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Heat transfer in a pipe under conditions of transient turbulent flow

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Abstract

This paper is concerned with the response of fluid temperature within a heated pipe to imposed excursions of flow rate. Experiments are reported in which measurements of wall temperature and local fluid temperature were made with fully developed turbulent flow of water in a uniformly heated tube during and after ramp-up excursions of flow rate between steady initial and final values. The fluid temperature measurements were made using a traversable temperature probe incorporating a thermocouple capable of responding to turbulent fluctuations of temperature. Local values of mean temperature and RMS temperature fluctuation were obtained by ensemble averaging the results from many tests in which the same flow excursion was applied in a very repeatable manner with fixed values of inlet fluid temperature and heat flux. Further measurements were made under conditions of steady flow rate at a number of values over the range covered in the transient flow experiments. The results obtained in the experiments with transient flow show that there is a significant delay in the variation of ensemble-averaged wall temperature and striking perturbations in the variations of RMS fluctuation of wall temperature and local fluid temperature. These stem from the delayed response of turbulence to the imposed excursions of flow rate. They provide independent confirmation of ideas concerning the modelling of time scales for the production and diffusion of turbulence in pipe flow which were developed by the present authors in the course of earlier work. Ensemble-averaged local fluid temperature also varies in an unusual manner. Instead of falling monotonically with increase of flow rate, as might be expected, it starts to rise at some stage, reaches a peak value and then falls again. The release of heat stored in the pipe wall contributes to this behaviour. Computational simulations of the present experiments were performed using a spatially fully developed formulation of the equations for unsteady turbulent flow and heat transfer in a boundary layer utilising turbulence models of low Reynolds number, k–ε type. Comparisons between predicted and measured variations of temperature are presented in the paper. These show that the predictions differ significantly from model to model and that detailed agreement with experiment is not obtained using any of the models. However, certain interesting features of the observed temperature variations, such as a delay in the response of outer wall temperature and perturbations in local fluid temperature, are present in the computed results. © 1999 Elsevier Science Inc. All rights reserved.

Keywords: Heat transfer; Flow rate excursions; Transient response; Turbulence models

Notation

d	pipe inside diameter (mm)
r	pipe inside radius (mm)
t	time (s)
$\langle T \rangle$	ensemble averaged temperature (°C)
T'	root mean square temperature fluctuation (°C)
U_τ	friction velocity (m/s)
U_m	mean velocity (m/s)
y	distance from the wall (mm)

Greek

ν	kinematic viscosity (m^2/s)
τ	wall shear stress (N/m^2)

Subscripts

f	fluid
w	wall

1. Introduction

Heat transfer under conditions of transient turbulent flow in pipes is encountered in a variety of engineering applications. It is common practice in such applications to use a pseudo-steady state approach for the purpose of modelling system behaviour. Energy conservation is applied on a one-dimensional basis using local values of wall temperature and fluid temperature. Heat transfer is related to the difference between wall and fluid temperature using standard empirical equations which were developed for steady conditions. This approach fails to take account of influences which the transient nature of

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the flow might have on turbulence and the diffusion of heat. Its limitations were highlighted by results from the laser Doppler aneomometry study of turbulent flow in a pipe during ramp-type excursions by He (1992). This showed that under such conditions the turbulence differs significantly from that in steady flow. Time scales for the response of turbulence production and for the diffusion of turbulence from the near-wall region of the flow into the core flow were established in that study (see Jackson and He (1993)). Computational simulations of the experiments using a variety of turbulence models were subsequently reported (see Jackson and He (1995)).

A number of investigations of non-periodic transient flows have been reported in the literature. Kataoka et al. (1975) examined the start-up response to a step input of flow rate in a pipe. Maruyama et al. (1976) studied turbulence structure in transient turbulent pipe flow following a sudden change of flow rate. Transition from laminar flow to turbulent flow in a pipe under conditions of transient flow was examined by Kurukawa and Morikawa (1986) and delayed transition in pipe flow with constant acceleration starting from rest was investigated by Lefebvre (1987). The effects of abrupt free-stream velocity changes on turbulent boundary layers were investigated by Brereton et al. (1985).

Stimulated by the results of the investigation of He (1992), experiments were undertaken to study the response of the temperature field in a heated pipe to ramp-type excursions of flow rate. Experimental work by Büyükalaca (1993) using a pipe of similar dimensions was followed by computational studies (Jackson et al. (1994)). Previously, the problem of transient turbulent flow in heated pipes had received relatively little detailed attention. Koshkin et al. (1970) reported measurements made following step changes of electrical power input and with various types of flow transient. Dreitser (1979) analysed experimental data for power and flow transients in pipes to establish some limits for the applicability of quasi-stationary relations for calculating heat transfer. Later, Kalinin and Dreitser (1985) proposed correlation equations for calculating heat transfer coefficient under the conditions of imposed flow transients. More recently, Gibson and Diakoumakos (1993) reported an experimental study of the flow and thermal fields in an oscillating turbulent boundary layer on a heated wall. This yielded values of time-averaged mean and turbulent velocity, time-averaged mean temperature and turbulent heat flux.

In the present paper, the experimental results from the investigation of Büyükalaca (1993) are given detailed consideration and are compared with computational simulations.

2. Experimental arrangement

Water at near atmospheric pressure was used as the working fluid. Fig. 1 shows the general arrangement of the flow loop, the test section and the control and data acquisition systems. The water flowed from a header tank downwards through a test section made from stainless steel pipe of bore 48.34 mm, wall thickness 1.29 mm and total length 7.45 m. It then passed through a flow control valve and a turbine flowmeter into a base tank from where it was pumped back continuously to the header tank. This was done at a flow rate in excess of that through the test section and the surplus therefore drained back directly to the base tank through the overflow line. The rate of flow could be varied with time in an arbitrarily chosen and extremely repeatable manner by means of a pneumatically-actuated valve which was controlled by signals supplied by a computer through a digital to analogue converter. That computer also monitored the water flow rate, receiving signals from the turbine flowmeter via a counter timer module. Another computer was used to monitor and store the thermocouple signals received from the test section via scanning units and high precision, microprocessor-controlled digital voltmeters.

The test section had an unheated length of 3.7 m for flow development. This was followed by a section of length 3.0 m which was uniformly heated by direct resistive means using alternating electrical current. This was provided by a low voltage, high current power supply system consisting of a step-down transformer and a variable auto-transformer. The outside of the heated length of pipe was covered by pre-formed, cylindrical sections of thermal insulation material of very low thermal conductivity.

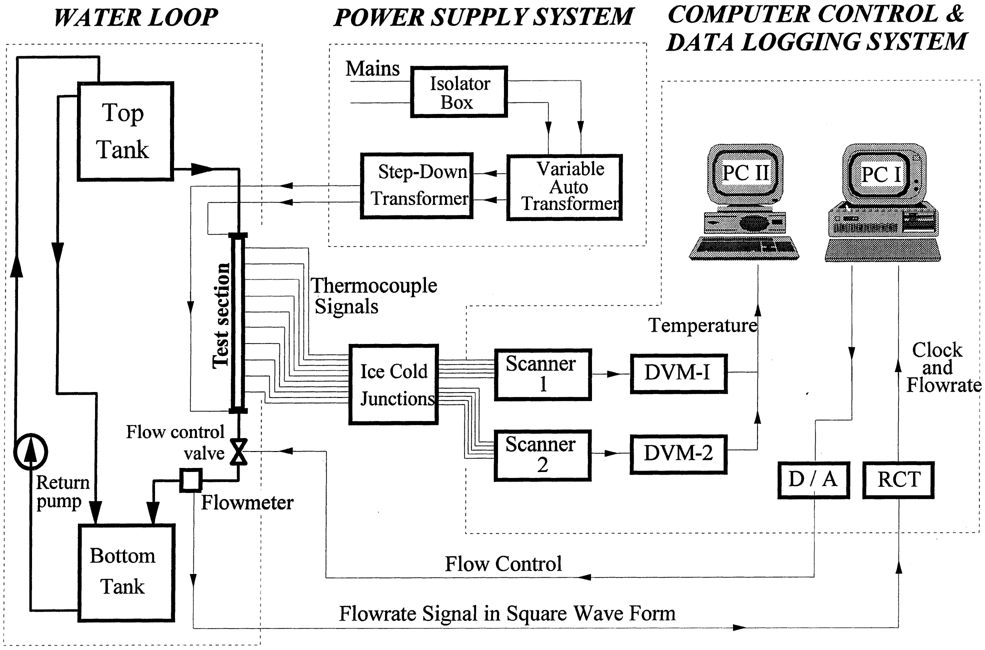

Fig. 1. Arrangement of flow circuit, power supply, flow control and data acquisition system.

