Sharp entry and transition effects for laminar combined convection of water in vertical tubes

G. S. Barozzi*, A. Dumas* and M. W. Collins†

In previous work the authors showed a sharp entry to have a definite effect on laminar forced convection to water in a vertical circular tube. The study has been extended to situations of strong aiding natural convection, and new experimental data and numerical predictions are reported. The expected entry effect is confirmed, but it is found to be less marked in a strong combined convection field than in the previous forced convection study. The experimental data also include evidence of transition from laminar flow, and a possible criterion of transition is investigated, based on the axial location of minimum local Nusselt number. This is shown to be consistent with some results obtained by Kemeny and Somers. Fresh experimental and predictive data for this criterion are compared with the experimental correlation of Lawrence and Chato based on a criterion of temperature fluctuations

Keywords: *convection, entry effects, fluid flow*

In recent publications Barozzi *et al*[1] and Collins[2] postulated that an abrupt (as opposed to smooth) entry affected the laminar flow-field and heat transfer in a circular tube. This hypothesis may be stated as follows. The sharp entry results in 'necking' of the streamlines, so that separation occurs and a recirculation region forms (Fig 1). The centre-line velocity for this sharp entry is therefore higher than it would be for a smooth entry in this region. Reattachment would also occur, however, and the flow development would then be expected to follow the smooth entry case. These flow-field changes also affect heat transfer and experimental data for the sharp entry of Barozzi *et al*[1] were compared by Collins[2] with corresponding numerical predictions, but for a smooth entry. Relative to a smooth entry, the sharp entry firstly appears to increase heat transfer, then further downstream decreases it. Eventually, experiment and predictions converge, leading to the expected conclusion that heat transfer far from entry is independent of the entry geometry.

This hypothesis is supported by other previously published data. In the written discussion to Collins' study[3] of adiabatic developing flow, Lockett[4] reported flow separation with sharp entry tubes for Re above about 1000. Later, Collins[5] found a consistent effect when comparing predictions with experimental data of Martin and Fargie[6]. The experiment used a sharp entry whereas predictions assumed a smoothed entry. The centre-line velocity was initially above the predicted level, slowly converging to it downstream. The heat transfer comparison was also consistent with that postulated above.

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Initially, the experimental value was higher than predictions, then there was a region where it was lower, followed eventually by convergence of the data further downstream (Fig 6 of Ref 5).

Barozzi *et al*[1] isolated the possible effect of entry geometry on heat transfer by considering any other factors which could affect standard constant property heat transfer. Two of these were temperature-dependence of viscosity and viscous dissipation. Also, since the experimental work involved the heating of water flowing vertically upward, it was appreciated that natural convection effects were probably present. Estimates of the effect on forced convection heat transfer were made using the Eckert and Diaguila equation (Ref 7, Eq. (10)) and the Metais and Eckert diagram[8]. However, these proved unreliable. Also, the equation given by Petukhov *et al*[9] was used; this predicted a maximum increase of 15% in Nu_x. Eventually, comparable numerical predictions were made by Collins[2]. The analysis and computer program used[10] allowed for all important effects, except that of the sharp entry. Since the analysis accommodated combined convection, it was possible to quantify it by comparative runs with and without the effect. In fact a maximum increase in Nu_x of about 40% was predicted. The general reliability of the predictions was confirmed, because of the

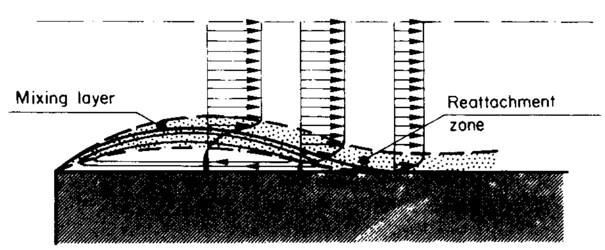


Fig 1 Postulated flow field at inlet to tube

convergence of experimental and predicted Nu_x at distances far from entry. This convergence was irrespective of the magnitude of the combined convection effect.

Certain runs of the original experimental investigation[1] displayed very high Nu_x values at large distances from entry; it was deduced that these runs were probably subject to strong natural convection effects and, therefore, they were separated from the main body of the data and not reported. Further consideration of these runs, and a second set of new numerical predictions, showed that the high Nu_x values could probably be identified with transition from laminar flow. The latter is a familiar phenomenon in laminar combined convection, and usually empirically defined in terms of temperature fluctuations[11]. Moreover, it should be noted that other general experimental data exist for combined convection of water in vertical tubes. The work of Lawrence and Chato[12], Scheele, Hanratty *et al*[11,13], and Kemeny and Somers[14] is relevant. Again, the reliability of the numerical analysis used here has been demonstrated by comparisons with these data[15,16]. In this study, then, we investigate the influence of substantial combined convection on the postulated entry effect. Also, we examine the question of there being an alternative transition parameter to the observable temperature fluctuations.

