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EMPIRICAL EQUATION FOR TURBULENT FORCED-CONVECTION HEAT TRANSFER FOR PRANDTL NUMBERS FROM 0.001 TO 1000

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SUMMARY

A review is made of some of the experimental data and analyses applicable to convective heat transfer in fully turbulent flow in smooth tubes with liquid metals and viscous Newtonian fluids. An empirical equation is evolved that closely approximates heat-transfer values obtained from selected analyses and experimental data for Prandtl numbers from 0.001 to 1000. The terms included in the equation are Reynolds number, Prandtl number, and an empirical diffusivity ratio between heat and momentum.

INTRODUCTION

Proposals for electric-power generation on space vehicles have stimulated increased interest in the use of liquid-metal heat-transfer loops with nuclear power sources. As part of a comprehensive heat-transfer program being conducted at the NASA Lewis Research Center, a literature survey was made to determine the need for further basic research on fully turbulent forced-convection heat transfer with liquid metals as the working fluid. In considering that viscous Newtonian fluids will also have application in other flow and heat-transfer systems on many space vehicles, the desirability of a single, relatively simple equation for the prediction of fully turbulent forced-convection heat transfer over a wide range of Prandtl numbers (from less than 0.04 for liquid metals to over 100 for oils) becomes evident. For the most part investigators have developed analyses and equations applicable over only a limited range of Prandtl or Reynolds numbers. Considerable doubt exists as to the validity of extending these limited equations over the wide variations in fluid properties and flow conditions characterized by Prandtl and Reynolds numbers.

Herein a review is made of some of the published data and analyses applicable to viscous Newtonian and liquid-metal fluids. An empirical equation, based on selected heat-transfer models, is then evolved that yields convective heat transfer, for engineering purposes, over a Prandtl number range from 0.001 to 1000 and a Reynolds number range from 2.1×10^3 to 10^7 for fully turbulent flow in smooth round tubes.

PRESENT STATUS OF TURBULENT FORCED-CONVECTION HEAT TRANSFER

This section provides a brief synopsis of and background material on some of the analyses and data commonly referred to in the literature; it is suggested that the references be consulted for details.

Liquid Metals

Convective heat transfer in liquid metals ($Pr \ll 0.1$) differs from that usually ascribed to conventional fluids in that the molecular conduction in the core of the fluid flowing in a tube cannot be neglected in comparison with eddy diffusion. Martinelli (ref. 1) extended the analogy between heat and momentum transfer to low Prandtl numbers. Lyon's study (ref. 2) is an extension and simplification of Martinelli's analysis. The main differences between these studies is that Martinelli assumed a uniform surface temperature along a tube, whereas Lyon assumed the same transverse heat flow per unit area to exist over the entire tube wall. Martinelli and Lyon both assumed identical diffusivities for both heat and momentum; however, as stated in reference 3, Lyon also carried a ratio of these quantities different from 1.0 throughout his analysis. On the basis of his analysis Lyon proposed the following simplified equation for predicting convective heat transfer with liquid metals:

$$Nu = 7.0 + 0.025\ Pe^{0.8} \tag{1}$$

(Symbols used herein are defined in the appendix.) It should be noted that equation (1) is independent of Prandtl number except as it occurs in the Peclet number.

Jenkins (ref. 4) and Deissler (ref. 5) modified the mixing-length theory to apply to low Prandtl number fluids by accounting for the heat transferred by conduction to a turbulent particle (eddy) as it moves transversely away from the heated tube surface, so that the heat and momentum diffusivities cannot be considered equal. Both investigators assumed that the heat diffusivity is reduced to a value below that for momentum diffusivity. Deissler also provides a simplified equation for predicting the convective heat transfer with liquid metals:

$$Nu = 6.3 + 0.00022\ Pe^{1.3} \tag{2}$$

Although equation (2) was developed for a Prandtl number of 0.01, it should apply equally to other Prandtl numbers, because Deissler's analysis showed that the relation of Nusselt to Peclet number was substantially independent of Prandtl number.

Lykoudis (ref. 6) and Viskanta (ref. 7) have used somewhat different analytical models for the diffusivity ratio between heat and momentum than those of the preceding investigators. In both of these closely related analyses the diffusivity ratio in the low Prandtl number range is less than 1.0 and varies as a function of Prandtl number, approaching a value of zero as the Prandtl number approaches zero. Therefore, the analyses of Lykoudis and Viskanta differ from those discussed previously in that the variation of Nusselt number with Peclet number is also dependent on Prandtl number. Viskanta's analysis differs from that of Lykoudis mainly because of the effect of different velocity profiles on mixing-cup temperature and velocity (Kármán as compared with Lykoudis velocity profile). In general the Viskanta analysis yields a somewhat higher Nusselt number for a particular Peclet number than does the Lykoudis analysis; for example, at a Peclet number of 10^5 and a Prandtl number of 0.02 (mercury) Viskanta obtains a 12 percent higher Nusselt number than that of Lykoudis. At very low Peclet numbers, less than 10^3, the results of Lykoudis and Viskanta are substantially the same.