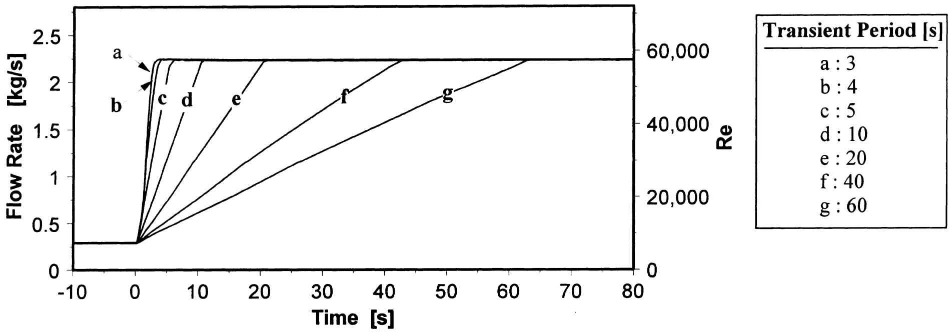

Fig. 2. Imposed excursions of flow rate with fixed initial and final values and various time periods.

The temperature of the heated section of the stainless steel pipe was measured at seventeen axial locations along its length by chromel alumel thermocouples welded to the outside surface. The water temperature was measured at the test section inlet and outlet by means of fixed thermocouple probes mounted within the flow. Near the downstream end of the test section, 54.3 diameters from the start of heating and 131 diameters from entry to the test section, local measurements of fluid temperature were made using a traversable temperature probe incorporating a thermocouple capable of responding to the turbulent fluctuations of temperature in the water. This axial location was chosen with a view to ensuring that fully developed hydrodynamic and thermal conditions were achieved there at the commencement of an imposed excursion of flow rate. It was sufficiently upstream of the outlet of the test section to be completely unaffected by end effects.

The electrical power input to the test section was maintained at the same value in each of the experiments with the current and voltage being recorded automatically by the data acquisition system. Because the flow circuit formed a closed loop, the heat supplied to the water had to be removed continuously during the tests in order to keep its temperature constant at inlet to the test section. To do this, water was withdrawn steadily from the base tank, pumped through a cooling coil in a chilled bath and returned to the base tank.

The imposed excursions of flow rate in the main series of experiments were as shown in Fig. 2. The flow rate was caused to vary in such a way that the Reynolds number at inlet to the pipe increased linearly with time from an initial steady value of about 7.4×10^3 to a final steady value of 5.7×10^4. The time period over which this took place ranged from 3 to 60 s. All the experiments were carried out with an inlet fluid temperature of 19.1°C and a uniform wall heat flux of 8.8×10^3 W/m^2. It was ascertained that with this heat flux buoyancy influences were negligible over the entire range of conditions covered.

Each experiment was repeated many times and ensemble averaging was employed to obtain mean values, both in the case of local fluid temperature at the traversing station and the outer wall temperature. This enabled values of root mean square temperature fluctuation to be obtained. Measurements of temperature using the traversable thermocouple probe were mainly made at five particular radial positions. However, some experiments were conducted making measurements at eleven radial positions for flow rate excursions of time period 4 s.

Additional transient flow experiments were carried out to study the effect of varying the starting value of flow rate whilst keeping the ramp-rate constant. This was done by suitably choosing the values of time period for each excursion. The imposed excursions of flow rate were as shown in Fig. 3. In these experiments, temperature measurements using the traversable thermocouple probe were only made at one radial position ($r = 11.47$ mm).

Finally, a series of experiments was performed under conditions of steady flow rate at a number of values distributed throughout the range covered in the transient flow experiments. Measurements were again made of both outer wall temperature and local fluid temperature at the various radial locations referred to earlier. This enabled direct comparisons to be made between results obtained at corresponding values of flow rate under conditions of steady and varying flow rate.

3. Results

3.1. Experiments with a 3 s time period

3.1.1. Wall temperature measurements

The wall temperature measurements presented here were made at the same axial location as the measurements of local fluid temperature, i.e., at a distance 2.625 m downstream from the start of heating. Variations of ensemble-averaged outer wall temperature and RMS fluctuation of outer wall temperature from experiments with excursions of time period of 3 s are shown in Fig. 4(a) and (b) respectively. The period during which the flow rate varied is indicated on the figures by the shaded area. Also shown on the figures are the corresponding distributions for conditions of steady flow.

It can be seen that, after an initial delay of about two seconds, ensemble-averaged outer wall temperature begins to

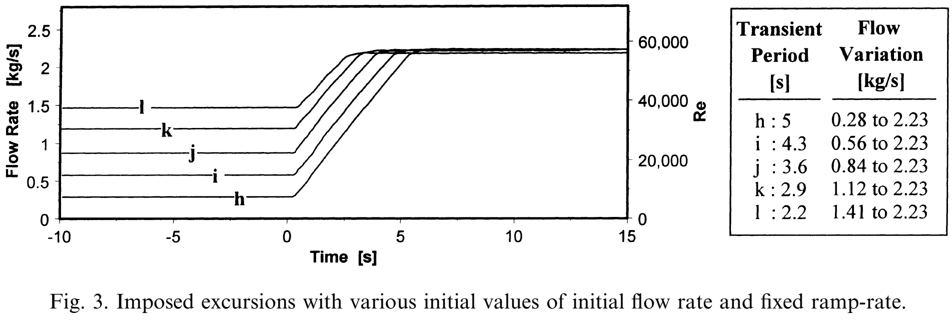

Fig. 3. Imposed excursions with various initial values of initial flow rate and fixed ramp-rate.

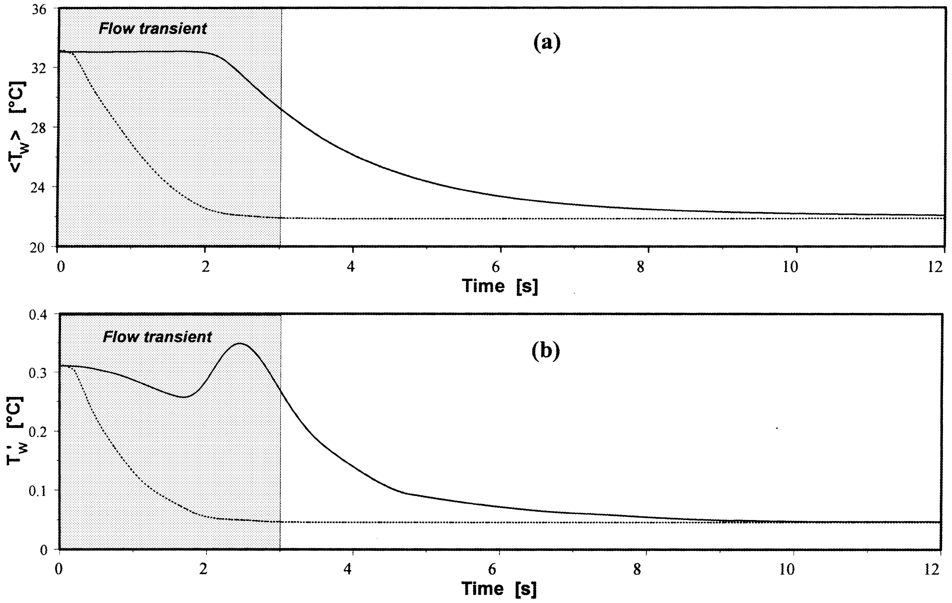

Fig. 4. Variation with time of ensemble averaged mean and RMS wall temperature fluctuation for a flow rate excursion of time period 3 s (solid line: transient experiment, dashed line: steady-state experiment).

decrease and then falls monotonically with time, decaying to a new steady value about 9 s after the flow rate excursion has ended.