Experimental and theoretical methods

The methods used in this work are fully reported elsewhere[1,5,10] but, for the sake of completeness, are summarised here.

The experimental work used a test loop shown in Fig 2(a). The copper test section was 1.0 m in length and 10 mm in internal diameter. The entry geometry is shown in Fig 2(b), the contraction ratio being 26.5. The uniform wall heat flux distribution was provided by resistance heating, and mineral wool insulation reduced radial heat losses to below about 2%. Fluid bulk temperatures before entry and after exit, together with a good sample of wall temperatures, were measured with an accuracy of better than 0.1°C. The local Nusselt numbers have an assessed accuracy of about 10%.

The theoretical work used a treatment of the complete equations for two-dimensional laminar flow and heat transfer in a circular duct. Temperature dependence of viscosity, viscous dissipation, the axial effect of natural convection, and additional property variations are accommodated. Hence the method is appropriate for the current study. Finite difference approximations were used, together with Gaussian elimination of the simul-

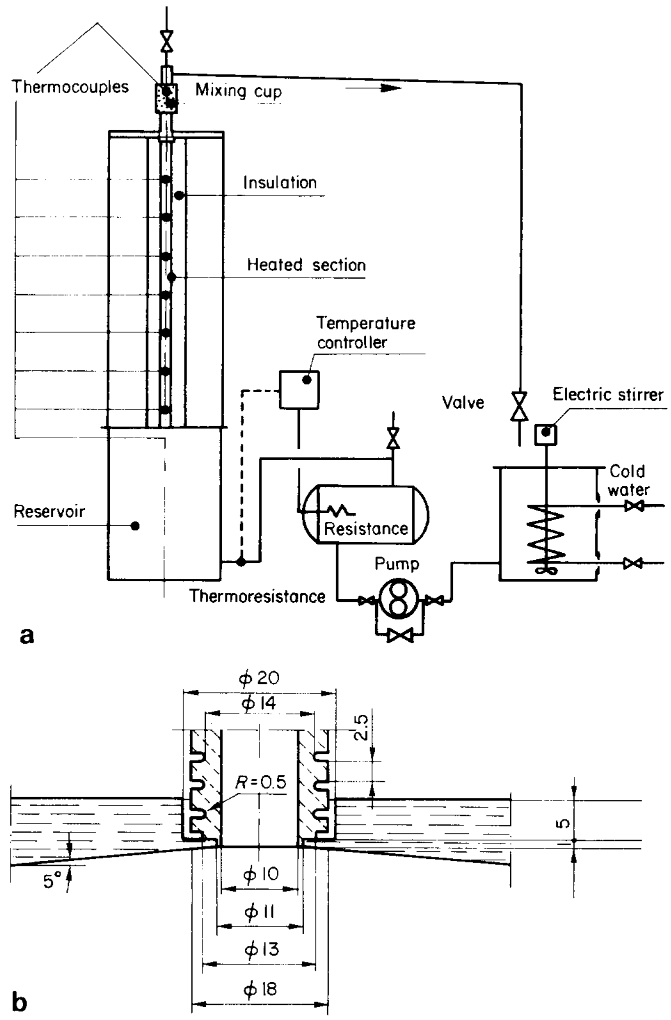


Fig 2 Experimental apparatus (a) Test installation; (b) Geometry of inlet

Notation

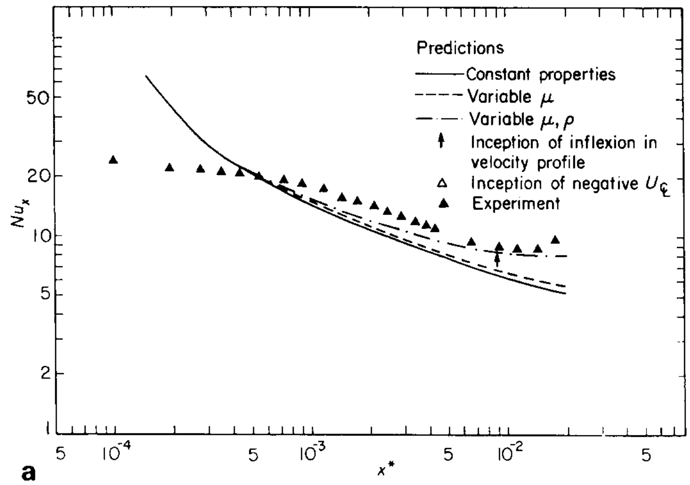
c	Specific heat of the fluid at constant pressure, J/kg K
D	Inner pipe diameter, m
g	Gravitational acceleration, m/s^2
Gr_R	Grashof number based on radius, $\beta R^4 gq/(\nu^2\lambda)$