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Finally it should be noted that the diffusivity ratio used in the analyses of Deissler, Lykoudis, and Viskanta all include a term that is obtained from experimental data. For example, Lykoudis presents the following equation (ref. 6) for the diffusivity ratio:

$$\sigma = \frac{6}{\pi^2}\left(e^{-c_2/Pr} + 0.25\ e^{-4c_2/Pr}\right) \tag{3}$$

where c_2 is obtained by matching Lykoudis' analysis with the experimental lead-bismuth data of Johnson (ref. 8). The value of c_2 was found to be 0.01 and was furthermore assumed to be valid and constant for all liquid metals and Prandtl numbers.

The analytical heat-transfer results of Lyon, Deissler, Lykoudis, and Viskanta are shown in figure 1 plotted in terms of Nusselt number as a function of Peclet number. Also shown in figure 1 are ranges of experimental data, normalized by Lubarsky (ref. 9), obtained primarily with mercury and a lead-bismuth mixture ($0.02 < Pr < 0.04$). Of the several analytical results shown in figure 1, the analysis of Lykoudis clearly shows the variation of Nusselt number with Prandtl number for a constant value of Peclet number, whereas Deissler's and Lyon's analyses show no dependence on Prandtl number, as stated previously. At Peclet numbers less than 100 all the analyses yield a Nusselt number of approximately 7. The experimental data generally fall considerably below Lyon's analytical values. Deissler's analytical curve is in good agreement with the experimental data for Peclet numbers less than 1000; however, the trend of the curve deviates markedly from the experimental data for Peclet numbers greater than 1000. Lykoudis' and Viskanta's analytical curves appear to be good representations of the experimental data throughout the range of Peclet numbers shown. It should be recalled, however, that Lykoudis and Viskanta used a portion of the experimental data shown in figure 1 in order to evaluate the constant c_2 in equation (3); hence the good agreement between the analytical values and the experimental data would be expected.

Viscous Fluids

Convective heat transfer with conventional liquids ($Pr > 0.5$) is difficult to correlate on the basis of Peclet number only, especially for viscous oils. Correlation in terms of Reynolds number is therefore preferred to Peclet number, since the former correlates not only liquids but also gases. For Newtonian fluids with a Prandtl number near 1.0 fully turbulent forced-convection heat transfer for flow through smooth tubes has been expressed by the following empirical equation:

$$Nu = ARe^{a}Pr^{b} \tag{4}$$

where A, a, and b have been determined experimentally. Various investigators have obtained a variety of values for these constants, which for the most part are applicable over only a short range of Prandtl and Reynolds numbers. Theoretical studies have resulted in a similar plurality of equations. Equation (4), familiar to most thermodynamicists, is generally referred to as the Colburn equation (ref. 3) and for such fluids as air and water represents experimental data reasonably well when expressed as

$$Nu = 0.023\ Re^{0.8}Pr^{0.33} \tag{4}$$

The general form of the Colburn equation is valid for $Pr \gg 1.0$ only when different constants are used for various Prandtl number ranges. Hofmann (ref. 10) developed two equations to cover a Prandtl number range from about 0.1 to over 1000. These equations result in a nonlinear relation between Nusselt number and Prandtl number for a constant Reynolds number when plotted on log-log coordinates. The Colburn equation, on the other hand, in a particular Prandtl number range yields a straight-line variation for a similar plot of variables. Metzner (ref. 11) conducted an analysis similar to that of Hofmann but developed a somewhat different equation for Prandtl numbers much greater than 1.0. At high Prandtl numbers (over 100) Metzner assumed equality between

Schmidt number (mass transfer) and Prandtl number. Deissler (ref. 12) presents an extensive analysis of convective heat transfer for Prandtl and Schmidt numbers up to 3000 which compares favorably with data. This contribution by Deissler is considered by many to be one of the outstanding in the field.

For purposes of simple comparison, heat-transfer values calculated from the works of Colburn, Hofmann, Deissler, and Metzner are shown in figure 2 in terms of Stanton number as a function of Prandtl number (from 0.5 to 1000) for Reynolds numbers of 10^4 and 10^6. The deviation of Metzner's curve from Hofmann's curve for Prandtl numbers greater than 100 may possibly be attributed to somewhat different analytical approaches. Hofmann's work for the most part agrees well with Deissler's analysis. For a Reynolds number of 10^4 the agreement is good up to a Prandtl number of 100, with Deissler thereafter indicating a higher Stanton number with increasing Prandtl number than Hofmann. For a Reynolds number of 10^6 agreement seems good up to Prandtl numbers of 1000.

