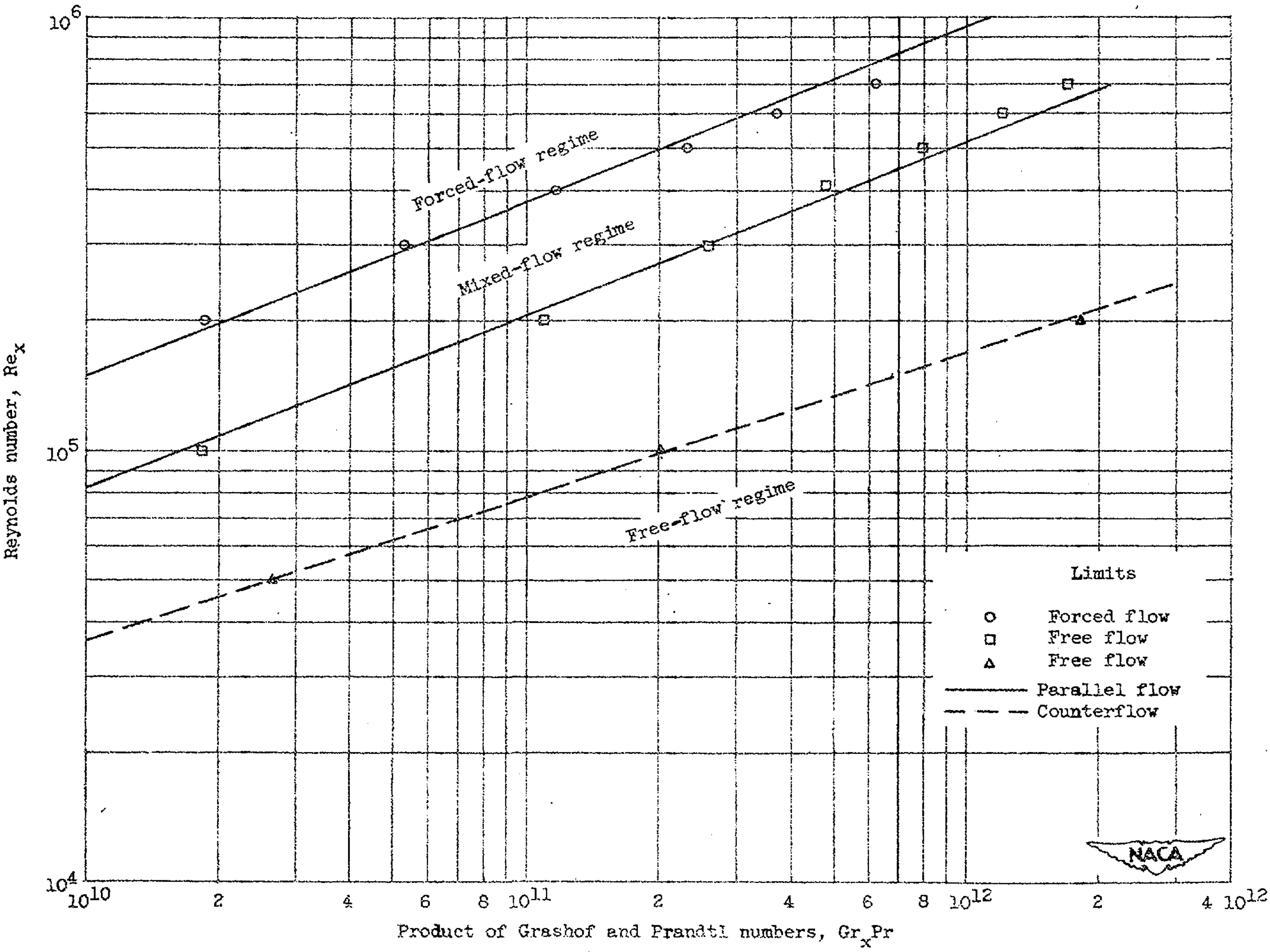

Fig. 8 Free and forced convection limits for turbulent flow tube with length to diameter ratio of 5 and Prandtl number of 0.7 (ref. 3).