Gr	Grashof number based on diameter, $\beta D^4 gq/(\nu^2\lambda)$
h	Convective heat transfer coefficient, W/m^2 K
Nu_x	Local Nusselt number, hD/λ
Pr	Prandtl number, $\mu c/\lambda$
q	Wall heat flux, W/m^2
r'	Radial coordinate, m
r	Non-dimensional radial coordinate, r'/R
R	Inner pipe radius, m
Re	Reynolds number based on diameter, $U_m D/\nu$
Re_R	Reynolds number based on radius, $U_m R/\nu$
U	Fluid velocity, m/s
U_m	Mean fluid velocity, m/s
x^*	Non-dimensional axial coordinate, $x/(DRe_m Pr_m)$
x'	Axial coordinate, m
x	Non-dimensional axial coordinate, x'/R
β	Coefficient of thermal expansion, K^{-1}
λ	Thermal conductivity of the fluid, W/mK
μ	Dynamic viscosity of the fluid, kg/ms
ν	Kinematic viscosity of the fluid, m^2/s

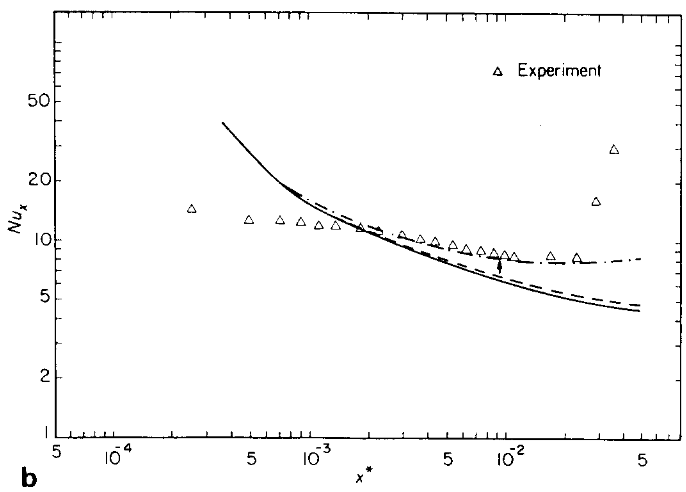
Subscripts

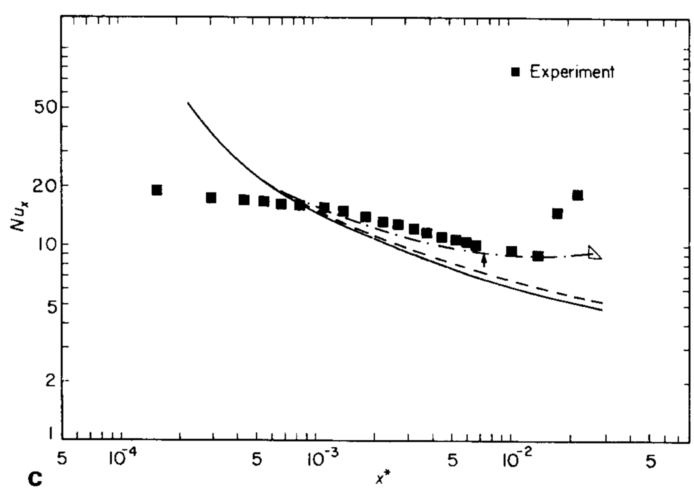
℄	Centre-line
L	Properties evaluated at position of minimum Nu_x
m	Properties evaluated at mid-tube position
o	Properties evaluated at tube entry

Table 1 Experimental data

Run	Re_m	Pr_m	Gr_m/Re_m	Inlet temperature, °C	Heat flux, kW/m^2
1	847	4.96	1487	26.3	12.84
2	344	4.81	1799	26.5	5.79
3	607	4.55	2518	26.9	12.20
4	938	4.39	3163	26.1	21.55
5	864	4.18	3980	26.1	22.00
6	412	3.87	5516	27.1	12.00
7	721	3.78	6120	27.5	22.00







taneous equations, and a marching procedure in the axial direction. The step-wise energy balance was a constraint on the solution. Predictions using the computer program have been compared with varied experimental and theoretical data, and in virtually all cases the accuracy has been very good.