PROPOSED EQUATION FOR TURBULENT FORCED-CONVECTION HEAT TRANSFER

Assumptions

The following assumptions were made for the presently proposed empirical heat-transfer equation:

(1) Over the range of Prandtl numbers from 0.001 to 1000 the Nusselt number varies with the 0.8 power of the Reynolds number.

(2) An empirical diffusivity ratio σ^* shall approach 1.0 for Prandtl numbers greater than 0.5 and decrease with decreasing Prandtl number for Prandtl numbers less than 0.5. The values of σ^* for Prandtl numbers less than 0.5 shall be determined to yield the Nusselt number variation with Prandtl and Peclet numbers shown in figure 1 for Lykoudis' analysis.

(3) For zero Prandtl number the Nusselt number shall be 6.8, which is considered the lowest theoretical limit for turbulent flow (ref. 6).

(4) For Prandtl numbers greater than 0.5 the relations between Nusselt, Prandtl, and Reynolds numbers presented by Hofmann (ref. 10) shall be considered valid.

Development of Empirical Equation

An equation having the general form

$$Nu = B\left[f_1(Pr)\right] + C\left[f_2(Pr)\right]Re^{0.8}Pr^{\left[f_3(Pr,Re)\right]} \tag{5}$$

appeared to be indicated from cross plots of data and considerations of previous analyses. Superficially this form of equation appears to be similar to that developed by Lyon for liquid metals rather than that given by Colburn for air and water. However, the Prandtl number function $f_1(Pr)$ in the first term on the right side of equation (5) may be allowed to vary from a value of 1.0 at $Pr = 0$ to a negligible value at high Prandtl numbers. Therefore, when $f_1(Pr) \rightarrow 0$ at high Prandtl numbers, equation (5) takes the form of the Colburn equation. A simple relation for $f_1(Pr)$ which yields the desired variation with Prandtl number can be expressed by

$$f_1(Pr) = \frac{1}{(1 + Pr)} = \theta \tag{6}$$

By inspection, when $Pr = 0$, the second term on the right side of equation (5) is zero; hence, from equations (5) and (6), $Nu = B$ when $Pr = 0$. It has been previously stated that the lowest theoretical limit of Nu for turbulent flow is 6.8 and occurs when $Pr = 0$ (ref. 6); therefore, $B = 6.8$. The first term of equation (5) can now be written

$$B\left[f_1(Pr)\right] = 6.8\,\frac{1}{(1 + Pr)} = 6.8\,\theta \tag{7}$$

Consider now the term $f_2(Pr)$, which represents the diffusivity ratio. For $Pr > 0.5$, $f_2(Pr)$ approaches 1.0, while C can be taken as a constant identical to that used in the Colburn equation. Therefore for $Pr > 0.5$

$$f_2(Pr) \cong C \cong 0.023 \tag{8}$$

Equation (5) can then be written for $Pr > 0.5$ as

$$Nu \cong 0.023\,Re^{0.8}Pr^{\left[f_3(Pr,Re)\right]} \tag{9}$$

Cross plots of Nu, Pr, and Re based on Hofmann's analysis then yield the function $f_3(Pr,Re)$ quite readily. An equation for $f_3(Pr,Re)$ that fits Hofmann's heat-transfer curves quite well can be written

$$f_3(Pr,Re) = 0.41\ Re^{0.04}\left(\frac{1}{1 + Pr}\right)^{0.1} \tag{10}$$

or, since $1/(1 + Pr) = \theta$,

$$f_3(Pr,Re) = 0.41\ Re^{0.04}\theta^{0.1} \tag{11}$$

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For $Pr < 0.5$, an expression for $f_2(Pr)$ that will satisfy the second assumption stated at the beginning of this section (while not significantly affecting eq. (9) for $Pr > 0.5$) can be written

$$f_2(Pr) = \left[1 - \frac{1}{(1 + 19Pr + 100Pr^3)}\right] = \sigma^* \tag{12}$$

This equation yields decreasing values of σ^* (empirical diffusivity ratio) with decreasing Pr values for $Pr < 0.5$ while yielding a σ^* value approaching 1.0 for $Pr \gg 0.5$.

The final equation for convective heat transfer for fully turbulent flow in a smooth round tube can now be written

$$Nu = 6.8\ \theta + 0.023\ \sigma^* Re^{0.8} Pr^{0.41}\ Re^{0.04}\theta^{0.1} \tag{13}$$

Equation (13) can be used to obtain the Nu against Pe function developed by Viskanta (ref. 7) by modifying the σ^* relation given in equation (12) as follows:

$$\sigma^*_{mod} = 1 - 1/(1 + 28Pr + 100Pr^3) \tag{14}$$

Use of σ^*_{mod} in place of the original σ^* has a negligible effect on the Nusselt number calculations for viscous Newtonian fluids (Prandtl numbers > 0.5).