In contrast, the response of RMS fluctuation of outer wall temperature is non-monotonic and involves three stages. During the first stage, it decreases in a smooth manner for about two seconds. Then it increases sharply for a fraction of a second, peaking at a value above the initial one. Finally, it decays in an exponential manner, reaching a steady value about 7 s after the flow transient has ended.

3.1.2. *Measurements of local fluid temperature*

Variations of ensemble-averaged fluid temperature and RMS temperature fluctuation at five radial locations ($r = 22.67$, 21.63, 19.01, 11.47 mm and on the centre line) are shown in Fig. 5(a) and (b), respectively. Again, the corresponding distributions for conditions of steady flow are also presented.

As can be seen, ensemble-averaged local fluid temperature responds to the imposed excursion of flow rate within a fraction of a second at all the radial positions considered. These responses also involve three stages. Firstly the temperature decreases, slowly at first but at a rate which increases with time in a smooth manner. Then there is a perturbation during which it either increases and then peaks before decreasing again, or, at the near wall and at the mid-radius positions, simply decreases for a short period at a relatively slower rate without peaking. Finally, it decays in an exponential manner to a

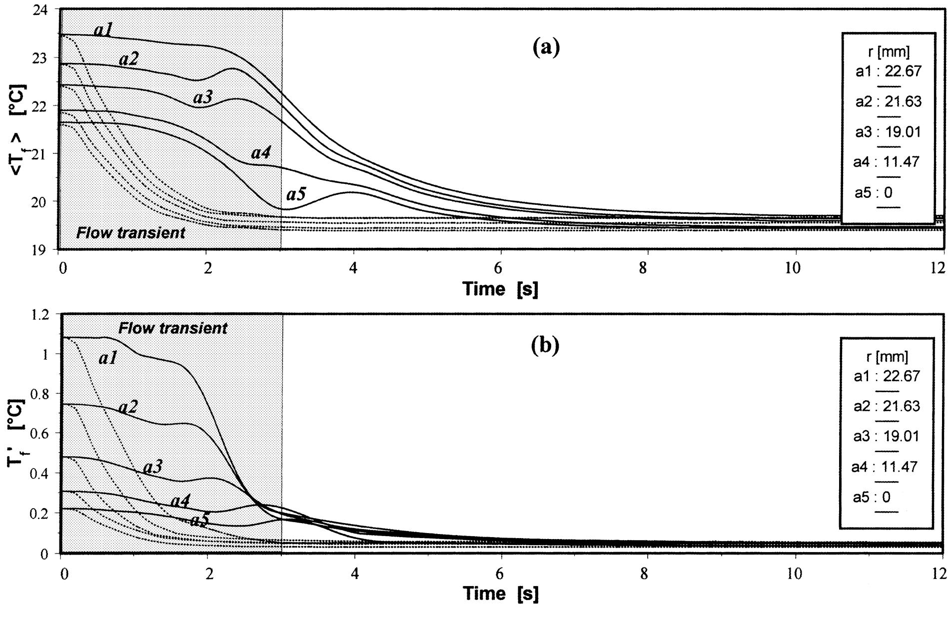

Fig. 5. Variation with time of ensemble averaged mean and RMS fluid temperature fluctuation for a flow rate excursion of time period 3 s (solid line: transient experiment, dashed line: steady-state experiment).

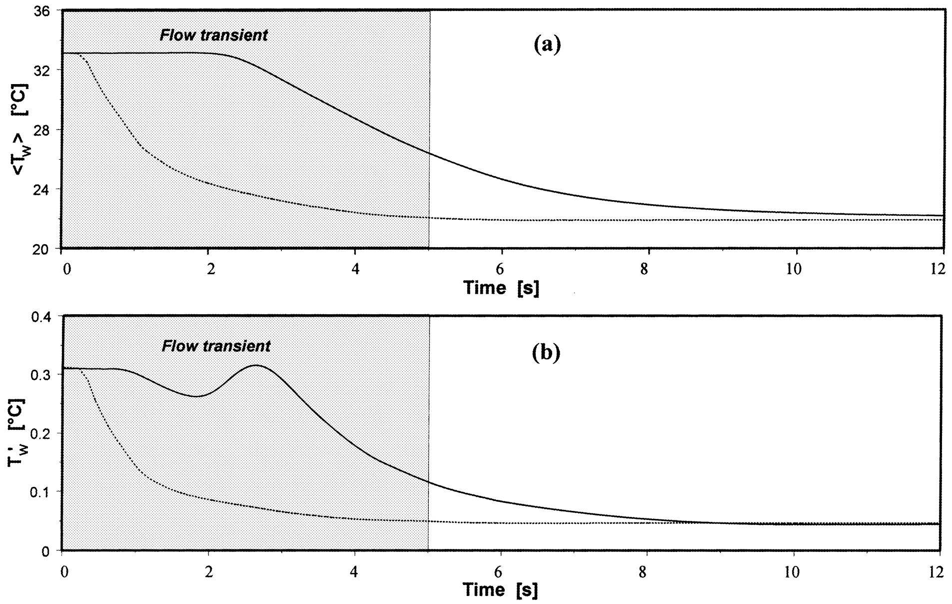

Fig. 6. Variation with time of ensemble averaged mean and RMS wall temperature fluctuation for a flow rate excursion of time period 5 s (solid line: transient experiment, dashed line: steady-state experiment).

steady value. Some effect of the excursion of flow rate can still be seen, up to 7 s after the excursion has ended, at all the radial positions where measurements were made.

The pattern of behaviour in the case of RMS fluctuation of fluid temperature is similar to that of ensemble-averaged fluid temperature in that the variation is in three stages and perturbations are seen. However, there are some detailed differences. The perturbations occur earlier than in the case of ensemble-averaged local temperature. Examination of the responses at different radial positions reveals that the time from the beginning of the flow rate excursion to that at which a perturbation occurs increases systematically with distance from the wall.

In both Figs. 4 and 5 big differences can be seen between the temperature responses for transient flow and the corresponding distributions for steady flow. The transient flow results lie well above the latter throughout the period of the imposed flow transient and also for several seconds afterwards.