Experimental and theoretical comparison

Seven typical sets of experimental data are reported here and defined as in Table 1 in order of increasing Gr_m/Re_m. For each run, predictions were made assuming a uniform inlet velocity profile. The following schemes were used:

(A) Constant properties, with *Re* and *Pr* set at their experimental inlet values.
(B) As (A) but allowing μ to vary with temperature.
(C) As (B) but allowing ρ to vary with temperature; this forms a combined convection case.

The heat transfer data are presented as before (Ref 2, Fig 1) for ease of comparison. Figs 3(a)–(d) give Nu_x — x^* plots for Runs 1, 2, 3 and 6 respectively. These show results for all schemes and experiment. Figs 4(a)–(d) respectively give predictions of centre-line velocity development for the corresponding runs of Fig 3. The order of runs indicates also the progressive effect of combined convection upon the developing flow-field.

From Figs 3(a)–(d) three axial regions of interest are evident. There is firstly an overprediction, then an underprediction of heat transfer, followed in general by very high experimental Nu_x. The first two regions are consistent with the first set of data given in Fig 1 of Ref 2. Hence, the influence of the sharp-edged entry is again confirmed by the comparison of predicted and experimental heat transfer. Table 2 summarises the various predicted effects for all runs at an axial location chosen upstream of the high Nu_x values.

Firstly, the effect of allowing μ to vary with temperature is relatively modest, but certainly not negligible. The first results displayed the same behaviour[2]. Also, this is confirmed by the corresponding effect on the flow-field in Figs 4(a)–(d). There the constant property curves

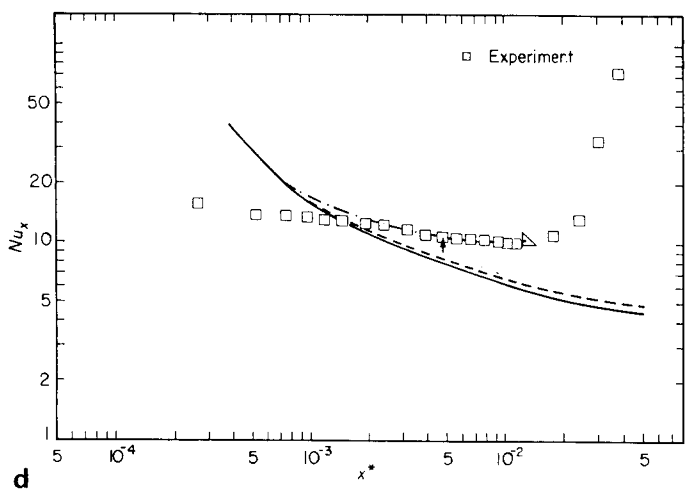
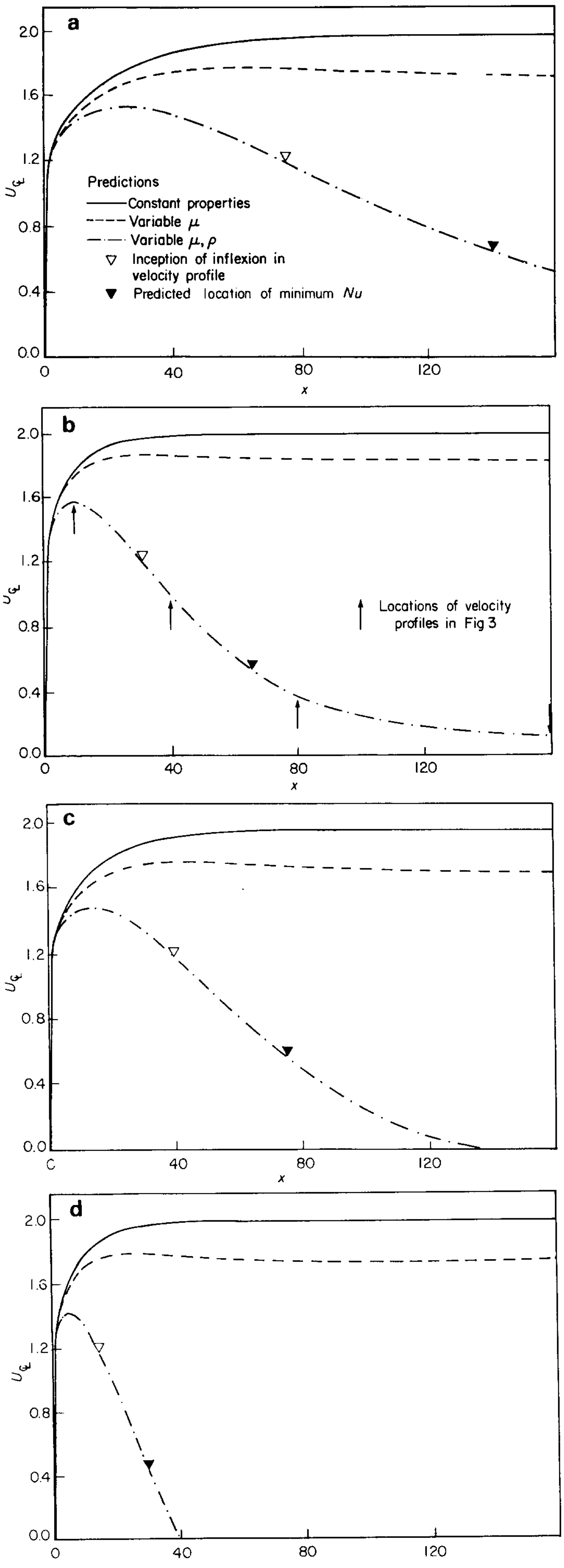