RESULTS AND DISCUSSION

The Nusselt number variation with Peclet number obtained by Lykoudis is shown in figure 3 together with values calculated by use of equation (13). In general the calculated values agree well with those obtained by Lykoudis. For very low Prandtl numbers, of the order of 0.001, equation (13) predicts a Nusselt number about 10 percent lower than that of Lykoudis at a Peclet number of 10^4. At a Peclet number of 10^2 the calculated values from equation (13) group about a Nusselt number of approximately 7.0 for the Prandtl number range shown; the curves of Lykoudis show a similar trend except for the case of a Prandtl number of 0.1, which yields a Nusselt number of about 8.7.

A comparison of results obtained from equation (13) and the analytical curves of both Lykoudis and Hofmann over a combined Prandtl number of 0.001 to 1000 is shown in figure 4 in terms of Stanton number as a function of Prandtl number for a Reynolds number of 10^6. The good agreement between values calculated from equation (13) and those of the two analyses in their particular Prandtl number range of applicability is apparent. The deviation of the values calculated by use of equation (13) from those of Hofmann in the range $0.1 < Pr < 0.5$ is attributed to the latter's fairing of the viscous-fluid curves into curves obtained from a liquid-metal heat-transfer analysis similar to that of Lyon. Such a procedure results in higher Stanton numbers in the liquid-metal range than are predicted by Lykoudis and equation (13). The dip in the curve at a Prandtl number near 1.25×10^{-2} is shown on a larger scale in figure 5, where Stanton number is again plotted as a function of Prandtl number for a Reynolds number of 10^6. Included also in figure 5 are curves based on Lyon (eq. (1)) and Deissler (eq. (2)). The curve based on Deissler's work shows a dip near a Prandtl number of 5×10^{-3} and generally exhibits a form and trend of Stanton number variation with Prandtl number similar to Lykoudis' curve and equation (13). The curve based on Lyon's work shows no dip. The dips in the curve are believed to be associated with the diffusivity-ratio relations considered by each investigator.

SUMMARY OF RESULTS

The following result and recommendation for further work were obtained from a study of available literature on convective heat transfer for fully turbulent flow in smooth tubes:

1. An empirical equation was evolved that closely approximates heat-transfer values obtained by the analyses of Lykoudis for liquid metals and Hofmann for viscous Newtonian fluids. Based on these analyses, the empirical equation is valid for Prandtl numbers from 0.001 to 1000 and Reynolds numbers from 2.1×10^3 to 10^7. The terms included in the equation are Reynolds number Re, Prandtl number Pr, and an empirical diffusivity ratio between heat and momentum σ^*; they are related as follows:

$$Nu = 6.8\ \theta + 0.023\ \sigma^* Re^{0.8} Pr^{0.41}\ Re^{0.04} \theta^{0.1}$$

where

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$$\theta = 1/(1 + Pr)$$

$$\sigma^* = 1 - 1/(1 + 19Pr + 100Pr^3)$$

2. Experimental data to verify the analysis of Lykoudis for Peclet numbers greater than 1000 and Prandtl numbers less than 0.02 should be an objective of experiments in a general study of heat transfer with liquid metals.

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National Aeronautics and Space Administration
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APPENDIX

c_p	specific heat, Btu/(lb mass)(°F)
D	tube diameter, ft
f_1,f_2,f_3	functions
G	mass velocity, lb mass/(hr)(sq ft)
h	heat-transfer coefficient, Btu/(hr)(sq ft)(°F)
k	thermal conductivity, Btu/(hr)(ft)(°F)
Nu	Nusselt number, hD/k, dimensionless
Pe	Peclet number, RePr, dimensionless
Pr	Prandtl number, $\mu c_p/k$, dimensionless
Re	Reynolds number, GD/μ, dimensionless
St	Stanton number, Nu/PrRe, dimensionless
θ	Prandtl factor, 1/(1 + Pr), dimensionless
μ	fluid viscosity, lb mass/(hr)(ft)
σ	analytical diffusivity ratio, dimensionless
σ^*	empirical diffusivity ratio, dimensionless