Abscissa $Gr_{bx} Pr_b = Ra_{bx}$ Ordinate Re_{bx}

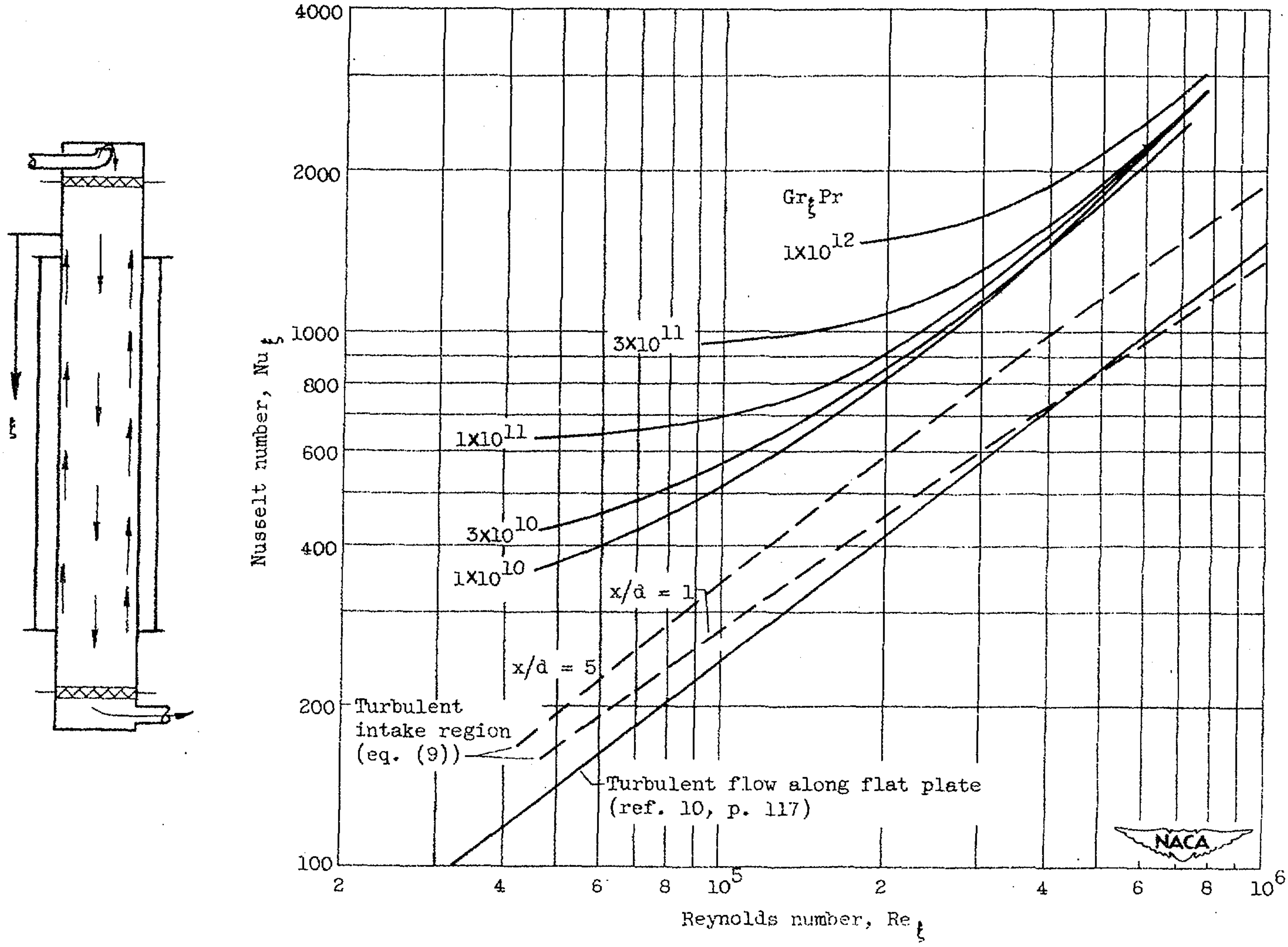

Fig. 9 Dimensionless correlation of mixed free and forced convection heat transfer coefficients for turbulent counterflow (ref. 3).

