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Interaction of free and forced convection in horizontal tubes in the transition regime

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Experimental investigations of the heat transfer by combined free and forced convection to water in a horizontal tube with a uniform heat flux have revealed many interesting features of the transition from laminar to turbulent flow. Fluctuations in fluid temperature and overall pressure drop variations facilitated the study of the transition regime.

The first phase of the experiments studied the extreme cases of combined forced- and free-convection transition regimes. For forced convection without heat transfer (isothermal flow) the results compared well with the existing data, predicting a transitional Reynolds number of about 2300. For free convection with no flow, the records of temperature fluctuations during transient heating indicated the transition regime.

In the second phase, extensive measurements were made for the combined forced- and free-convection case. A plot of the Reynolds number against the Rayleigh number Ra_q enabled the present results ($L/D = 150$) to be compared with those of Petukhov & Polyakov (for X/D ratios 40 and 100).‡ The results show that beyond transition two types of turbulence – hydrodynamic and thermal – can be distinguished depending on whether the fluctuations are predominantly in velocity or in temperature. For large values of Re and Ra_q these two regions merge into turbulent, combined free and forced convection.

In the transition regime two types of flow are encountered: unstable flow characterized by pulses and a stable flow with stable fluctuations. While a curve in the plot of heat input *vs.* flow velocity demarcates the two regimes, the main features of transition are described by means of an intermittency factor defined as the ratio of thermal fluctuation at any point to a corresponding magnitude of thermal fluctuation on the demarcating curve.

The iso-intermittency lines drawn in the transition envelope assist in describing the structure of transition. The concentration of these lines at the central area of the envelope indicates the region of maximum coupling between thermal and hydrodynamic effects.

A qualitative study of inlet turbulence confirmed the prediction of Mori *et al.* for air. The results presented here along with those of Mori *et al.* and Petukhov & Polyakov indicate that thermally induced secondary flows attenuate the

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‡ X = length from the start of flow; L = effective length of heated test section; D = inner diameter of tube.

fluctuations in low inlet turbulence flows, while they restabilize the flow as the inlet turbulence is increased. Also, the effect of inlet turbulence on transition to an unstable flow regime was studied. In general, an increase in the inlet turbulence brought about an increase in the critical Rayleigh number.

1. Introduction

Flow with heat transfer in tubes has been a subject of interest for many decades. With appreciable effects of heat transfer taken into account, the flow behaviour is decided by the orientation of the tube. Investigations with vertical tubes by Hallman (1958), Scheele (1962), Scheele & Hanratty (1962, 1963), etc., revealed the effect of heat transfer in influencing the shape of the axial velocity profiles. However, in the case of horizontal tubes, where the velocity and gravity vectors are at right angles to each other, secondary flows also arise as has been shown by Mikesell (1963), Mori *et al.* (1966), Newell & Bergles (1970) and Hussain & McComas (1970). Information has been collected and the system classified into three separate regimes, namely forced convection, combined free and forced convection, and free convection, by Gebhart (1961) and Metais (1960). Further, the works of Gill & Lee (1962), Mikesell (1963), Mori *et al.* (1966), McEligot *et al.* (1966), etc., brought forth many interesting features.

Although air has been used as the fluid medium in the bulk of the investigations in horizontal tubes, the recent work of Petukhov & Polyakov (1970) considered water. Their work described several boundary regimes of flow, distinguishing the laminar, transition, turbulent and backflow cases. Their work also discussed the effect of different X/D ratios (for $X/D = 40$–100).

In the present study extensive experimental investigations in the transitional regime of combined free- and forced-convection heat transfer to water in a horizontal tube were conducted under uniform heat flux conditions.

2. Experimental apparatus and techniques

Apparatus

Figure 1 (*a*) shows schematically the heat-transfer loop. Water from the overhead tank flows under gravity through an inconel tube (6 ft long, 0·25 in. in diameter and 0·01 in. thick), a cooler and a flow meter, finally discharging into a sump tank. The circulating pump delivers the cooled water in the sump tank back to the overhead tank through a demineralizer and a deionizer. The flow through the test section can be controlled by means of valves provided at the inlet of the test section and exit of the cooler. Adjusting the speed of the pump gives a constant head in the overhead tank and thus a uniform flow through the tube. By changing the flow rate of cooling water through the counterflow heat exchanger (cooler), the outlet temperature of water can be reduced to that in the overhead tank. Thus, control of inlet water conditions is possible. Two copper flanges at the ends of the test section avoid local heating while electrical power is supplied to heat the tube. A vacuum chamber surrounding the tube provides an effective insulation to the test section.

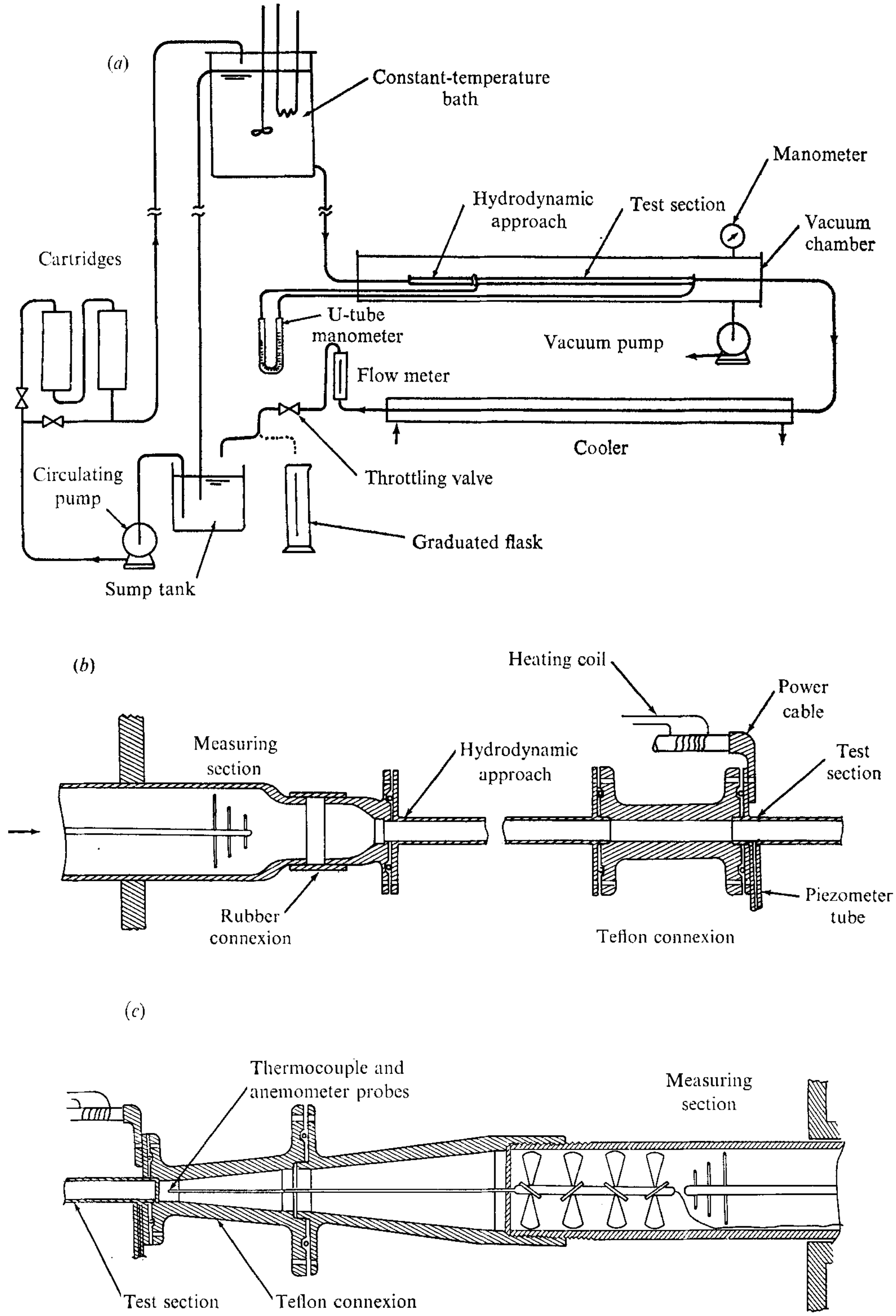

FIGURE 1. Apparatus. (*a*) Heat-transfer loop. (*b*) Inlet connexions. (*c*) Outlet connexions.