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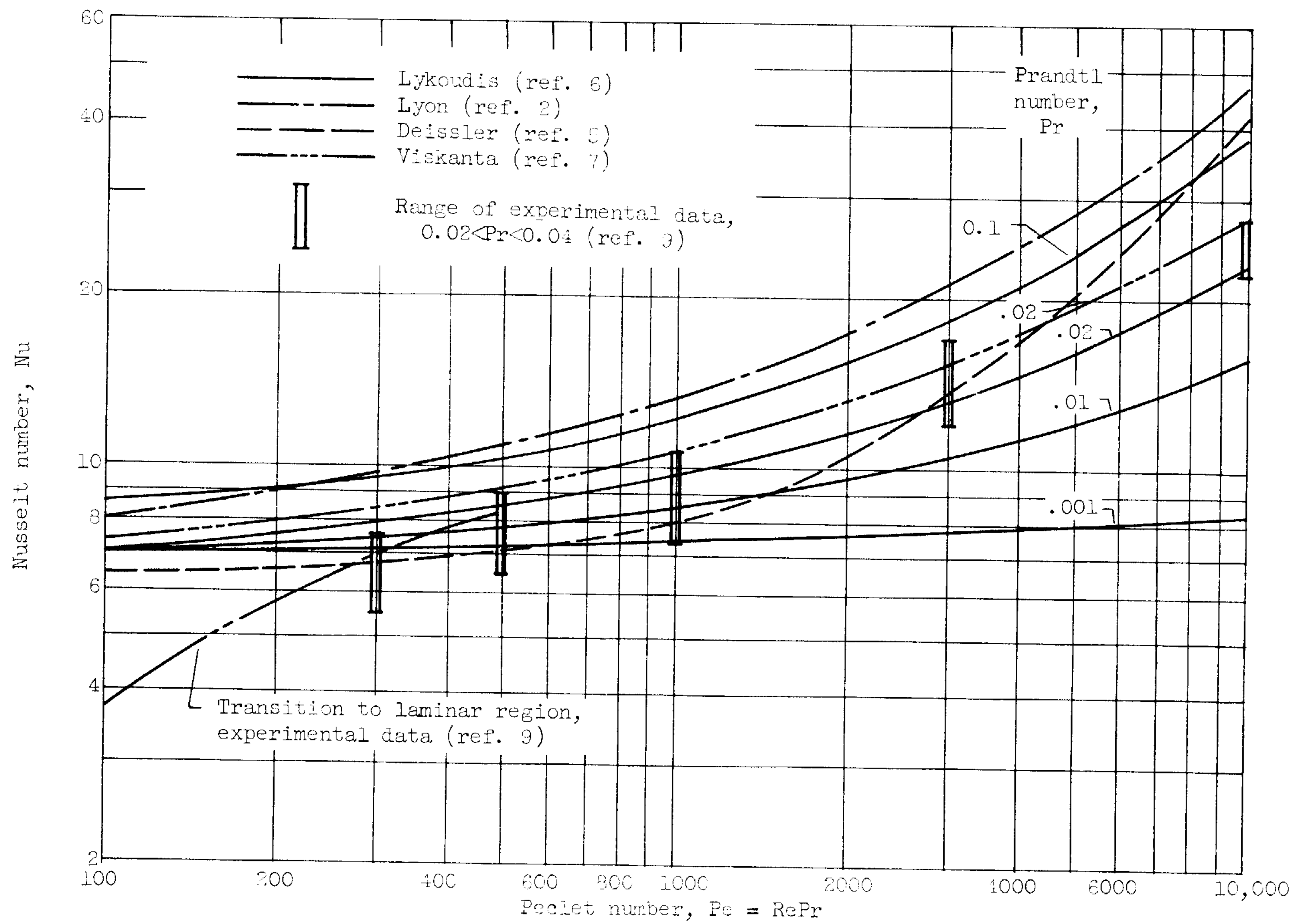

Figure 1. - Comparison of Nusselt number variation with Peclet number and Prandtl number from analytical convective-heat-transfer studies and experimental data.