Fig 3 Heat transfer comparisons: (a) Run 1, Re_m *— 847,* Pr_m *— 4.96; (b) Run 2,* Re_m *— 344,* Pr_m *— 4.81; (c) Run 3,* Re_m *— 607,* Pr_m *— 455; and (d) Run 6,* Re_m *— 412,* Pr_m *— 3.87*



display hydrodynamic development well within the first half of the duct. The effect of variation of μ on these curves is definite and indicates it should certainly be accommodated in any analysis. This directly confirms the conclusion reached by Greene and Scheele[17] in exactly the same context that 'the constant viscosity analysis is clearly inadequate'.

Again from Table 2, the effect of allowing ρ to vary is very substantial in these runs, and indicates a strong influence of combined convection.

Quantitatively, Figs 3(a)–(d) show that the underpredictions of Scheme (C) here are much less than in Ref 2. Table 2 shows that in the majority of the runs an axial position is reached where experiment and theory agree.

The following reason is suggested for the closer agreement here. If a recirculation region is postulated near the entry, the downward fluid near the wall will be subjected to an opposed combined convection. This situation (Ref 13, p 73) leads to a sudden transition from laminar flow if the natural convection is sufficiently strong. In any case, however, it is logical to suggest that any recirculation would be weakened. Consequently there will be a more rapid recovery downstream to the condition which would have obtained with a rounded entry configuration. Summarising, any postulated sharp-edged entry influence is of less consequence in a strong combined convection field that in a forced convection field.

Transition from laminar flow

The final region of interest is the extreme downstream. Now Fig 3(a) is similar to Fig 1(a) of Ref 2, in that there is a recovery in Nu_x, which is more marked here. However, Figs 3(b)–(d) and runs not shown here all show very high experimental Nu_x which is a quite new feature. If the corresponding flow-fields in Fig 4 are examined, the reason for this is clear. All predictions of velocity profiles in this study show the development of a point of inflexion. This is exemplified by the set of developing profiles shown in Fig 5, which relate to indicated positions on Fig 4(b).

The significance of the point of inflexion has been discussed at some length by Scheele and Hanratty[11], and,

Table 2 Summary of predicted heat transfer at position of minimum experimental Nu_x

Run	Predicted increase in Nu_x: Due to μ $\frac{(B)-(A)}{(A)}\%$	Predicted increase in Nu_x: Due to ρ $\frac{(C)-(B)}{(A)}\%$	Scheme (C) Nu_x − experimental Nu_x $\frac{(C)-(EXPT)}{(EXPT)}\%$
1	7.44	36.25	−6.641
2	4.28	51.01	−4.912
3	7.00	46.16	−0.762
4	9.90	40.96	−0.301
5	10.23	58.84	+4.624
6	6.42	66.33	+2.201
7	9.95	70.28	−5.547

Fig 4 (left) Centre-line axial velocity predictions (a), (b), (c), (d) as for Fig 3