The details of inlet and outlet connexions are shown in figure 1 (*b*) and (*c*). Before the hydrodynamic approach of 60 diameters to the test section, a mixing chamber is provided to measure the bulk temperature of the inlet fluid. A similar one after the test section can be seen in figure 1 (*c*). A Teflon connexion separating the test section and the hydrodynamic approach reduces conduction losses. A set of copper coaxial twisted vanes (see figure 1 (*c*)) mounted on a steel tube is placed inside the mixing chamber to reduce the velocity of flow and thus measure the bulk temperature. Along the diffuser axis is shown the tube extending up to the exit end of the test section, where the thermocouple and anemometer measurements were made. More details are reported by Kupper (1968).

Measurements

The thermal measurements include heat input to the test section, the test-section wall temperatures and the inlet and outlet bulk fluid temperatures, along with temperatures for the counterflow heat exchanger. The heat input is measured by a watt meter and temperatures by a thermocouple, the e.m.f.'s being read by a universal potentiometer and a suspended galvanometer. For the transition fluctuations, a single-channel strip-chart recorder is used to obtain temperature–time records.

The quantity of water flowing through the tube was found by measuring the volume of water collected during a known time interval. The static pressure drop across the test section was measured by a U-tube manometer.

Detection of transition

Though visual methods have been used to detect transition in forced- and free-convection flows, they are, in general, unsuitable for obtaining quantitative information concerning the fluctuations (except in the case of schleiren and interferometric studies). Since transition is characterized by fluctuating quantities, measurements of these fluctuations give greater insight into transition-flow behaviour. Thus, the present set of experiments was devoted to recording the fluctuating signals. The signals may be a result of fluctuations in pressure drop across the test section, velocity or temperature. Though all these were measured, the temperature–time records, being a simple means for study, were the most extensive.

The pressure drop across the test section was measured using a U-tube manometer. With a low-density fluid immiscible with water used as the manometer fluid, the fluctuations were clearly noticeable. Large fluctuations indicated the onset of transition, while a large increase in pressure drop characterized turbulent flow in the pipe. Thus, the demarcation line between laminar and turbulent regimes could be established clearly. However, in the region characterized by temperature fluctuations in secondary flows caused by free convection, this method could not furnish the necessary information.

Temperature fluctuations could be easily measured and recorded. For this reason, extensive measurements of temperature fluctuations were made in the experiments. Wall temperature variations have been used by Kalinan & Yarkho

(1966) to detect transition. The thickness of the wall of tube may have a considerable effect in damping out these fluctuations. Hence, fluctuations of the fluid temperature were recorded by directly inserting thermocouple probes at the centre of the tube. The downstream end was selected for the position of the probe because the maximum effects of temperature and velocity fluctuations could thus be studied. A similar probe at the inlet end of the test section allowed the inlet fluctuations in temperature to be studied.

A hot-wire anemometer probe was used for studying the fluctuations in velocity at the downstream end of the tube. The fluctuations were fed on to a dual-beam cathode-ray oscillograph and photographed. However, only the number of photographs necessary to establish transition regimes was taken. Since the number of runs was large, and continuous recording was necessary, motion-picture photographs would have been uneconomical considering the amount of information that could be derived from them; therefore thermocouple recording was used.

3. The experiments

Calibration experiments and primary experiments were the two categories of experiments conducted. Details of the calibration of instruments such as thermocouples, the flow meter and the anemometer will be omitted for brevity. Runs conducted with a laminar flow of water under combined free and forced convection established the suitability of the rig for the study experiments.

To establish the suitability of the instrumentation and the methods previously described for the study of transition, the two extreme cases of combined convection, namely isothermal flow and heat transfer without flow, were investigated. Greater insight could be obtained as a result of this investigation.

The primary experiments were directed towards the study of the onset of transition, the oscillations and fluctuations during transition, the effect of inlet turbulence on transition, and relaminarization effects on the boundary regimes of flow. These will be described in the following sections.

Fluid flow without heat transfer

Methods of study of flow through tubes have been fairly well established in the literature. The experimental procedure consists of noting the pressure drop across the test section and the flow through the tube. The flow is increased step by step until fluctuations develop in the manometer, indicating transition. Each time the flow is increased, the pressure drop and the flow are measured. After the fluctuations start growing, a sudden increase in the pressure drop will indicate turbulence.

Further, in the present set of experiments, a method of detecting transition using a thermocouple was attempted. Though the flow was isothermal, when a high sensitivity recorder was used, the fluctuation during transition could produce fluctuating signals from a thermocouple probe. A typical record is shown in figure 2(*a*). It was interesting to note that both the pressure fluctuations on the manometer and the fluctuating signals from the temperature record occurred