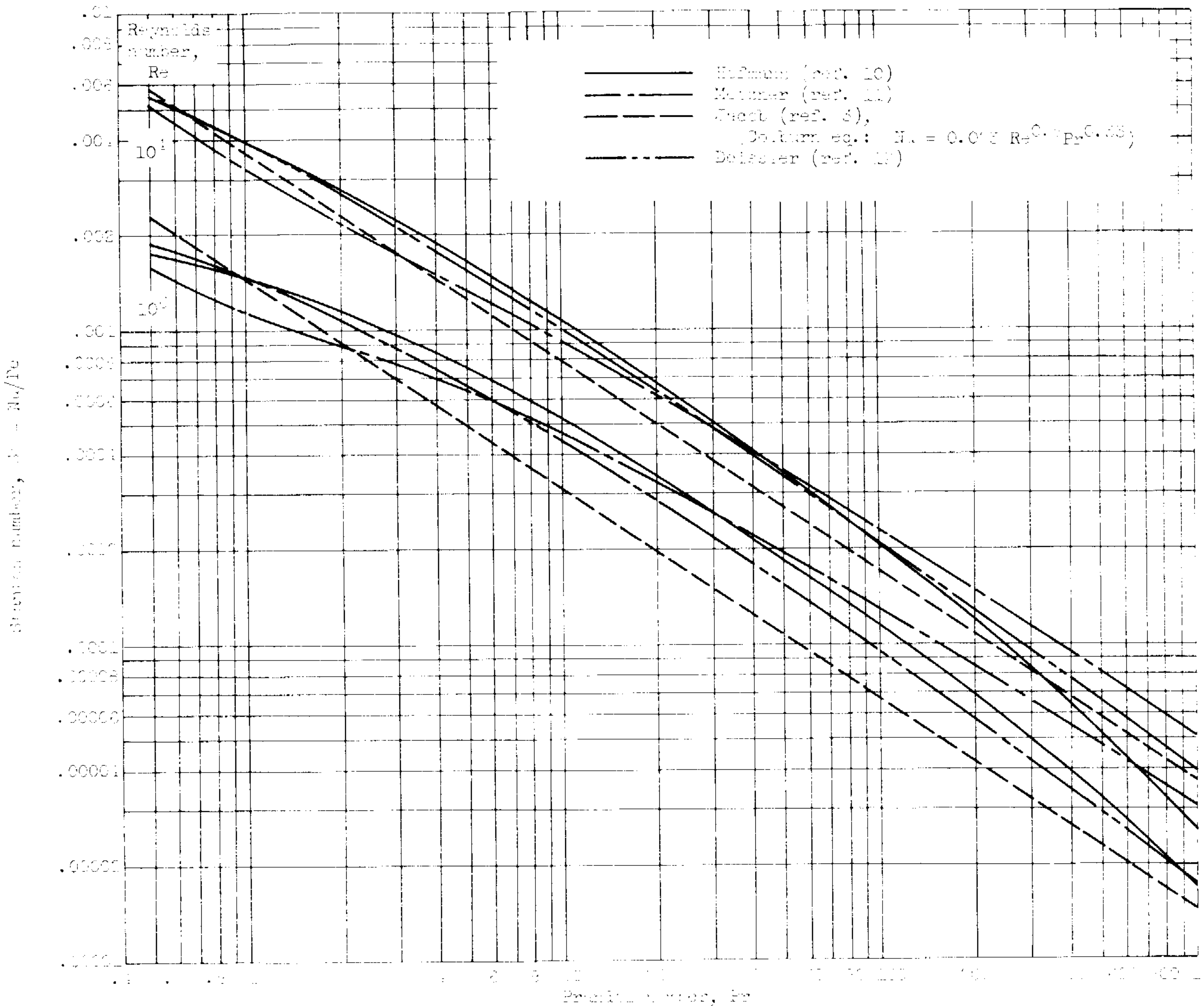

Figure [illegible]. - [illegible] Prandtl number [illegible] of Hofmann, Martinelli, [illegible], and Deissler.