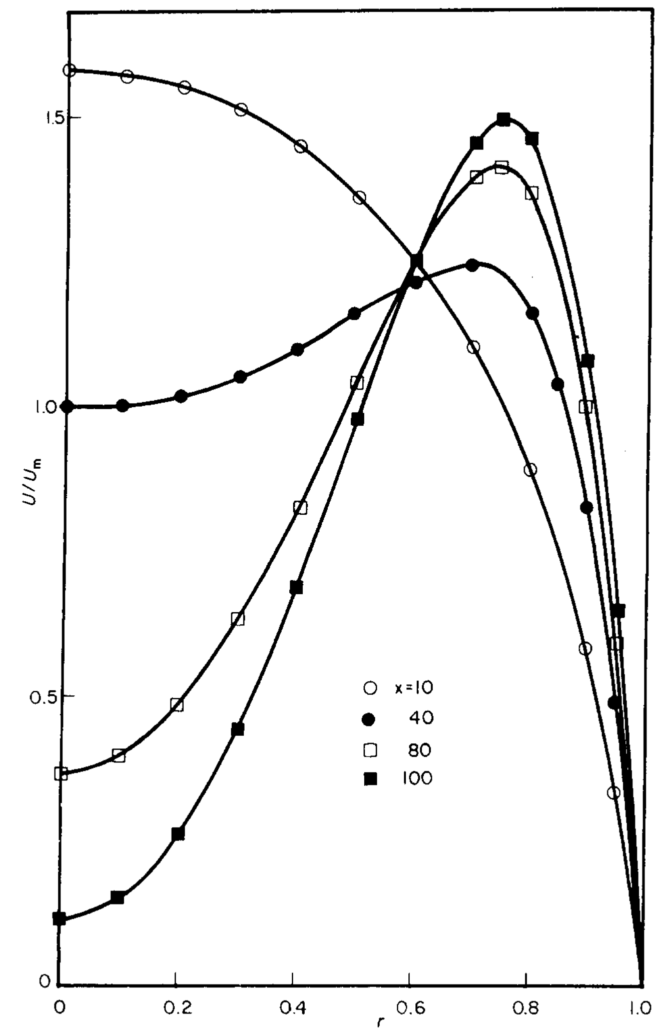


Fig 5 Developing axial velocity predictions for Fig 4(b)

for example, by Lighthill[18]. A major conclusion of Ref 11 (p 244) is that instability of flow is first associated with a point of inflexion in the axial velocity profile. Transition from steady laminar flow is associated with the growth of small disturbances, which however require a certain length before becoming observable.

This question of observability is of some significance. In fact, Scheele and Hanratty *defined* transition as the condition for which fluctuations in the fluid temperature at outlet‡ were first observed, a temperature difference of 0.1°C being the minimum observable. Lawrence and Chato[12] used a similar qualitative definition, but with a fluctuation minimum of 0.05°F (Fahrenheit). The later work of Greene and Scheele[17] retained the definition but without giving a precise minimum.

The question then arises of there being any alternative criterion for transition. Lawrence and Chato[12] correlated the velocity profiles which existed at experimental transition, and obtained a 'functional' transitional parameter. This parameter depended on the wall viscosity, the centre-line and maximum axial velocities, and the radius value for the latter. The transition parameter was presented in Fig 9 of Ref 12 as an unique function of entrance Reynolds number. There is, however, no real analytical justification for this, and Collins showed in Fig 7 of Ref 16 that it did not correlate the data of Scheele *et al*[11,13]. It was concluded by Collins[10] that it was inadequate as a transition criterion. In this connection, Fig 4 shows that at the axial location of minimum Nu_x, say, the centre-line velocity is not really constant. Hence, there is insufficient evidence to use the flow-field to define transition.

Minimum Nu_x correlation

An alternative to observable temperature fluctuations is to use the heat transfer results. Fig 3 shows that not only do analysis and experiment agree on the magnitude of the local Nu, but also on its location. Further downstream, the laminar theory predicts a slight increase, but the experimental results are much higher. It should, of course, be noted that this agreement between theory and experiment downstream of the position of velocity profile point of inflexion, implies that instability has not yet developed appreciably. Also, we might suppose that the agreement for minimum Nu implies that it may occur upstream of a position where observable fluctuations arise in the fluid temperatures.

These heat transfer effects are consistent with a discussion by Kemeny and Somers[14] using some experimental wall temperature data + for combined convection for oil. They concluded that transition to nonlaminar flow is normally indicated by either a reversal in wall temperature, or a smaller rise in temperature than expected, as distance from entry increases. The minimum Nu_x suggestion is qualitatively consistent with this.