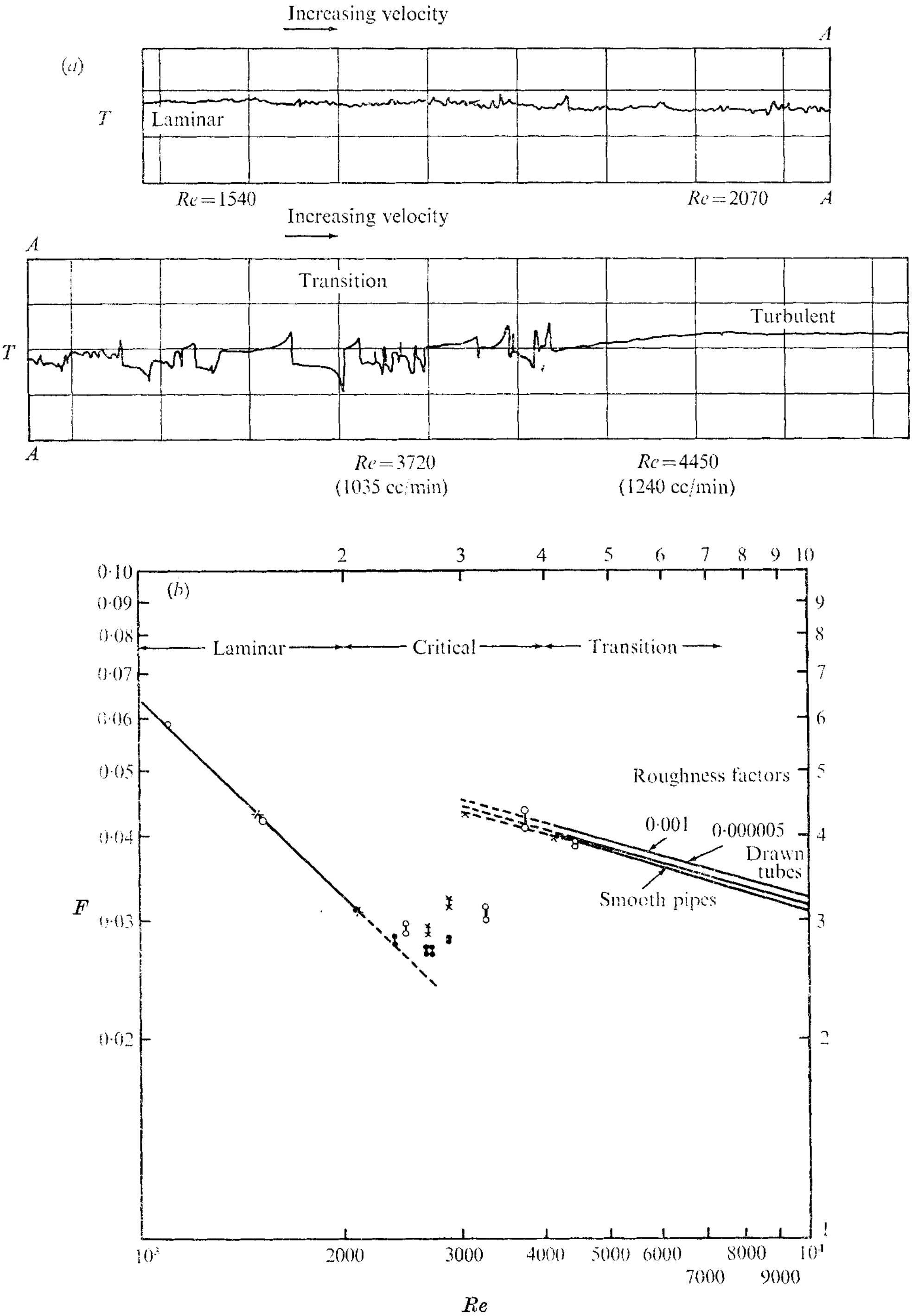

FIGURE 2. (a) Detection of transition in flow without heat transfer. (b) Comparison with results of Moody (curves). Present experiments: ○, without inlet probe (C_1); ×, with inlet probe (C_3); ●, with inlet probe and inlet copper disks (C_2).

Description	Critical Reynolds number
Results of Mori *et al.* (1966) (without turbulence generator)	7700
Present results	
Case C_1	4450
Case C_2	3200
Case C_3	3000
Results of Mori *et al.* (1966) (with turbulence generator)	1800

TABLE 1. Comparison of critical Reynolds numbers for flow without heat transfer

simultaneously. Further, it can be noticed that a small temperature drop accompanied each increase in the flow rate. However, the magnitude of this drop was of the order of 0·01 °C only. The fluctuations suddenly developed at transition and decayed gradually towards a uniform signal output at turbulence. The thermocouple probe at the inlet section did not show fluctuations.

The effect of inlet turbulence was studied qualitatively. Runs were performed without any obstruction at the inlet (C_1), with a holder for thermocouples placed concentrically with the mixing chamber at the inlet (C_2, see figure 1*b*) and with a thermocouple probe extending up to the inlet of the test section (C_3). Cases C_1, C_2 and C_3 were expected to introduce inlet turbulence. By referring to figure 1, it can be noted that case C_3 would cause considerable disturbance, which will be reflected in the results.

Figure 2(*b*) compares the present experimental results with those of Moody (1944). The three cases C_1, C_2 and C_3 are plotted. Very good agreement can be observed in the laminar region. For case C_1, the transition occurs at a much lower value of a Reynolds number† of 3000. The results for the turbulent region fall between the two lines for smooth pipes and drawn tubes with a roughness factor of 0·00025. The fluctuations in friction factor calculated by using pressure-drop readings are shown by vertical lines. A sudden decay of fluctuations at the turbulent regime can be observed.

Table 1 compares the present results of transition with those of Mori *et al.* (1966) to establish a clear picture of inlet turbulence. The results indicate clearly that the inlet turbulence accelerates transition and the present results fit between the extreme values of Mori *et al.* It may be recalled that they had used a violent turbulator to create turbulence at the inlet in their experiments.

Heat-transfer experiments with no flow

When water contained inside a closed tube is heated at the circumference, the temperature of the fluid increases continuously. Heat is transferred to the fluid from the tube by pure free convection. As the temperature increases with time,

† $Re = VD/\nu$, where ν is the kinematic viscosity of water and V is the mean velocity in the tube. $F = 2gD\Delta P/LV^2$, where ΔP is the pressure drop across the test section and g the acceleration due to gravity. Unless otherwise stated all properties are evaluated at mean tube-wall and bulk-fluid temperatures.

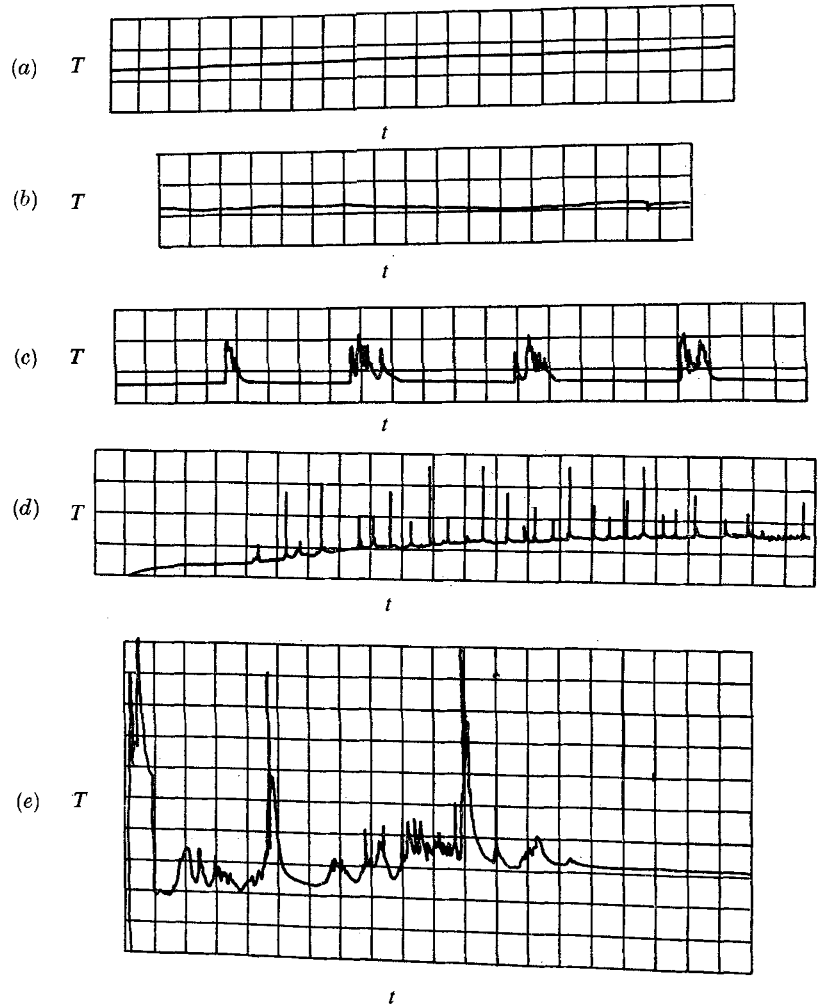

FIGURE 3. Temperature–time records for free convection. (*a*) $Q = 10$ W. (*b*) $Q = 20$ W. (*c*) $Q = 35$ W. (*d*) $Q = 50$ W. (*e*) $Q = 150$ W.

laminar transition and turbulent free convection exist during the transient heating. Ultimately one would reach the boiling stage. Depending on the rate of heating, the different regimes will exist for varying durations of time. In the present set of experiments temperature–time records were obtained for varying rates of heating during the entire transient periods. While, for very low rate of heating (like $Q = 10$ W†), the temperature–time history covered a long period, large heat inputs ($Q = 150$ W) caused boiling in a few minutes. Only those portions of the records which are relevant to the present development are chosen for brevity. The record from the temperature probe at the exit is taken to be representative of temperature fluctuations anywhere inside the test section for lack of better measurements.

