RESPONSE OF TEMPERATURE IN HEATED PIPE FLOW TO RAMP-TYPE EXCURSIONS OF FLOW RATE

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ABSTRACT. An experimental study is reported of turbulent heat transfer to water in a uniformly heated pipe during ramp-type excursions of flow rate in which it decreased linearly with time starting from a steady condition and finishing at another one. The variation with time of outer wall temperature and fluid temperature at a number of radial positions was measured. Some measurements were also made under conditions of steady flow. The experimental results revealed a very slow response of temperature to the imposed flow excursions and big differences between temperature measured during transient flow and under steady flow conditions.

INTRODUCTION

Although transient turbulent pipe flow has been the subject of a number of investigations over the past few years, attention has been concentrated on one particular aspect of it, the so called "pulsatile" case, where flow rate varies in a sinusoidal manner about some mean level. Non-periodic transient flow in pipes has received relatively less attention. Until 1992, transients in which the flow rate varies linearly with time starting from a steady state flow condition and finishing at another one were not studied even though excursions of such a kind were of clear practical interest. Some recent measurements of the response of mean flow and turbulence in a pipe during ramp-type transient flow (He, (1992)) have revealed striking departures from pseudo-steady state behaviour and have yielded new information concerning time scales for turbulent production and diffusion.

Stimulated by these results, an investigation of the response of the temperature field in heated pipe flow to ramp-type flow excursions was undertaken (Büyükalaca (1993)). This showed that very big differences existed between temperature measured during transient flow and that under steady flow conditions at corresponding flow rates. In the case of ramp-up flow experiments (see Jackson, Büyükalaca and He (1996)) there was an initial delay of about 2 seconds before mean (ensemble-averaged) outer wall temperature began to respond to an imposed flow transient. Ensemble-averaged local fluid temperature and RMS temperature fluctuation both responded to the imposition of flow transients within a fraction of a second at all radial positions but exhibited striking perturbations in their variation.

Computational simulations of these experiments were made using several turbulence models (see Jackson *et. al.* (1994)). These provided additional insight into the processes involved, particularly in the near-wall region where measurements were not possible.

In the present paper, results from ramp-down experiments are reported and discussed. The experiments were conducted under similar conditions to those in the ramp-up case. To the knowledge of the present authors, no investigation of ramp-down transient flow has previously been reported.

EXPERIMENTAL ARRANGEMENT

The experiments were carried out using water under conditions of fully developed flow in a vertical electrically heated stainless steel pipe of internal diameter of 48.34 mm and wall thickness 1.29 mm. Figure 1 shows the arrangement used. The test section had an unheated hydrodynamic development section of length 3.7 m followed by one of length 3.0 m which was heated by resistive means. A linear variation of flow rate was achieved in a repeatable manner over prescribed periods of time using a computer controlled valve, a turbine flowmeter being used to measure the flow rate.

Wall temperature was measured using thermocouples attached to the outer surface at a number of axial locations along the heated length. Local measurements of fluid temperature were made using a traversable thermocouple probe at a distance 2.62 m downstream of the start of heating. The probe was capable of responding to turbulent fluctuations of temperature. Other measurements included, inlet and outlet fluid temperature, heating current and applied voltage. All the signals were supplied to a computer-controlled data acquisition system.

The flow rate was caused to decrease from 2.23 kg/s ($Re=5.7\times10^4$) to 0.28 kg/s ($Re=7.4\times10^3$) over various periods of time from 3 to 60 seconds. Figure 2 shows the imposed flow transients and the corresponding Reynolds numbers. All the experiments were carried out with an inlet fluid temperature