3.2. Experiments with 5, 20 and 60 s time periods

As can be seen from Figs. 6–11, the time taken for the temperature field to reach its new steady state becomes progressively longer with increase in the time period of the flow rate excursion from 5 to 20 to 60 s. However, the general pattern of behaviour found in the experiments is similar to that

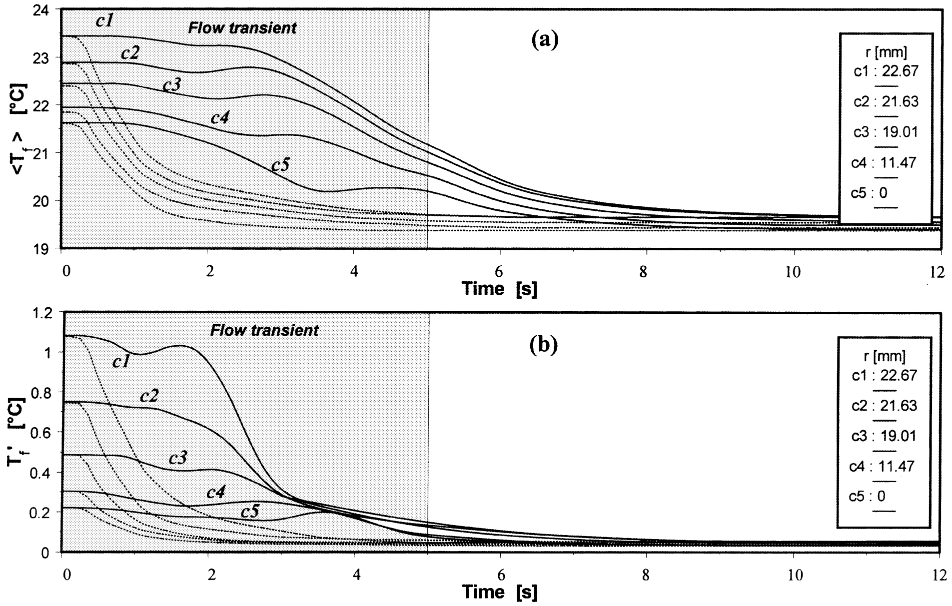

Fig. 7. Variation with time of ensemble averaged mean and RMS fluid temperature fluctuation for a flow rate excursion of time period 5 s (solid line: transient experiment, dashed line: steady-state experiment).

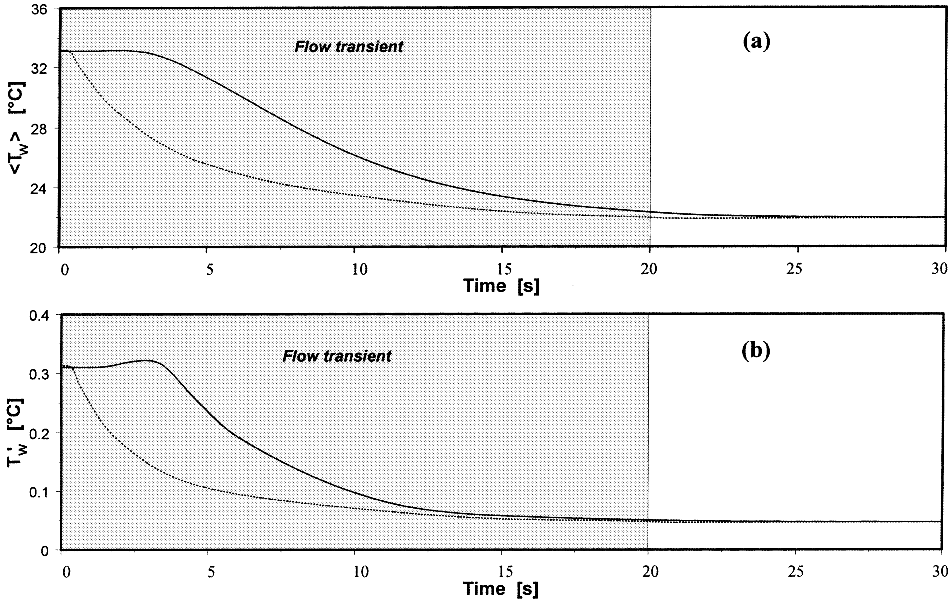

Fig. 8. Variation with time of ensemble averaged mean and RMS wall temperature fluctuation for a flow rate excursion of time period 20 s (solid line: transient experiment, dashed line: steady-state experiment).

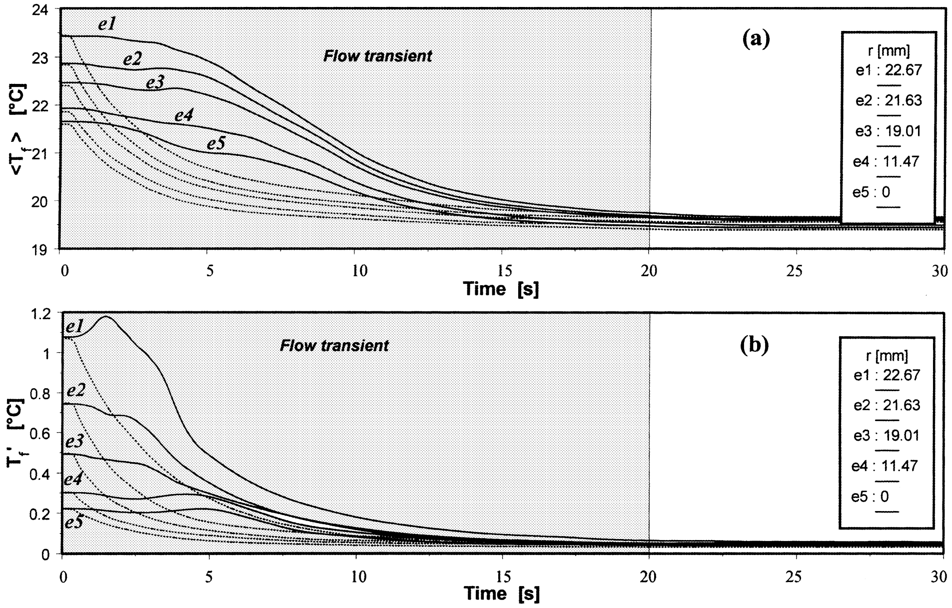

Fig. 9. Variation with time of ensemble averaged mean and RMS fluid temperature fluctuation for a flow rate excursion of time period 20 s (solid line: transient experiment, dashed line: steady-state experiment).

for the excursion of 3 s time period. In each case there is a delay in the initial response of ensemble-averaged outer wall temperature, and a perturbation in the response of RMS fluctuation of outer wall temperature. The time scales involved are similar to those for the 3 s excursion but there is a tendency for them to increase slightly with increase of time period.

In the case of both ensemble-averaged local fluid temperature and RMS fluctuation of fluid temperature the responses again involve three stages and the time from the beginning of the flow rate excursion to that at which a perturbation occurs again increases systematically with distance from the wall. The time at which a peak occurs on the perturbations increases with increase in the time period of the excursion.

The extent to which wall temperature and local fluid temperature continue to vary after the excursion has ended is small for a time period of 20 s and negligible for one of 60 s. However, even in these cases, differences between the transient flow responses and the distributions for conditions of steady flow are still clearly evident.

3.3. Experiments varying the starting flow rate but keeping the ramp-rate fixed

In this series of experiments, as the starting flow rate was increased the time period of the flow rate excursion was adjusted so as to keep the ramp-rate constant (see Fig. 3).

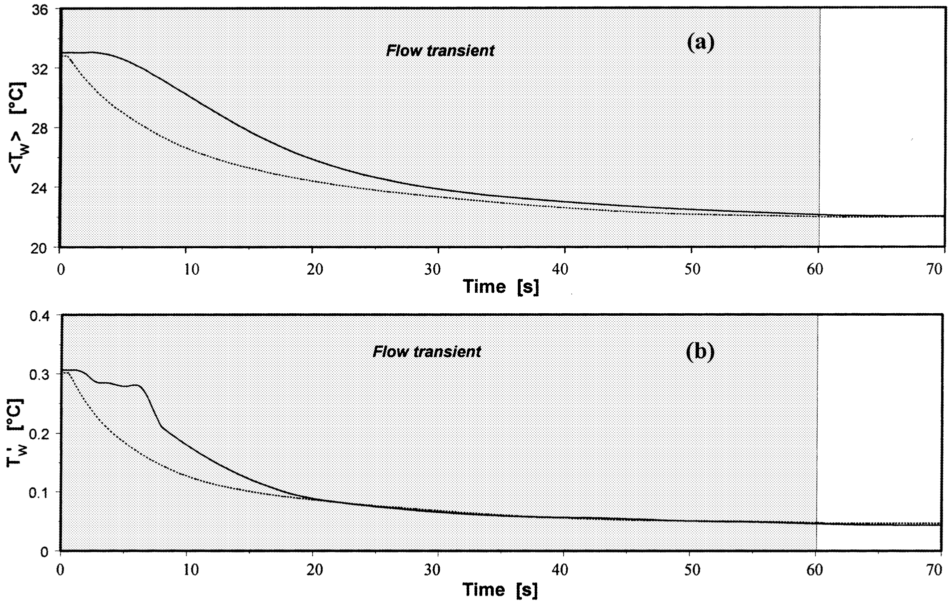

Fig. 10. Variation with time of ensemble averaged mean and RMS wall temperature fluctuation for a flow rate excursion of time period 60 s (solid line: transient experiment, dashed line: steady-state experiment).