Figures 3 (*a*)–(*e*) are for increasing heat inputs from 10 to 150 W. Figure 3 (*a*)

† Q = total heat input to the test section.

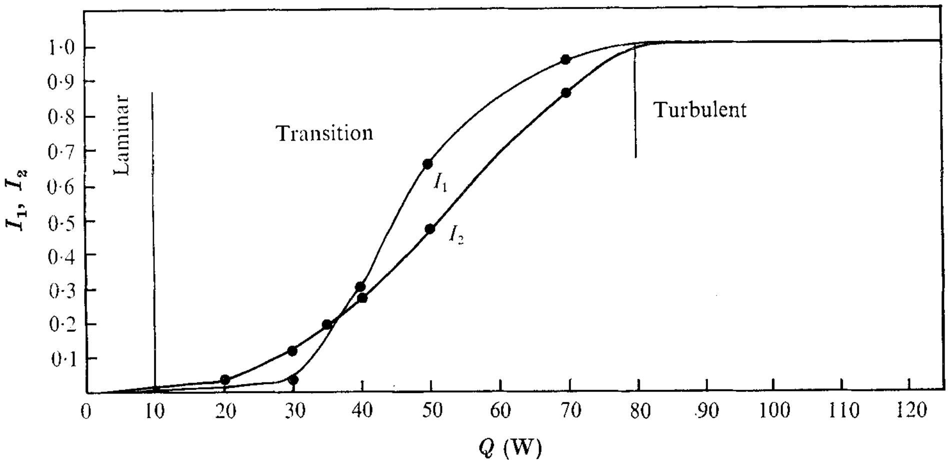

FIGURE 4. Free-convection transition regime.

shows very few fluctuations, and therefore the flow can be regarded as laminar. With the higher heat load of 20 W in figure 3 (*b*) a small pulse in temperature can be observed. This type of pulse may indicate the attenuation of disturbances in the fluid. These attenuated thermal pulses, which have larger amplitudes, can be observed in figure 3 (*c*). Further, the growth of the pulses with time may also be observed. In figure 3 (*d*), at 50 W, the temperature fluctuations are predominant in the flow field. The frequency of pulses has increased and the pattern is quite different from the earlier one of figure 3 (*c*). Figure 3 (*e*) shows violent temperature fluctuations, which indicate turbulence and boiling in the tube.

Thus, a picture of the flow situation can now be visualized. After the initial laminar regime, transition flow characterized by pulses leads to a turbulent structure. The probable reason for the oscillatory or the pulse flow may be attributed to the periodic cancellation and attenuation of fluctuations in secondary flow.

The results of the above set of experiments can be represented by defining an intermittency factor I_1 as the ratio of the time during which fluctuations exist to the total time during which measurements are made. The plot of I_1 versus the heat input to the test section in figure 4 shows that there is a steep increase in the value of I_1 for $30\,\mathrm{W} < Q < 70\,\mathrm{W}$ and there are asymptotic approaches at the beginning and end. This facilitates the classification of the entire region into laminar (case of no pulses), transition and turbulent regimes, as shown in figure 4. A factor I_2 defined as the ratio of the amplitude of fluctuation to that at transition is quite useful in presenting a quantitative measure of fluctuations encountered in transition. The variation of I_2 with respect to the heat input is shown plotted in figure 4 also. A close similarity between the two curves I_1 and I_2 suggests that the amplitude and frequency of pulsations are closely related. This may indirectly strengthen the explanation given earlier for the formation of pulses in the flow.

Primary set of experiments

As was emphasized earlier, exhaustive thermocouple records were taken to provide information in the different flow regimes. The present set of experiments was devoted to procuring greater insight as to the type of unstable and stable transitional flows.

4. Experimental procedure

The experiments conducted have been categorized into two sets. The first set involved increasing the flow at a fixed heating load. The continuous thermocouple records provided information about the transition. The flow rate was increased in steps and at each step we noted a decrease in the temperature of the fluid. After the temperature–time record showed negligible differences in mean temperature at different intervals, the flow rate was increased to a higher value. The transition was indicated by the thermocouple charts, pressure fluctuations and anemometer signals, and steady-state readings were taken. When the flow rate had been increased until the turbulent regime had been reached, it was decreased in steps to study the influence of reversed experimental conditions. These experiments were repeated for different heat inputs to the test section.

In the second set of experiments the heat input was increased at a fixed flow velocity. Thermocouple records of temperature versus time gave detailed information. The experiments were repeated for different flow velocities.

The above two series of experiments were repeated for the three types of inlet conditions, C_1, C_2 and C_3, mentioned previously. These results were obtained to study the effect of inlet turbulence on different transition boundaries.

Finally, the above sets of experiments were conducted in a region of very small Reynolds number. These experiments were performed at a range of Rayleigh numbers which were very low compared with those of Mikesell (1963), for which backflow conditions were observed.

5. Experimental results

Representative temperature–time records are presented in figures 5 and 6. Figures 5 (*a*)–(*d*) are typical records of the first set of experiments. Figures 5 (*a*) and (*b*) correspond to a constant heat load of 0·5 kW, while figures 5 (*c*) and (*d*) are for 1 kW. Further, figures 5 (*a*) and (*c*) are temperature–time records for increasing flow rates, while figures 5 (*b*) and (*d*) are for decreasing flow rates.

The data in figure 5 (*a*) were taken starting from a low velocity of 0·2 ft/s. The small fluctuations recorded indicate oscillations in the flow. A careful observation reveals small bands of temperature variations occurring periodically. However, the magnitude of these pulses is slightly greater than that of the average fluctuations. These fluctuations remain the same, more or less, even for a velocity of 0·674 ft/s. However, for 1·25 ft/s a clear amplification of fluctuations indicating transition can be observed. The region is characterized by fluctuations of large stable amplitude. Further increases of the flow to 1·61, 1·76 and 1·84 ft/s reduce