Abscissa $Re_{b\xi}$ Ordinate $Nu_{b \cdot \xi}$

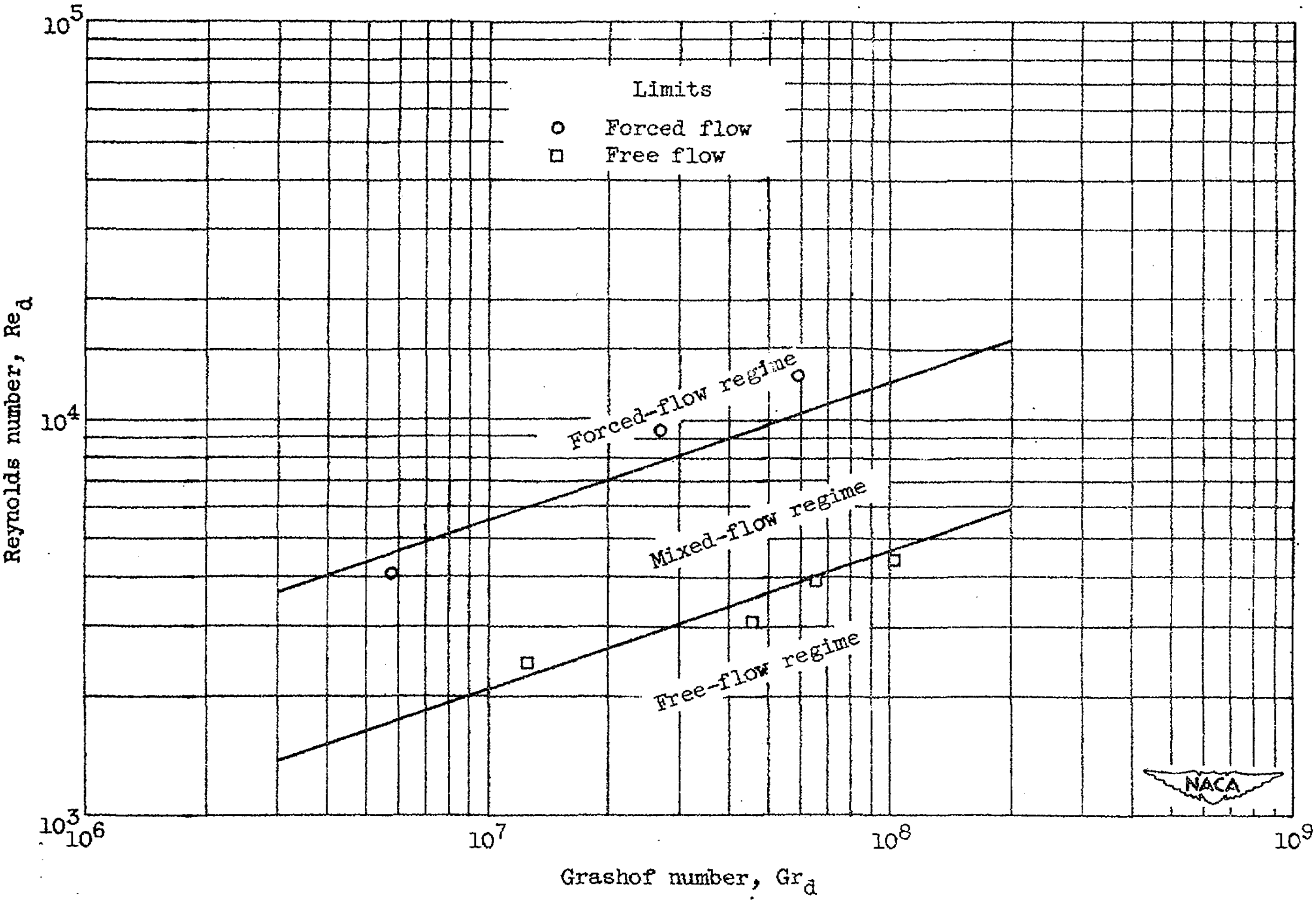

Fig. 10. Free and forced convection Limits for experimental results obtained by Watzinger and Johnson (ref. 39). Length to diameter ratio of tube, 20: Prandtl number appriximately 3.0 (ref. 3).