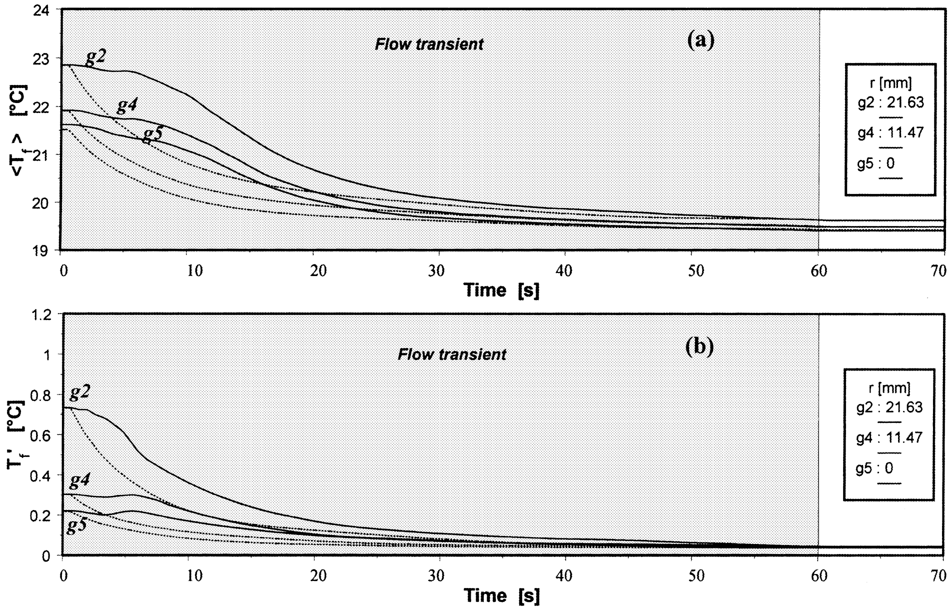

Fig. 11. Variation with time of ensemble averaged mean and RMS fluid temperature fluctuation for a flow rate excursion of time period 60 s (solid line: transient experiment, dashed line: steady-state experiment).

Measurements of local fluid temperature were only made at one radial location, $r = 11.47$ mm.

Fig. 12(a) and (b), respectively, show the variation with time of ensemble-averaged outer wall temperature and RMS fluctuation of outer wall temperature for each of the values of initial flow rate covered. From Fig. 12(a) it can be seen that an initial delay in ensemble-averaged outer wall temperature is evident in all the cases but its value decreases markedly with increase of initial flow rate. Referring next to Fig. 12(b), perturbations in RMS fluctuation of outer wall temperature can be seen in all cases. However, they occur earlier with increase of initial flow rate and are of reduced magnitude.

Fig. 13(a) and (b), respectively, show the variation with time of ensemble-averaged fluid temperature and RMS fluctuation of fluid temperature at the radial location $r = 11.47$ mm. It can be seen that perturbations are evident in both cases but they become less pronounced with the increase of initial flow rate and eventually difficult to discern.

4. Discussion

4.1. Factors which influence the response of temperature to excursions of flow rate

In order to interpret the present results it is helpful to try to identify the various fluid flow and thermal phenomena which might affect the response of the temperature field to imposed

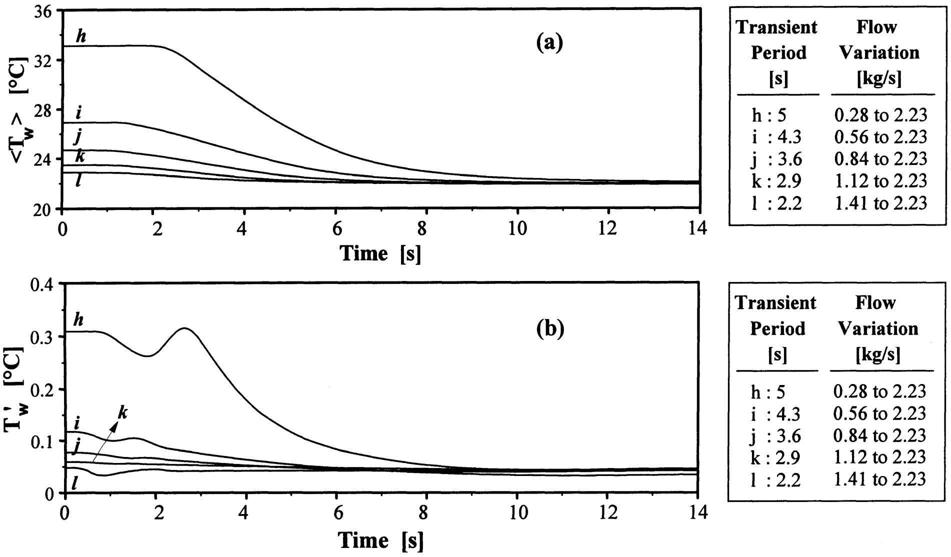

Fig. 12. Variation with time of ensemble averaged and RMS wall temperature fluctuation.

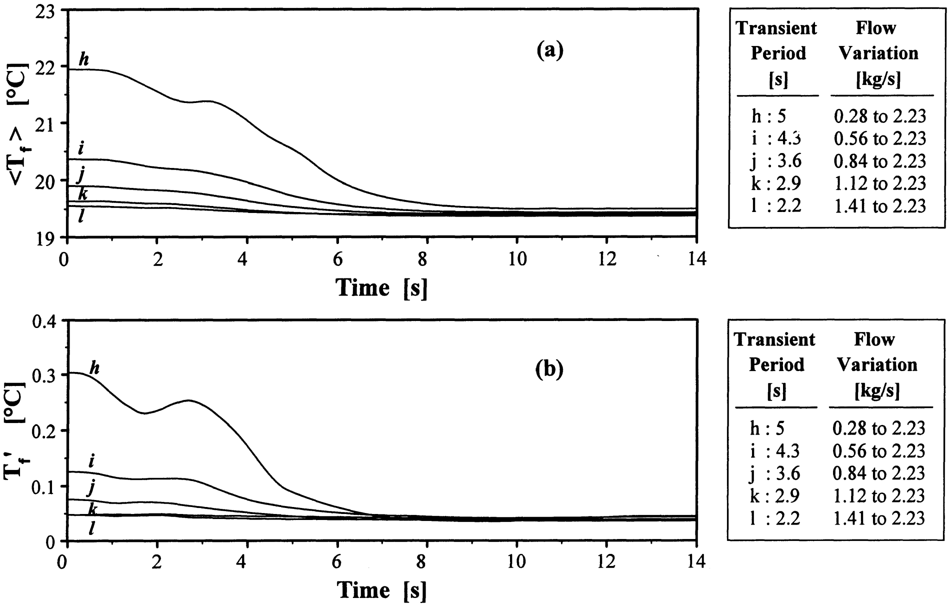

Fig. 13. Variation with time of ensemble averaged and RMS fluid temperature fluctuation.

excursions of flow rate in the case of turbulent flow in a heated pipe. One which is of particular importance in the present study, is the response of turbulence. Jackson and He (1992, 1993) reported LDA measurements by He (1992) of ensemble-averaged mean velocity and turbulence during transient flow in a unheated pipe where the pipe diameter, experimental conditions and imposed excursions of flow rate were similar to those in the present study. In the near-wall region, the axial component of turbulence responded almost immediately to the excursion of flow rate but the radial and circumferential components in that region exhibited a response which was delayed by about 1 s. As a consequence, the responses of turbulent shear stress and turbulent kinetic energy were also delayed. Further away from the wall all three components of turbulent velocity exhibited delays. These increased in magnitude with distance from the wall, reaching values of about 4 s at the centre of the pipe. In experiments where the initial and final flow rates were kept constant as the time period of the excursion was varied, the delay at any given radial position remained essentially unchanged. However, when the initial flow rate was increased, keeping the ramp-rate constant, the delays decreased.