It is, perhaps, unfortunate that Kemeny and Somers do not give a correlation of their transition data, possibly because the parallel analytical work was never published[19]. Hence to investigate the alternative the data of Lawrence and Chato[12] must be used. They correlated their experimental data in terms of G_R/Re_R and a dimensionless axial length, and their curve is reproduced in Fig 6. Also shown are experimental and more comprehensive predictive data for the present work, based on minimum Nu_x. For (Gr_R/Re_R) between about 75 and 200 the two alternatives agree. For the current experimental range (values above 200) the distances are less than those of Lawrence and Chato, as suggested above. However, where Lawrence and Chato's correlation becomes very flat, with a cut-off value of (Gr_R/Re_R) of about 50 below which transition was not detected, the current predictions continue to give a minimum Nu_x. For (Gr_R/Re_R) below about 30, current predictions do not possess a profile inflexion. The minimum Nu_x values so obtained precede small increases in a virtually fully-developed thermal field at long downstream distances. They cannot therefore be attributed to a transition condition; the points so obtained are specially marked on Fig 6, and should be ignored. For (Gr_R/Re_R) between 30 and 50, both profile inflexions and Nu_x minima are predicted unlike Lawrence and Chato's measurements. This may mean that the suggested correlation is unreliable in this range, or it may mean that any temperature fluctuations are too small to measure. However, undoubtedly the minimum Nu_x does correlate in a similar manner to the experimental tem-

‡ The method used in Refs 11 and 12 was to fix the heat flux, then gradually reduce the flow rate until temperature fluctuations were observed at a particular thermocouple position

+ Data which, incidentally, are compared with predictions of Collins up to the transition region, in Fig 4 of Ref 15