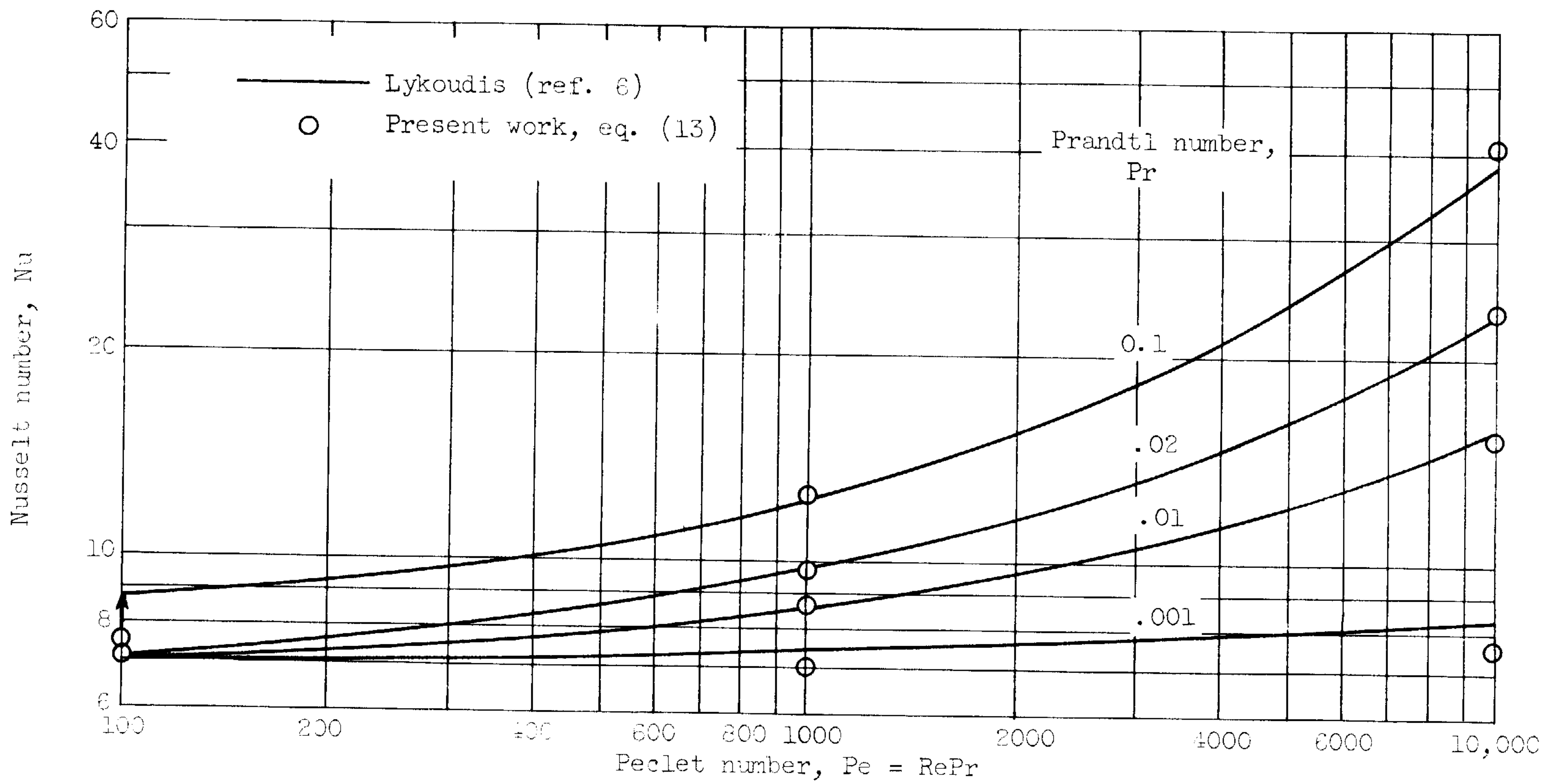

Figure 3. - Comparison of Nusselt number variation with Peclet number from analysis of Lykoudis with present work.