In the case of a ramp-up excursion of flow rate, the response of turbulence begins with increased production of turbulence in the flow near to the wall. However, turbulent eddies are only produced intermittently as local instabilities in the wall shear flow develop and lead to 'bursts' of turbulence. Thus, during an imposed excursion of flow rate the turbulence field responds after some delay, the magnitude of which is related to the turbulence bursting frequency. The time scale for such bursts is given by $C\nu/U_{\tau}^2$, in which U_{τ} is the friction velocity, ν the kinematic viscosity of the fluid and C a constant of value 125

(Blackwelder and Haritonidis, 1983). This expression was found to provide an estimate of the delay in the response of turbulence in the near-wall region in good agreement with that observed in the experiments of He (1992), referred to earlier.

The response of turbulence in the near-wall region is followed by increased transmission of turbulent kinetic energy towards the centre of the pipe through the action of turbulent diffusion. Thus, at any specified location within the flow, the response of turbulence exhibits a delay which is the sum of a delay in the response of turbulence production in the near-wall region and one associated with the time needed for diffusion of turbulence from the near-wall region to the location in question. The time scale for the latter process should depend upon the distance y involved and the friction velocity U_τ. A satisfactory description of observed behaviour in the case of the experiments of He (1992) was obtained by evaluating this using the ratio y/U_τ. In view of the fact that the hydrodynamic conditions in the present study are very similar to those in the investigation of He (1992), the turbulence field should exhibit a similar delayed response.

We next consider the thermal processes involved in the present study. The fluid temperature in a uniformly heated pipe through which the flow rate is increasing with time can be computed from a simple energy balance, performed on a one-dimensional basis following the motion of the fluid. This approach gives a volume weighted local mean value. Because the heating is uniform, the rise of temperature of the fluid as it flows through the tube is proportional to the time taken for it to travel from the start of heating to the location under consideration, i.e., the so called "residence time". In the case of a ramp-up excursion of flow rate, the residence time reduces as the excursion proceeds and consequently fluid temperature falls. After an initial delay associated with the response of the turbulence field, wall temperature also begins to fall. Energy stored in the pipe wall is then released along with the energy which is being steadily generated within it. Even in the case of a pipe having a very thin wall, this additional rate of heat release can in some circumstances be enough to modify the fluid temperature by a significant amount. The magnitude of the effect is directly related to the rate of change of wall temperature with time and this increases with reduction of the time period of the imposed excursion.

4.2. Discussion of the present results

We now seek to relate the ideas presented in the previous section to the present experiments, starting with those in which the imposed excursions of flow rate had a time period of 3 s (Figs. 4 and 5). As remarked earlier, big differences are evident, both during the period of the excursion of flow rate and for several seconds afterwards, between the temperature responses for transient flow and the corresponding distributions of temperature for conditions of steady flow. This is not surprising because the fluid residence time at the start of the flow rate excursion is about 16.5 s and this is large compared with the time period of the excursion of flow rate. Thus, even at the end of the excursion, the temperature of the fluid will only have fallen by a relatively small amount. A particular feature of the transient flow temperature responses is that they exhibit significant delays and striking perturbations. These stem from the delayed response of turbulence to the imposed excursions of flow rate.

4.2.1. Variation of wall temperature

We begin by considering the initial delay of about 2 s in the response of ensemble-averaged outer wall temperature which is evident in Fig. 4(a). For the conditions of the present experiments, the expression $C\nu/U_\tau^2$ yields a value of about 1.25 s for the time scale involved in the delayed response of turbulence production if the friction velocity at the start of the flow rate excursion is used in the calculation. Of course, it can be argued that because the flow rate is increasing during the delay period a somewhat higher value of U_τ might be more appropriate. However, it is not clear just how much higher it needs to be. Increasing U_τ would reduce the estimated delay.

Once additional turbulence production has occurred, several things follow as a consequence. A readjustment of temperature gradient through the action of molecular diffusion occurs within a viscous sub-layer of reduced thickness. This is accompanied by changes of temperature within the wall itself as a result of unsteady conduction. Whilst these processes take place, turbulent energy is being transferred outwards across the buffer layer and the turbulent region through the action of turbulent diffusion. As a result, the pipe wall and the fluid in the outer region of the boundary layer become more effectively 'thermally linked', so that heat can then be removed from the wall at an increased rate causing its temperature to fall.

The additional delay involved in the propagation of temperature disturbances through the fluid in the near-wall region cannot be estimated precisely. However, it is possible to place an upper limit on its value by assuming that the layer of fluid involved is the viscous sub-layer as it was at the start of the flow rate excursion. An estimate of the additional delay was made on the above basis by Büyükalaca (1993) using an approximate solution of the equation for unsteady molecular diffusion through such a layer. He obtained a value of 0.9 of a second. The corresponding delay in the propagation of temperature disturbances through the pipe wall by unsteady conduction was estimated to be 0.2 of a second, giving a combined value of about 1.1 s. If we add this to the 1.25 s obtained earlier for the delay in the response of turbulence production we obtain a total of 2.35 s as our estimate of the delay in the response of outer wall temperature. This is sufficiently close to the observed delay of about 2 s to warrant the conclusion that the physical picture just presented of the processes involved is substantially correct.

Turning next to RMS fluctuation of outer wall temperature, we see from Fig. 4(b) that this responds almost immediately to the imposed excursion of flow rate, falling slowly at first but at a rate which increases steadily. This is a consequence of the temperature of fluid in the near-wall region falling as a result of having experienced a reduced residence time. The fall in RMS fluctuation of outer wall temperature is followed, just under 2 s into the excursion of flow rate, by a sudden increase for about half a second until a peak value is achieved 2.5 s into the excursion. The onset of this perturbation in RMS fluctuation of outer wall temperature can be associated with the arrival of fluctuations of temperature at the outside surface of the wall which have resulted from increased fluctuations of temperature in the near-wall fluid following the response of turbulence there to the excursion of flow rate.

It is of interest that even though the wall and the fluid adjacent to it both act as thermal filters, with the result that some of the applied temperature fluctuation is damped out, the increase of temperature fluctuation in the near-wall region due to the response of turbulence there is still easily detectable on the outside of the wall.

The time from the beginning of the flow rate excursion to that at which a perturbation develops in outer wall RMS temperature fluctuation is just under 2 s, from which it can be inferred that the time actually taken for temperature disturbances to be propagated across the viscous sub-layer and through the wall is about half that deduced earlier. If the estimate of the initial delay in the response of ensemble-averaged outer wall temperature is revised taking account of this, very close agreement with observed behaviour is then obtained.

4.2.2. *Variation of fluid temperature*

We next consider the responses of ensemble-averaged local fluid temperature and RMS fluctuation of local fluid temperature shown in Fig. 5(a) and (b) respectively. The initial variation of fluid temperature following the imposition of a ramp-up excursion of flow rate and the factors which influence its subsequent behaviour have already been considered. Fluid temperature first tends to fall at all radial locations as convective heat transfer takes place with fluid velocity increasing everywhere but the turbulence field unchanged. Once the production of additional turbulence in the near-wall region commences and diffusion of turbulent energy into other regions gets under way, the thermal diffusion properties of the flow are greatly enhanced, heat is removed more effectively from the pipe wall and major changes occur in temperature profile shape. This is illustrated in Fig. 14, where radial temperature profiles are shown for various times during a flow rate excursion of time period 4 s. Particularly dramatic changes take place in the later stages of the excursion (2.5 s $< t <$ 4 s) during which the main release of stored heat from the pipe wall occurs. Under the conditions of the experiments with a time period of 4 s, the additional rate of heat release is similar in magnitude to the rate at which heat is being generated within the pipe wall and it therefore has a significant effect on the temperature field. As a result of the thermal diffusion properties of the flow changing rapidly and additional heat transfer from the wall, the temperature of the near-wall fluid begins to rise for a time before falling again later. As can be seen from the curves of ensemble-averaged local fluid temperature shown in Fig. 5(a) this temperature disturbance subsequently propagates into the core fluid.