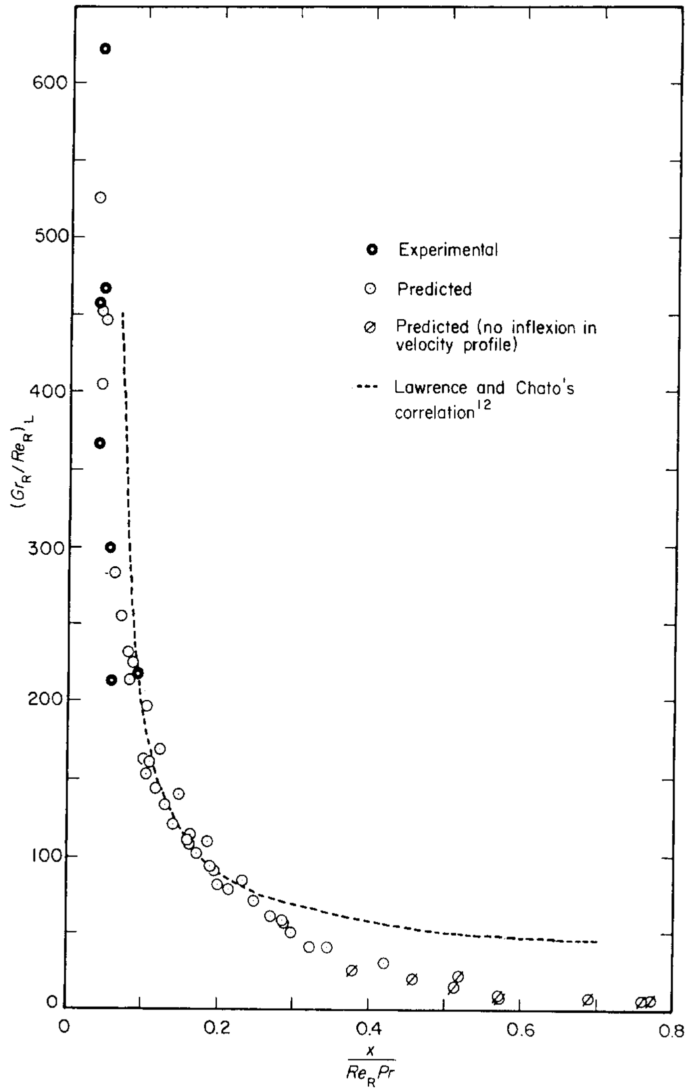


Fig 6 Comparison with correlation of Lawrence and Chato

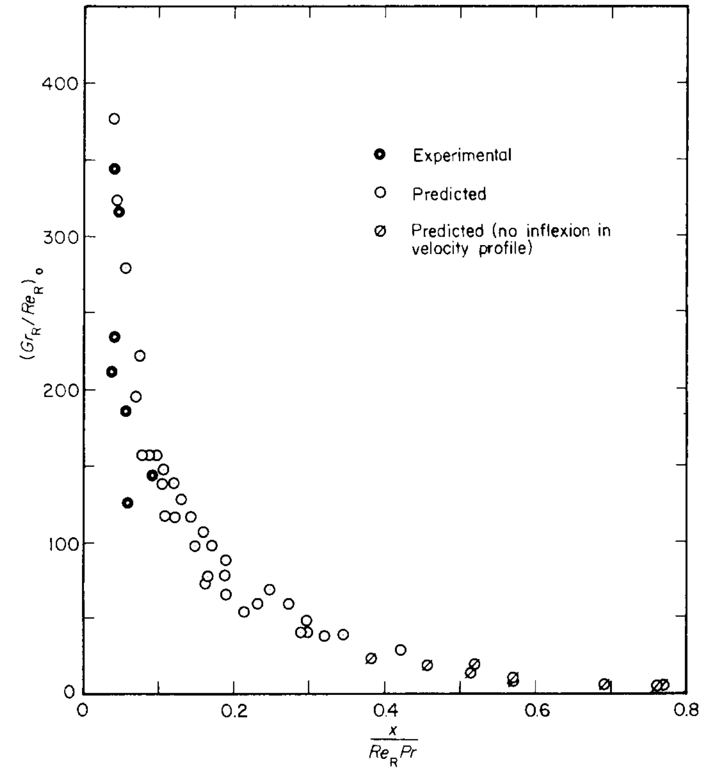


Fig 7 Alternative correlation using entry property values

perature fluctuations and its advantage is that it is predictable. Also, upstream of this condition the flow is always laminar.

In an attempt to make the correlation still easier to use, Fig 7 presents the same (currently-reported) data based on entry conditions only. However, the scatter has substantially increased, and the property base of Fig 6 is preferable.

Conclusions

A comparison has been made between data from experiments of Barozzi *et al* and the numerical analysis of Collins, for upward flow of water under strong combined convection conditions. The effect on heat transfer of an abrupt convergence is confirmed, but it is of less importance in a strong combined convection field than in a forced convection field. In addition, there is closer downstream agreement with theory, the latter of course being based on a rounded entrance configuration. Finally, the very high experimental Nu_x values obtained for large distances from entry are consistent with the occurrence of transition from laminar flow. This is on the basis of the growth of small disturbances from an unstable point of inflexion developing in the velocity profile. These points of inflexion are predicted by the theory.

Experimental transition data are usually based on temperature fluctuations. It is shown that a minimum Nu_x correlation is a possible alternative over a wide range of (Gr_R/Re_R), and is consistent with data of Kemeny and Somers.

Future work is intended to include varying the entry geometry to give an optimum for heat transfer. Also fluids should be tested of higher Prandtl number, and then of non-Newtonian flow characteristics.

Acknowledgements

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BOOK REVIEW

Fundamentals of Heat Treatment in Fusion Energy Systems

Eds M. S. Kazimi and O. C. Jones Jr.

This publication covers six papers presented at the 21st National Heat Transfer Conference, held in Seattle, USA, in July 1983. The papers are so specialised and cover such diverse topics that no attempt has been made to comment on their technical content. The papers are:

(1) 'Some thermal hydraulics aspects of the impurity control system for FED/INTOR (Fusion Engineering Device and International Tokamak Reactor)' by Y. S. Cha, R. F. Mattas, M. A. Abdou and J. R. Haines.

The paper is in two parts, dealing with temperature calculations for the limiter and divertor and an analysis of the tangential motion of the melt layer during plasma disruption.

(2) 'Experimental study of the enhancement of critical heat flux using tangential flow injection' by J. Weede and V. K. Dhir.

Describes an investigation of the critical heat flux condition in sub-cooled flow of Freon-113 through short vertical tubes and also local flow injection as a means of CHF enhancement.

(3) 'Review of sub-cooled flow boiling critical heat flux (CHF) and its application to fusion systems, Part 1: Fundamentals of CHF' by R. D. Boyd.

A survey covering the last 30 years of only CHF in the sub-cooled flow boiling regime. A summary of the fundamentals is followed by a discussion of mechanisms and the large number of relevant parameters is enumerated (134 references).

(4) 'Review of sub-cooled flow boiling critical heat flux (CHF) and its application to fusion energy system components, Part 2: Microconvective, experimental and correlational aspects' by R. D. Boyd.

Summarizes microconvective, instability, experimental and correlational aspects of CHF (124 references).

(5) 'Thermal performance of thermionic diodes for fusion power production' by J. F. Stubbins.

Shows that fusion product heating can be used to heat thermionic emitters to 2000°K at which temperature higher efficiencies are possible.

(6) 'Thermal analysis of a helium-cooled, tube-bank blanket module for a tandem mirror fusion reactor' by R. W. Werner, M. A. Hoffman and G. L. Johnson.

Describes the analytical model used to select the best tube bank design parameters. The blanket uses solid Li_2O as the Triton breeding material contained in tubes arranged as a two-pass cross-flow heat exchanger.

The papers are clearly written and well illustrated but inevitably will be of very limited interest.

B. N. Furber
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