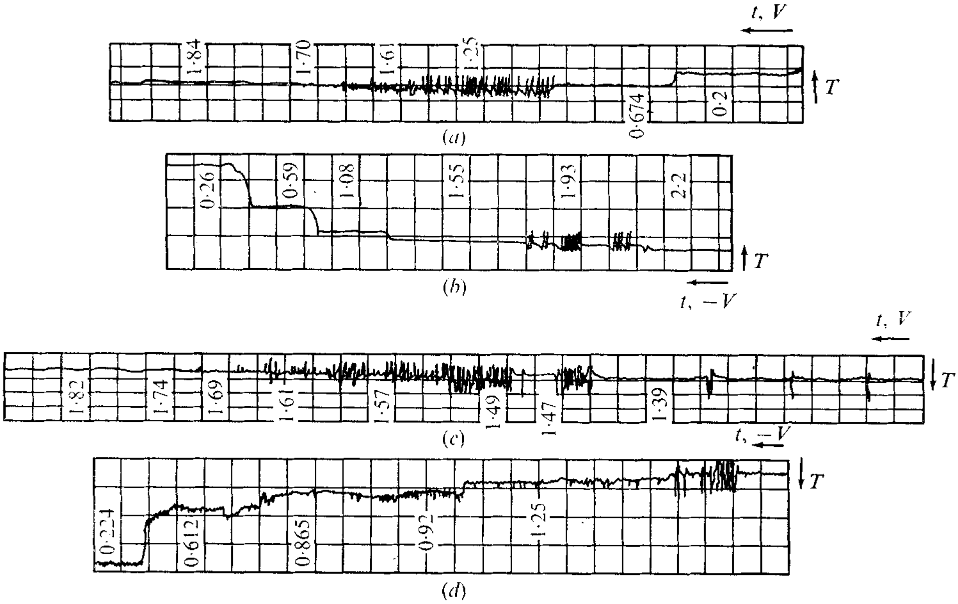

FIGURE 5. Temperature–time records for first set of experiments (fixed Q, velocity changing). t is time, V velocity (plus and minus signs referring to V increasing and decreasing respectively) and T is temperature. (a) $Q = 0{\cdot}5$ kW. (b) $Q = 0{\cdot}5$ kW. (c) $Q = 1{\cdot}0$ kW. (d) $Q = 1{\cdot}0$ kW.

the amplitude of fluctuations, eventually culminating in turbulent flow. Thus, a sudden transition from fluctuating flow and a gradual decay of fluctuations to hydrodynamic turbulence can be observed in figure 5(a).

Figure 5(c) illustrates the characteristics at a much higher thermal load of 1 kW. For velocities up to about 1·4 ft/s, periodic pulses can be observed. By recalling that this type of fluctuation was also encountered in pure free convection, it becomes evident that secondary flows have greater influence in this part of the transition regime. It is seen that the frequency of these periodic pulses increases with increasing flow rate, which finally results in a stable fluctuating regime. Also, in this regime of small amplitude fluctuations characterized by intermittent pulses, the amplitude of fluctuations grows with increasing flow rates. The variation of velocity is smaller than in figure 5 (a), where this stable transition exists. With velocities greater than about 1·8 ft/s there are no fluctuations in the system.

Figures 5(b) and (d) represent the temperature–time plots for the above two heat loads when the flow velocity is decreasing. These sets of experiments were conducted in an attempt to study the effect of relaminarization from turbulence. In general, it can be seen that transition occurs at a higher velocity range than those shown in figures 5(a) and (c). This effect of delayed transition reduces with higher heat load, as can be observed in figure 5(d). Further, the zone of pulse flow has been considerably reduced.

The results of the second set of experiments are illustrated through temperature–time records in figure 6. For a fixed velocity of 0·6 ft/s the heat rate was increased in steps up to about 1·3 kW and then decreased in steps as shown in figures 6 (a)–(c).

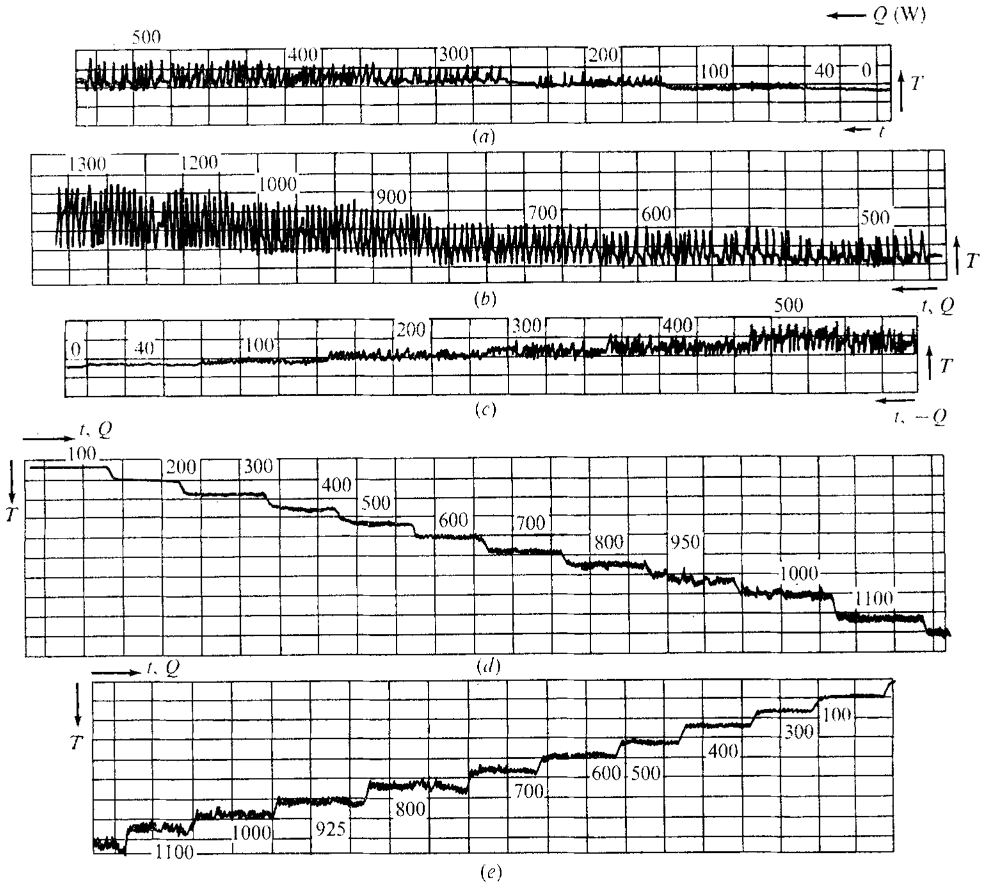

FIGURE 6. Temperature–time records for second set of experiments (fixed velocity, Q changing). (*a*) $V = 0{\cdot}6$ ft/s. (*b*) $V = 0{\cdot}6$ ft/s. (*c*) $V = 0{\cdot}6$ ft/s. (*d*) $V = 1{\cdot}4$ ft/s. (*e*) $V = 1{\cdot}4$ ft/s.

It is seen that fluctuations start around 15 W and the amplitude of fluctuations grows slowly until approximately 250 W, and then increases suddenly. These fluctuations resemble those observed for the pure free-convection case (figure 3). A further increase in heating increases the amplitude of fluctuations at almost a steady rate. Figures 6(*a*) and (*b*) indicate the complete temperature–time history for this case.

Figure 6(*d*) shows a similar plot at a higher velocity rate of 1·4 ft/s. It can be observed that the fluctuations develop gradually and transition is also more gradual in comparison with the plots for lower velocity in figures (6*a*) and (*b*). Transition is characterized by more violent fluctuations starting around 950 W. Figures 6(*c*) and (*e*) correspond to decreasing heat loads. No appreciable effect of delayed transition with respect to heat load can be seen in the figures.