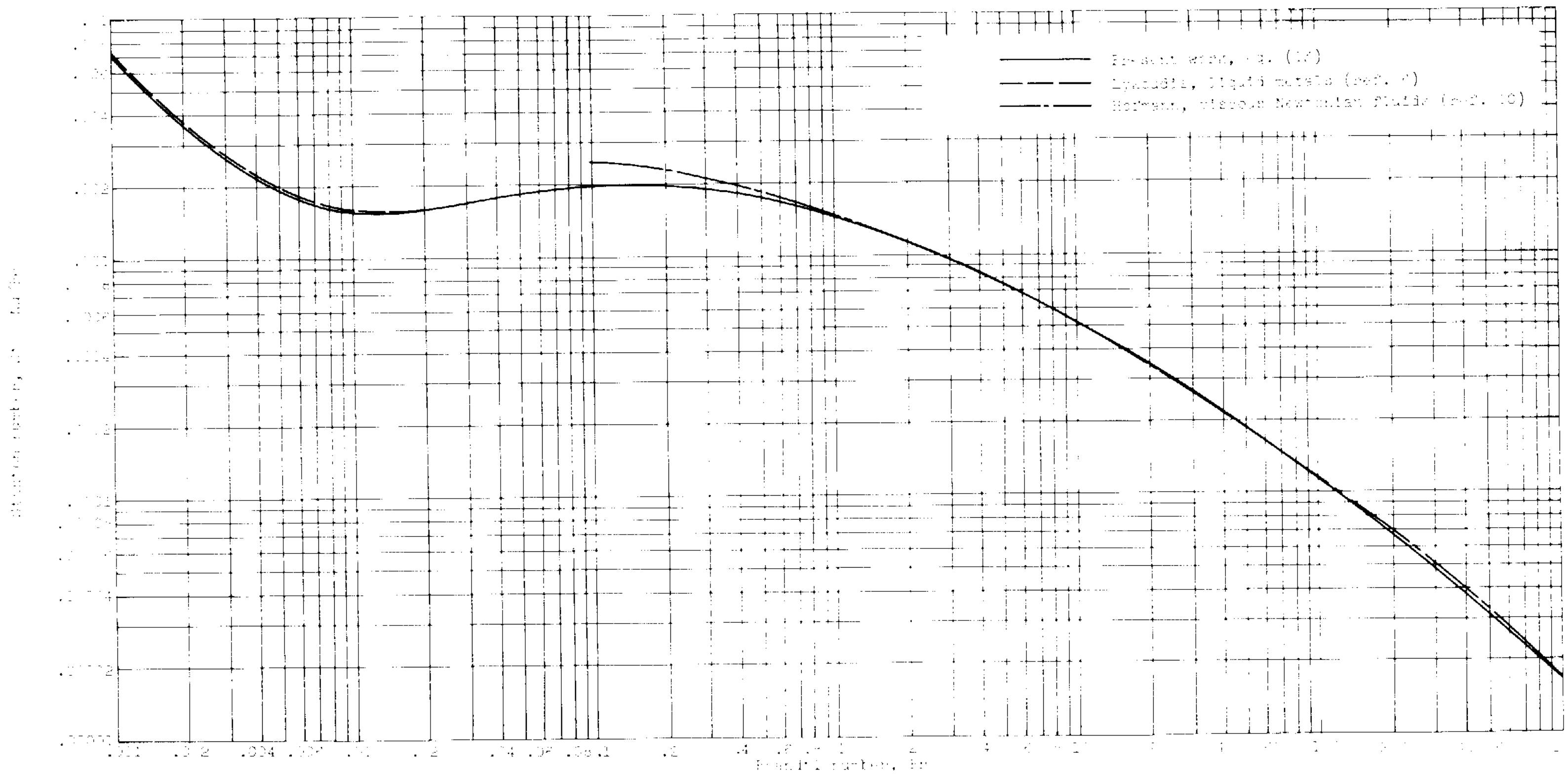

Figure 4. - Comparison of Stanton number variation with Prandtl number from analyses of Lyon... and Hormann... [illegible]
Reynolds number, Re, [illegible].

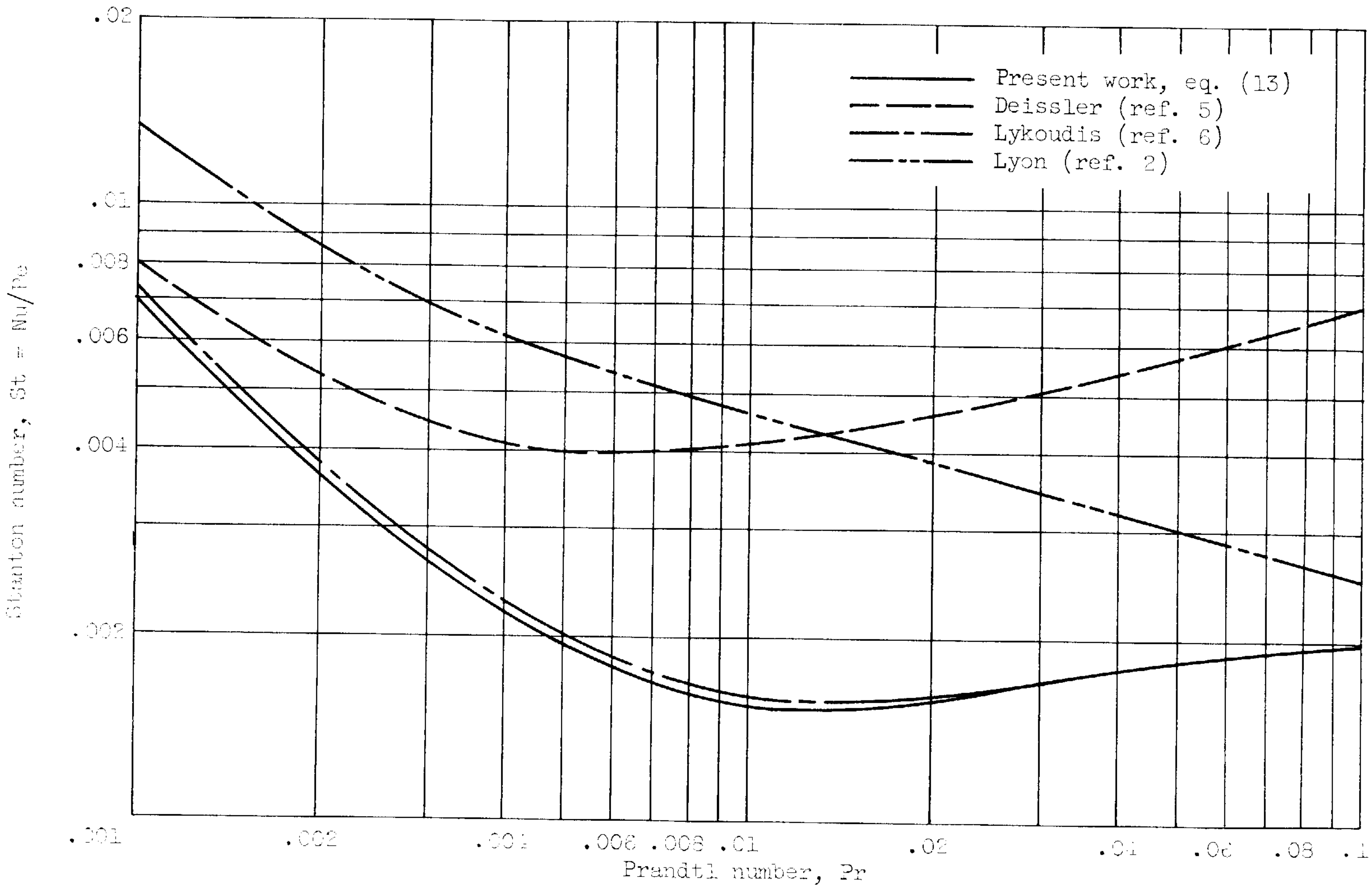

Figure 5. - Comparison of Stanton number variation with Prandtl number from analyses of Lykoudis, Lyon, and Deissler with values calculated from equation (13). Reynolds number, Re, 10^6.

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