Abscissa Gr_{bD} Ordinate Re_b

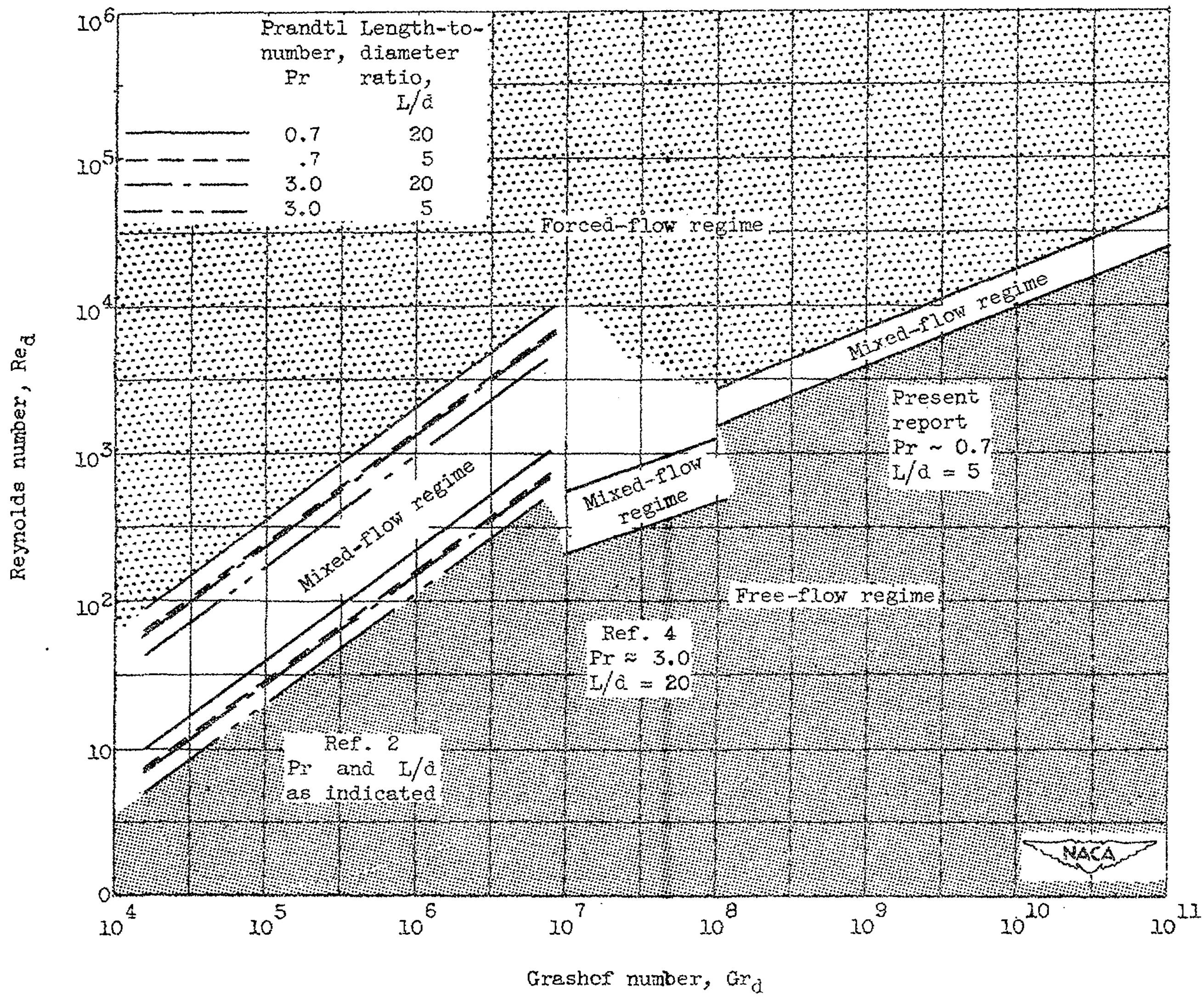

Fig. 11 Summary of available data on free-, and mixed flow regimes in parallel flow (ref. 3).

Abscissa Gr_{bD} Ordinate Re_b

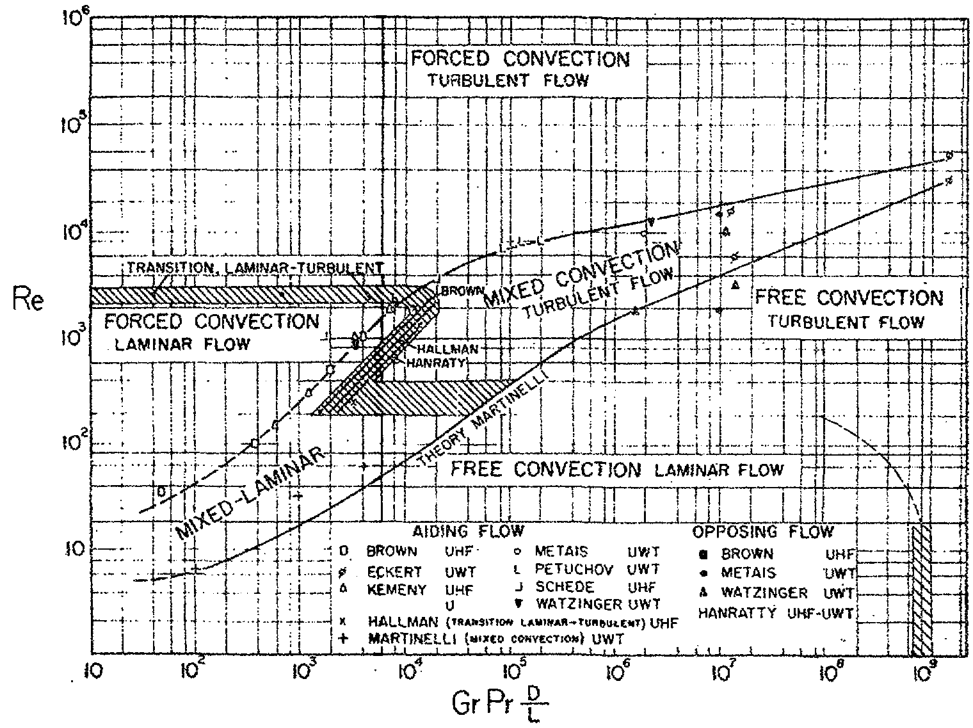

Fig. 12 Regimes of free, forced and mixed convection for flow through vertical tubes (ref. 24).

Abscissa $Gr_{bD} \cdot Pr_b \cdot \frac{D}{L}$ Ordinate Re_b

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