Thus, data such as those plotted in figures 5 and 6 have brought to light many interesting features. Using the methods of detection of transition from the pressure drop and use of an anemometer probe, the boundaries of several regimes of flow have been established. These results coupled with the information of figures 5

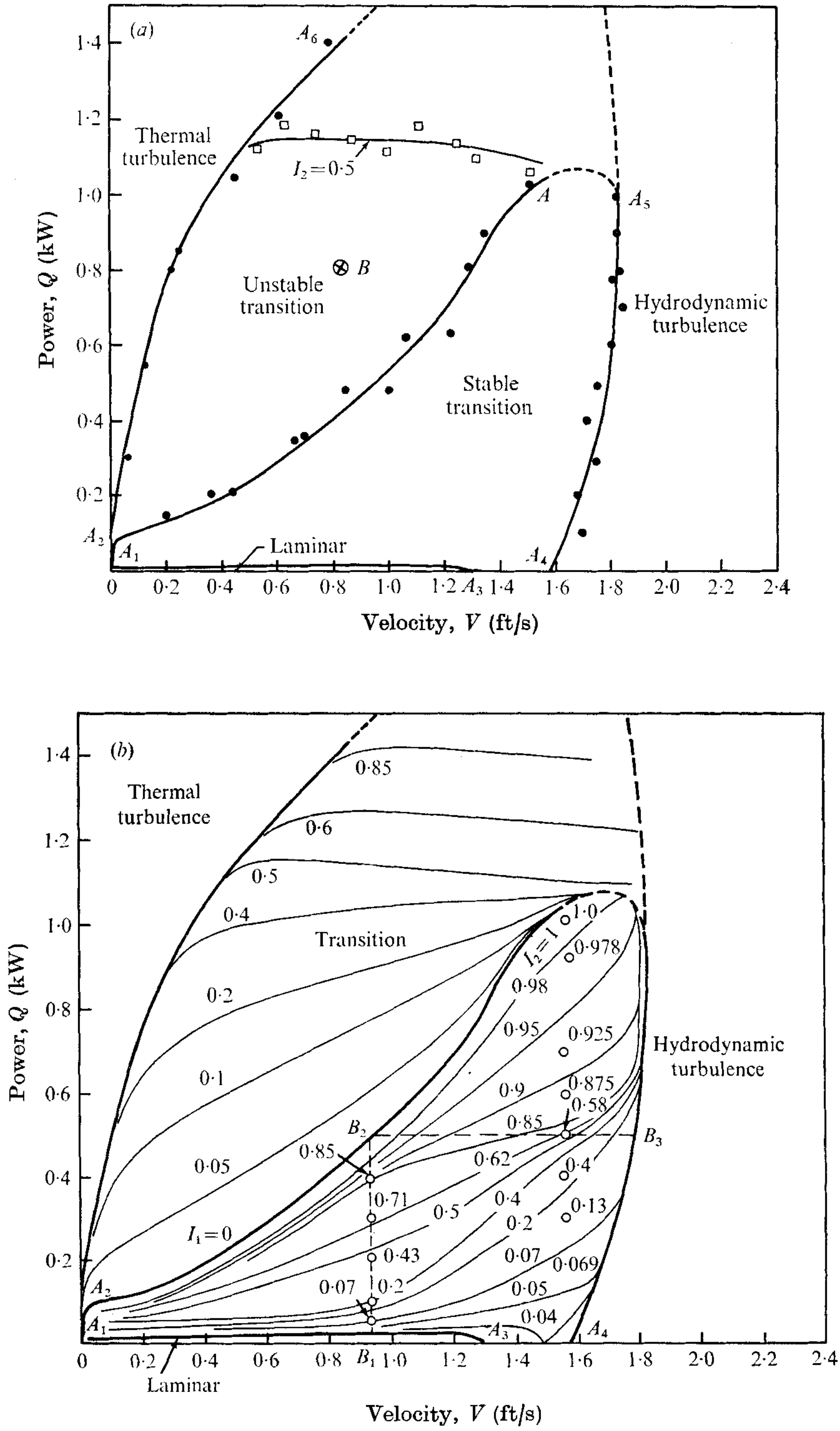

FIGURE 7. (a) Boundaries of transition. (b) Contour plot for equal intermittency values: iso-intermittency lines.

and 6 are illustrated in figure 7. Figure 7(*a*) shows the main features of transition. The basic variables, power input and flow velocity, are used to plot figure 7(*a*).

For very small heat loads, up to about 15 W, the effect of secondary flows is negligible and the transition and turbulence are governed by the value of velocity (more generally, the Reynolds number) in the tube. With increasing velocities, the heat load at which the secondary flows start causing transition of the main flow increases slightly as may be seen from the positive slope of the curve A_1A_3. At A_3 flow transition begins, and the flow becomes turbulent at A_4; these factors are characterized and thus detected by pressure-drop fluctuations as described previously. Previous results indicate that the flow can be considered turbulent for heat loads above 100 W and this is confirmed by point A_2 in figure 7(*a*). The loci of points A_2 and A_4 for increased flow velocity and heat load are shown by curves A_2A_6 and A_4A_5, respectively. Curve A_2A_6 indicates that the effect of free convection is predominant to the left of the curve and the flow turbulence is thus designated 'thermal turbulence'. Similarly, flow turbulence in the region to the right of A_4A_5 is termed 'hydrodynamic turbulence' because the governing behaviour of flow is predominantly hydrodynamic in character. Enclosed between these two curves is the transition regime.

It was observed in figure 5(*c*) that the transition flow is characterized by the 'pulse flow' followed by the sudden growth and gradual decay of fluctuations. The narrow region of velocity at which this sudden growth starts has been detected by sudden pressure-drop fluctuations starting in the flow. This region has been traced for the entire regime and is represented by the line A_1A. The experimental points show the scatter in detecting this line. For very small velocities, this line has been obtained by temperature–time records. By considering some point B to the left of curve A_1A, the characteristic feature of the flow can be described. When the experiment was performed with increasing velocities, pulses of temperature followed by low amplitude fluctuations were observed in the temperature–time records (see figure 5(*c*)). For the second set of experiments, where the heat input was increased, a region such as that containing point B is characterized by large fluctuations in temperature as shown in figure 6(*a*). Thus, the flow behaviour at points such as B in the region enclosed by curves A_1A and A_2A_6 depends on the previous history of the flow; i.e. a temperature fluctuation growth and a pulse type of flow are probable. Hence, this region has been designated a region of unstable transition. However, the region to the right of curve A_1A does not depend on the type of disturbance and the fluctuations are stable; the same data will be obtained in either set of experiments. Consequently, the region is called a 'stable transition region'. Thus, the entire regime of flow enveloped between the demarcating turbulence curves has been divided into stable and unstable transition regions.

More insight has been obtained into the transition regime from the temperature–time records. The results are obtained by plotting the iso-intermittency curves using the two intermittency factors I_1 and I_2 defined previously. A curve for $I_2 = 0{\cdot}5$ with experimental points has been plotted in figure 7(*a*). In figure 7(*b*) curves for I_1 varying from 0 to 0·85 in the unstable region and $I_2 = 0$–1 in the stable transition region are plotted.