Thus, we see that the onset of a perturbation in ensemble-averaged fluid temperature in the near-wall region is a consequence of the thermal diffusion properties of the flow having been enhanced. The perturbation therefore develops after the response of turbulence has occurred, just over 2 s into the excursion of flow rate.

In contrast, the perturbations on the curves of RMS fluctuation of local fluid temperature in Fig. 5(b) are a more direct manifestation of the response of turbulence to the imposed excursion of flow rate. As turbulent fluctuations of velocity build up locally, RMS fluctuation of fluid temperature tends to increase correspondingly, only to fall later as fluid temperature decays. The peaks which develop in the response of RMS fluctuation of fluid temperature propagate into the core region along with the turbulence. From Fig. 5(b) it can be seen that at the centre of the pipe the peak on the curve of RMS fluctuation of temperature occurs just over 3 s into the flow rate excursion. Combining the time scale for the response of turbulence in the near-wall region given by $C\nu/U_\tau^2$ with that for turbulent diffusion of turbulent energy from the near-wall region to the centre of the pipe given by R/U_τ, an estimate of 3.65 s is obtained for the time at which the turbulence there should respond to the imposed excursion of flow rate. This is sufficiently consistent with observed behaviour to warrant the conclusion that the expressions used above to estimate the time scales for the response of turbulence production and the turbulent diffusion of turbulent energy are valid.

4.2.3. *Effect of increasing the time period of the excursion*

We next consider the results obtained with excursions of time period of 5, 20 and 60 s in relation to those for a time period of 3 s. It can be seen from Figs. 4–11 that increasing the time period of the excursion, whilst keeping the values of the initial and final flow rates fixed, changes the overall response of the temperature field in a systematic manner. The temperature responses lie progressively closer to the corresponding steady state distributions as the time period is increased. Quasi-steady behaviour is approached towards the end of the excursion. However, even for an excursion of flow rate with a time period as long as 60 s (almost four times the fluid residence time at the start of the excursion) significant differences are still apparent between the transient responses and the steady state distributions in the early stages of the excursion. Delays in the initial response of outer wall temperature persist, as do perturbations in the responses of RMS fluctuation of outer wall temperature, local ensemble-averaged fluid temperature and RMS fluctuation of local fluid temperature.

The fact that the time scales for the delays and perturbations do not change very much with increase of the time period of the excursion of flow rate is consistent with the ideas presented earlier to explain and quantify them. In this series of experiments the friction velocity U_τ was constant at the start of the excursions and so the predicted time scales do not change. The tendency for the observed values to increase with increase of excursion time period could be taken as confirming the idea put forward earlier in this paper that it might be more appropriate to use an average value of U_τ over the period of the delay rather than the initial value. The characteristic value of U_τ which would be obtained if such an approach was to be

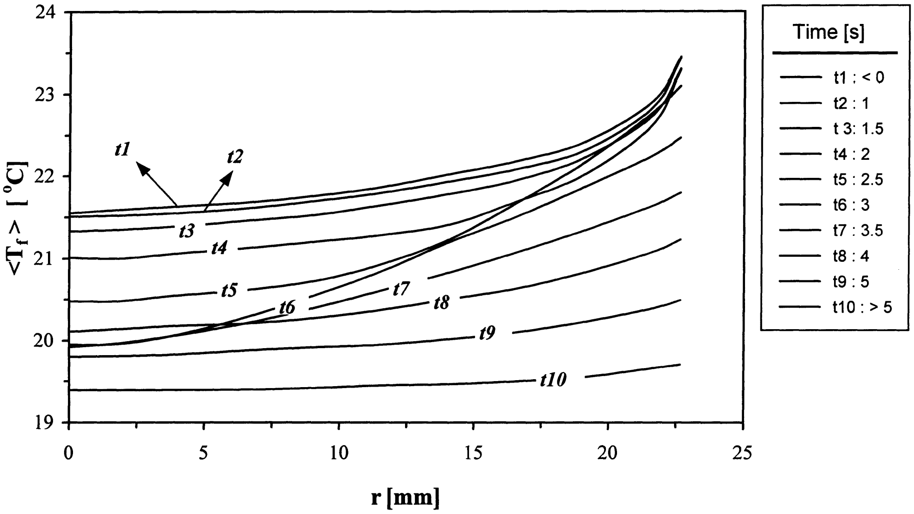

Fig. 14. Local ensemble averaged mean fluid temperature profiles at various times during an imposed excursion of flow rate having a time period of 4 s.

adopted would reduce. Thus, the time scales predicted for the response of turbulence production and the diffusion of turbulent energy would increase. However, it must be said that the observed increases of time scale are slight and the ideas just presented to explain them are rather speculative.

4.2.4. *Effect of increasing the flow rate at the start of the excursion*

Finally, we examine the results of the series of experiments in which the flow rate at the start of the excursion was increased keeping the ramp-rate fixed.

We again begin by considering the delay in the response of ensemble-averaged outer wall temperature. This reduces as the flow rate at the start of the excursion is increased. We have seen earlier that the delay is a consequence of the delay in the response of turbulence and delays associated with the propagation of temperature disturbances across the viscous sub-layer and through the pipe wall. With increase of initial flow rate, the value of U_τ at the start of the excursion increases, the thickness of the viscous sub-layer reduces and turbulence in the near-wall region responds more rapidly. These effects combine to cause the delay in the response of outer wall temperature to reduce. The value of U_τ at the start of the excursions in this series of experiments increases in a manner which is approximately proportional to the initial flow rate. If the simple approach to modelling the problem presented earlier in this paper is used to predict the delays in these experiments, the observed trends are well captured.

Perturbations in the variation of ensemble-averaged fluid temperature and RMS fluctuation of fluid temperature develop earlier as the starting flow rate is increased. This is because the time scales for production of turbulence and diffusion of turbulence into the core are both reduced. The variations of turbulence and temperature become progressively smaller with increase of initial flow rate and therefore the temperature perturbations are reduced in magnitude. Clearly, uncertainties in the experimental data become increasingly important under such conditions and ultimately limit the conclusions which can be drawn from the results.

5. Computational simulations

5.1. *Modelling approach*

The interpretation of the experimental results reported here has been greatly assisted by some associated computational work (see Jackson et al., 1994). In that study the present experiments were simulated by solving the unsteady forms of the equations for turbulent boundary layer flow and heat transfer in conjunction with the transport equations for turbulent kinetic energy and dissipation rate. Several well known low-Reynolds number k-ε turbulence models were used. The constants and functions in the turbulence models were as specified by the authors who originally developed them. Turbulent Prandtl number was assigned the fixed value 0.9 in order to relate turbulent conductivity to turbulent viscosity. Transient heat conduction within the tube wall was taken account of by solving the equation for unsteady heat conduction in that region simultaneously with the equations for fluid flow, energy transfer in the flow field.