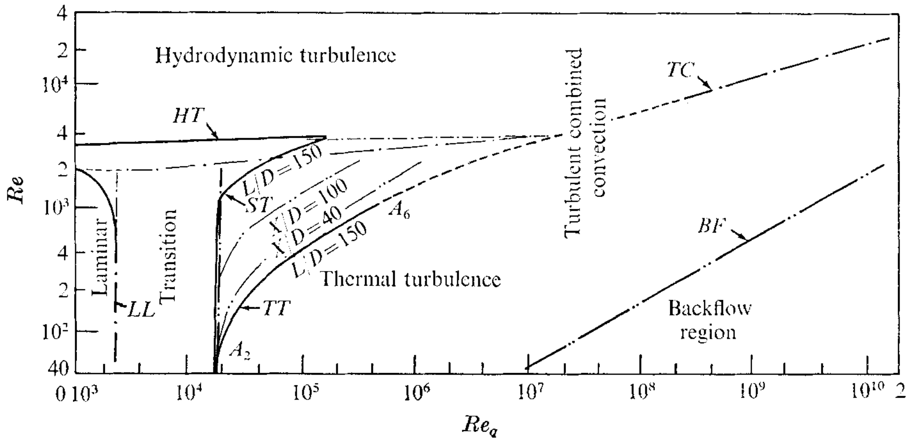

FIGURE 8. Boundaries of flow regimes. ——, present results.

In the unstable region the curves are widely spread initially near the $I_1 = 0$ line and become dense for larger power inputs; i.e. the width of pulses increases as the heat input is increased for a fixed velocity. For a given heat input, the increase in velocity decreases the width of the pulses only to a small extent. A similar plot in this region using I_2 can be obtained. Since the results do not bring about any new features, the plot is not presented. Thus iso-intermittency plots for I_1 in the unstable region describe the stratification of pulses in the flow.

Since I_1 is characteristic of the pulse type of flow, I_2 has been used in the stable region to study the transition structure. After drawing the iso-intermittency lines, two sets of experiments were performed to check the regions where the slopes of the iso-intermittency curves change drastically. These points are plotted in figure 7(*b*) at velocities of 0·925 ft/s and 1·55 ft/s along with the value of I_2 shown therein. The close agreement illustrates the repeatability of the experiments. For small values of velocity, up to about 0·8 ft/s, the uniform distribution of iso-intermittency lines indicates that the amplitudes of fluctuations vary linearly with heat input. However, the velocities play a greater role in deciding the amplitude of fluctuation. For a constant heat input, the fluctuation varies inversely with the velocity for moderate heat inputs (about 0–0·5 kW). However, large heat inputs and large velocities would present a region that has about the same amplitudes of fluctuations as at transition. The dotted lines B_1B_2 and B_2B_3 approximately demarcate the three regimes: the free-, forced- and mixed-convection stable transient regimes. Thus, the intermittency factor I_2 reveals the predominate features in stable transition.

The results discussed so far have been expressed in terms of the basic variables, the heat input and the flow velocity. The results of Petukhov & Polyakov (1970) have been used in figure 8 for comparison with the present results. The plot of Re versus Ra_q†, establishes the boundaries of flow regimes. The full lines are used for representing the present results for an L/D ratio of 150. The line A_2A_6

† $Ra_q = (g\beta qD^4/16\kappa\nu^2)(\nu/\alpha)$, where q is the rate of heat transfer per unit area β and α, are coefficients of thermal expansion and diffusivity, and κ the thermal conductivity.

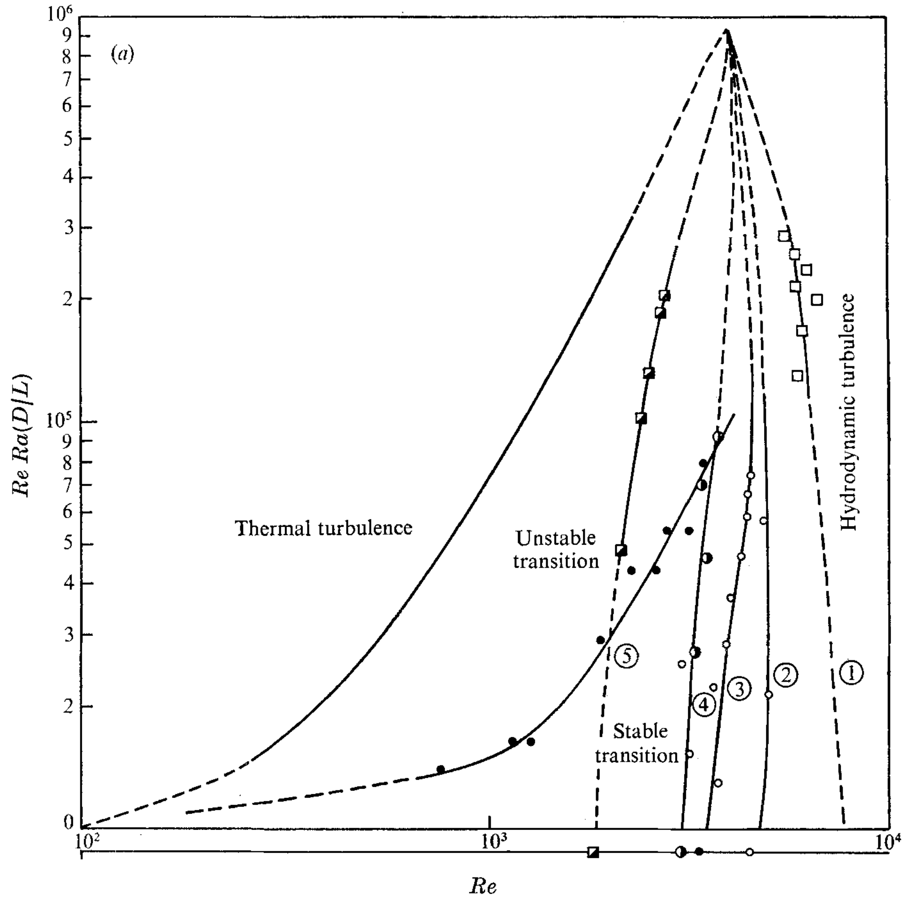

FIGURE 9. For legend see facing page.

demarcating the transition from thermal turbulence is also plotted. The use of dotted lines indicating predictions completes the picture by establishing boundaries of flow regimes for mixed convection. For values of *Re* greater than those given by the line *HT*, the region of hydrodynamic turbulence will be encountered. Similarly, for Ra_q greater than those values given by line *TT* (for $L/D = 160$) thermal turbulence occurs. For very high Rayleigh numbers the line *BF* denotes the line demarcating the backflow region. For smaller values of *Re* and Ra_q given by the line *LL*, laminar mixed convection exists. The region enveloped by the three lines *HT*, *LL* and *TT* represents the transition regime. For large values of Ra_q and *Re* where the two types of turbulence coalesce, the region is called turbulent combined convection. The line *TC* applies to this region.

The study of the effect of inlet turbulence for flow without heat transfer was discussed previously. The results† with flow and heat transfer are shown in figures 9(*a*) and (*b*). Figure 9(*a*) shows the effect of inlet turbulence on transition to hydrodynamic turbulence. The results of Mori *et al.* (1966) are plotted along

† $Ra = (g\beta\Delta T D^3/\alpha\nu)$, where ΔT = arithmetic mean temperature of tube wall minus bulk fluid temperature measured at mixing chamber at exit.

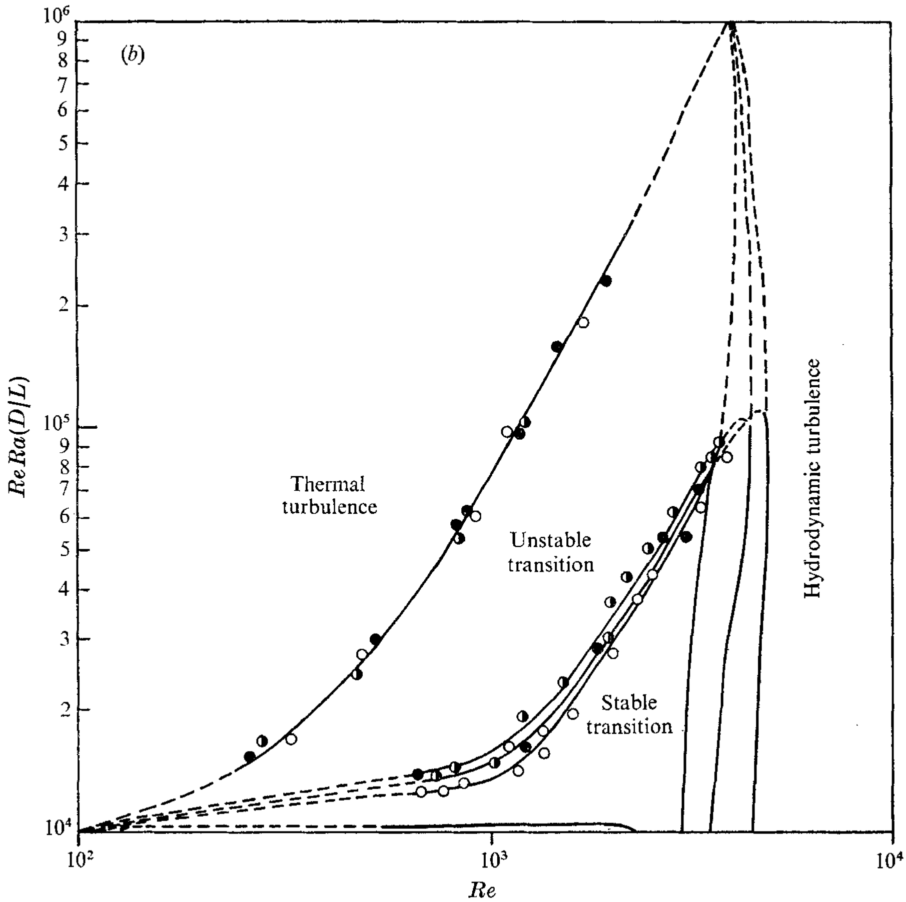

FIGURE 9. Effects of inlet turbulence. (*a*) On transition to hydrodynamic turbulence. Present results: ○, case C_1; ●, case C_2; ◑ case C_3. Mori *et al.*: □, no inlet turbulence; ◪, with inlet turbulence. (*b*) On stable transition and thermal turbulence boundaries. Present results: ○, case C_1; ●, case C_2; ◑, case C_3.

with the present results. With no inlet turbulizor, the results of Mori *et al.* (1966) are represented by curve 1 and the present results by curve 2. The difference between the two curves is due to the roughness factor for the tube. However, the general trend remains the same; i.e. the secondary flows accelerate transition to hydrodynamic turbulence. Curves 3 and 4 correspond to cases C_2 and C_3 discussed earlier, while curve 5 denotes the results of Mori *et al.* (1966) with a violent turbulizor. For curve 3 the secondary flows delay transition for lower values of $Re\,Ra\,(D/L)$ and become almost ineffective in deciding the boundary of transition. However, for curves 4 and 5 the influence of the secondary flows delaying the transition can be clearly seen. Thus, the present set of results strengthens the predictions of Mori *et al.* (1966) that inlet turbulence inhibits transition for large turbulizors. Further, from the present set of results, it becomes evident that there exists an initial turbulence that could nullify the effect of secondary flows completely in either delaying or accelerating transition to hydrodynamic turbulence. Another observation from the figure is that all the

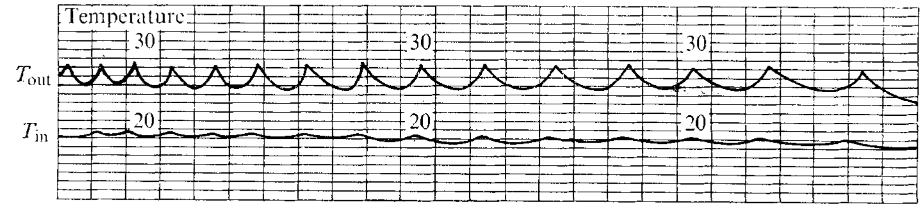

FIGURE 10. Temperature–time record of fluid entering and leaving test section.

curves appear to join at a point. This point also represents the point at which the lines HT and TT in figure 8(*a*) appear to meet. This may indicate that for sufficiently high Rayleigh numbers where the hydrodynamic and thermal turbulences could no longer be distinguished, the inlet turbulence does not have any effect.

Figure 9(*b*) shows the effect of inlet turbulence on other boundaries. The turbulizing does not bring about large influences on the demarcation line separating the stable and unstable transition regimes. In general, the turbulence at the inlet brings about a quicker transition as can be seen from the figure. The broken lines indicating a convergence to a single point may show that inlet turbulence will not influence no-flow conditions.

The influence of turbulence on the line demarcating the unstable transition from the thermal turbulence regime is almost negligible. This is the reason why the three lines in figures 9(*a*) and (*b*) are shown to converge at a single point on the line TT.

Figure 10 is presented to test the constancy of the inlet fluid temperature during transition. In spite of large variations in the temperature at the outlet end of the test section (T_{out}), the fluid temperature at the inlet (T_{in}) is fairly constant. Thus, the possible introduction of thermal disturbance was checked and it was found that the experimental set-up does not create any such thermal disturbance.

6. Conclusions

New aspects of combined free and forced convection interacting in the transition regime of a horizontal tube under uniform heat flux conditions were investigated experimentally.

(i) Hydrodynamic and thermal turbulence occur separately depending on whether the flow is predominantly hydrodynamic in character or whether free-convection turbulent flow dominates. These two regions merge for sufficiently high *Re* and *Ra* values, giving a regime called turbulence with combined convection. In this region the correlations of turbulent combined convection apply.

(ii) The transition regime lies between the two boundaries of turbulence.

(iii) The transition regime can be divided into unstable and stable regimes. The unstable regime is characterized by flow behaviour that depends on the previous history of the flow. A pulsating flow or a stable fluctuating flow is probable in this regime. However, the stable transition does not depend on the previous mode of flow growth.

(iv) By studying flow without heat transfer and heat transfer without flow in the tubes, intermittency factors have been defined to describe the transition structure. The temperature–time records used for this purpose establish the fact that stable transition also exhibits predominantly thermal, predominantly hydrodynamic, or mixed character in its structure. Approximate demarcation lines have been shown. In the unstable flow, the iso-intermittency lines establish the fact that the pulse flow is influenced more by secondary flows than by forced convection.

(v) The present results in conjunction with the results of Petukhov & Polyakov (1970) bring about a broader understanding of the entire combined convection phenomena.

(vi) A qualitative study of inlet turbulence on the boundary regimes of flow established many interesting features. First, the prediction of Mori *et al.* (1966) is strengthened by the results of the present experiments. Further, it appears that there exists a critical inlet turbulence that completely nullifies the effect of secondary flows in either accelerating or delaying transition to hydrodynamic turbulence. The effect of turbulence on transition to a stable region from an unstable region is to attenuate instability, but only to a small degree. Upon transition to thermal turbulence, the effect is negligible. This leads to the conclusion that inlet turbulence will have no effect on the turbulent flow regime of combined convection.

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