5.2. *Computational results*

5.2.1. *Predictions of wall temperature*

In Fig. 15, curves showing the computed variations of outer wall temperature obtained using three well known turbulence models, are presented for an excursion of time period of 5 s along with the experimental curve. The models used were those of Launder and Sharma (1974), Lam and Bremhorst (1981) and Shih and Hsu (1991). It can be seen that the results obtained using the three models differ even for conditions of steady flow. For the condition prior to the flow transient, the SH model gives a wall temperature of 32.8°C, which is close to the experimental value of 33.1°C. The corresponding predictions using the LS and LB models are about 5° and 3° higher, respectively. Corresponding discrepancies are evident for the steady condition achieved after the flow transient has ended. They are an inevitable consequence of the fact that when the models were originally developed they were 'tuned' by the various authors in different ways. As pointed out earlier, no attempt has been made to adjust them to fit our experiments.

It can be seen from Fig. 15 that in terms of reproducing the observed response of outer wall temperature to the imposed excursion of flow rate (including the initial delay), the LS model performs best, even though for steady conditions it exhibits the biggest discrepancy. It predicts a 2 s initial delay, which is very close to that observed experimentally. The LB model gives an initial delay of just over 1 s and the SH model predicts very little delay. The subsequent decay of outer wall temperature with time predicted by each of the models is similar.

5.2.2. *Predictions of local fluid temperature*

Computed variations of local fluid temperature obtained using the three models are shown in Fig. 16(a)–(c) along with the corresponding experimental curves. It can be seen that, to some extent, each of the simulations predicts a pattern of fluid temperature variation similar to that found in the experiments. Perturbations having a local minimum and maximum, developing at times which depend on radial position, are evident in each case. However, the predicted behaviour varies in detail from model to model and significant discrepancies exist between the experiments and computed results. All the models

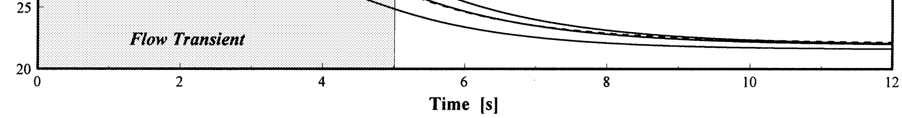

Fig. 15. Variation with time of predicted wall temperature for a flow rate excursion of time period 5 s (solid lines: simulations, broken line: experiment).

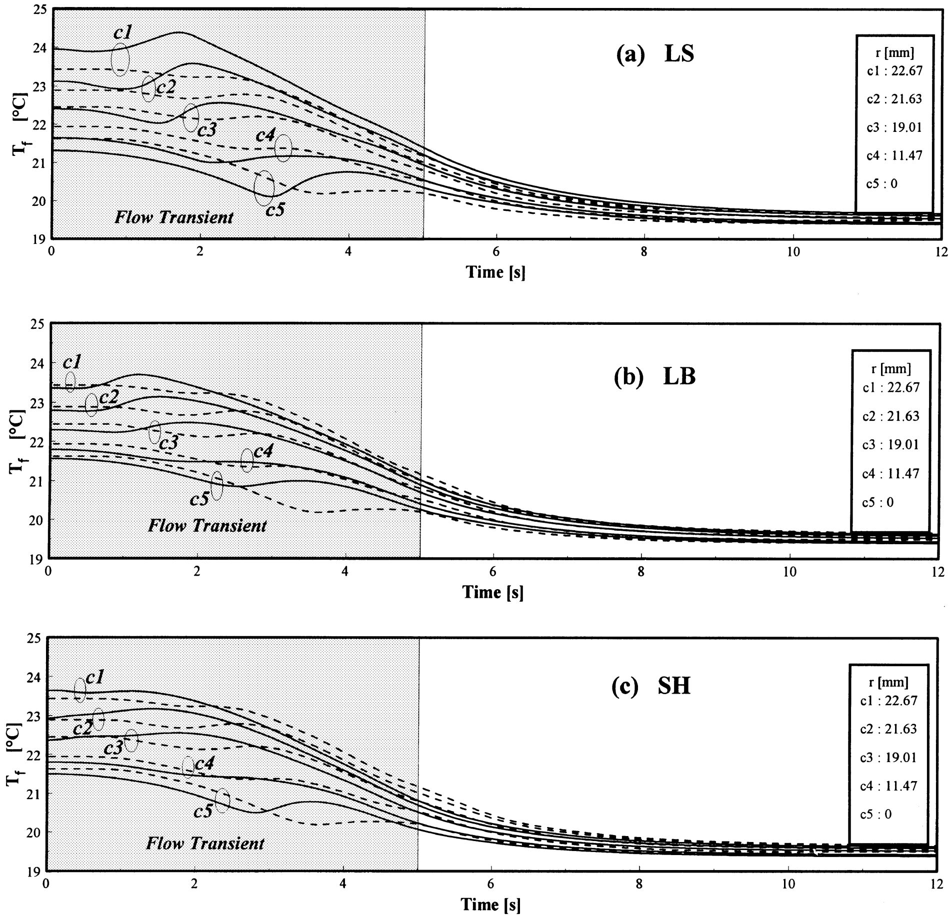

Fig. 16. Variation with time of predicted local fluid temperature for a flow rate excursion of time period 5 s (solid lines: simulations, broken lines: experiment).

tend to predict time scales for perturbations which are somewhat shorter than those observed. As an example, consider the predictions of the variation of temperature at the centre of the pipe. In the measurements shown, a peak occurs there after 4.5 s. However, as can be seen from Fig. 16, the corresponding value given by the LS model is about 4 s whereas the LB and SH models give values of about 3.5 s. The predicted responses obtained using the SH model are generally less satisfactory than those yielded by the other two models. As can be seen from Fig. 16(c), the temperature at radial positions c_2 and c_3 increases continually in the case of the SH model until it peaks. This is not so in the case of the other predictions, nor is it so in the experiment. Taking all aspects of the behaviour into consideration, it is felt that the LS model gives the best overall simulation of the experiments in spite of it not being well tuned for steady conditions. However, its performance was only marginally better than that of the LB model.

A useful outcome of the computational study was that the simulations provided information which was not available from the experimental study concerning the response of the temperature field within the wall itself.

6. Conclusions

There are very clear differences between the temperatures measured in the transient flow experiments and the values measured under conditions of steady flow for corresponding flow rates. Even for the longest flow rate excursion considered, the wall and fluid temperatures for conditions of transient flow lie well above the corresponding steady state values for much of the period of the excursion. For the shorter time periods quasi-steady thermal conditions are never approached. Most of the decay of temperature occurs after the flow rate excursion has ended.

Wall temperature exhibits a delayed response to imposed excursions of flow rate. This can be attributed to a delayed response in the production of turbulence followed by delays associated with the propagation of temperature disturbances through the near-wall fluid and the pipe wall.

The responses of RMS fluctuation of outer wall temperature exhibit perturbations having peaks which occur shortly after the ensemble-averaged outer wall temperature begins to respond. These are directly related to the response of turbulence in the near-wall region to the imposed excursions of flow rate.

Local ensemble-averaged fluid temperature and RMS fluctuation of fluid temperature both start to respond to the imposition of a flow transient within a fraction of a second at all radial positions. However, they also exhibit perturbations in their variation. The response of local fluid temperature can be explained in terms of a redistribution of temperature, following a delayed response of the turbulence field. This is accompanied by release of heat stored in the pipe wall.

Peaks on the curves of RMS fluctuation of local fluid temperature provide evidence concerning the response of turbulence in pipe flow to ramp-type excursions of flow rate which substantiates that from earlier work.

Simple ideas presented in the paper concerning the production and diffusion of turbulence in pipe flow have enabled satisfactory estimates to be made of delays in the response of wall temperature to the excursions of flow rate. Furthermore, they have also yielded time scales which match observed behaviour in terms of the onset and propagation of fluid temperature perturbations within the flow.

Computational simulations of the present experiments, using a fully developed flow formulation of the unsteady form of the governing equations incorporating three different low Reynolds number k-ε turbulence models produced results which display some of the interesting features of the experimental results, such as delays in the response of wall temperature and perturbations in fluid temperature variation. However, the predicted results differ significantly from model to model and there are clear discrepancies between the computed and measured variations of temperature.

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