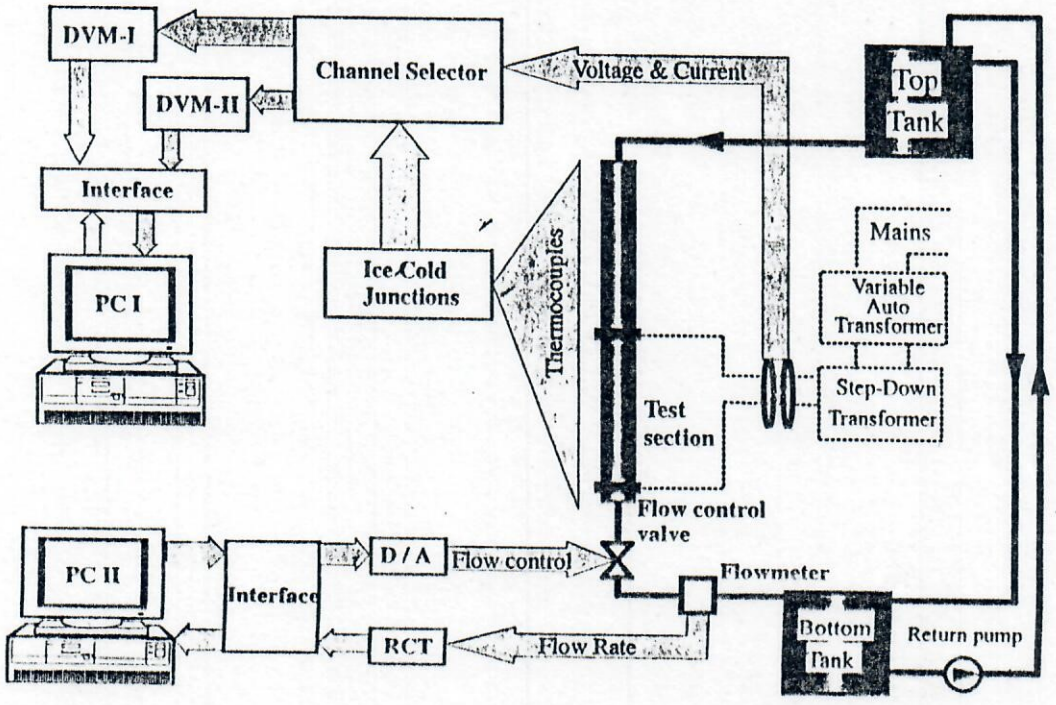


Figure 1. Arrangement of flow circuit, power supply, flow control and data logging system.

of 19.1 °C and a constant power input (wall heat flux 8.8×10^3 W/m^2). The conditions were such that influences of buoyancy were negligible. Measurements of fluid temperature were made at eleven particular radial positions in the 4 second time period experiments, five positions in the 5 second ones and one position in the rest. A series of experiments were also conducted under conditions of steady flow.

Each experiment was repeated many times and ensemble averaging was employed to obtain local values of mean temperature and root-mean-square fluctuation in the fluid and also outside of the wall.

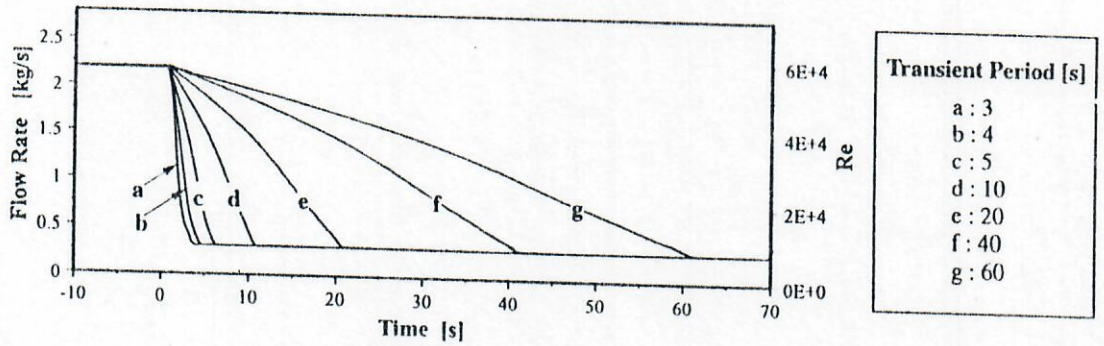


Figure 2. Imposed excursions of flow rate and Reynolds number.

RESULTS

Due to space limitations, only a representative selection results are presented here, although many other measurements were made.

The 4 Second Time Period Experiments

The variation of mean (ensemble-averaged) outer wall temperature for the 4 second time period transient flow case is shown in Figure 3 alongwith the corresponding distribution from steady flow experiments. Also shown is the "residence time" of the fluid (defined later). As can be seen, the outer wall temperature increases smoothly after only a short initial delay.

Figures 4(a) and 4(b) show, respectively, the local mean (ensemble-averaged) fluid temperature and RMS temperature fluctuation for a number of radial positions. From these it can be seen that during the flow excursion the increase of fluid temperature is only slight. Neither the local fluid temperature nor the RMS temperature fluctuation exhibit perturbations of the kind found in ramp-up flow transients (see Jackson, Büyükalaca and He (1996)). However, a three-stage pattern of behaviour is evident. At the beginning of the flow excursion, both local temperature and RMS temperature fluctuation increase smoothly for a time. In the second stage, the build-up slows down for a period. This is more pronounced in the core flow region than near the wall. In the case of RMS temperature fluctuation, the effect is not seen at all near the wall. The duration of the slow-down period varies with radial position being a maximum at the centre and becoming smaller towards the wall. In the third stage, local fluid temperature and RMS temperature fluctuation both rise smoothly at a renewed rate and approach their final steady state values slowly in an asymptotic manner.

In Figures 3 and 4, clear differences are evident between the transient and corresponding steady flow values. A striking feature of transient results is the very considerable time needed for steady state conditions to be achieved following a flow excursion (about 60 seconds).

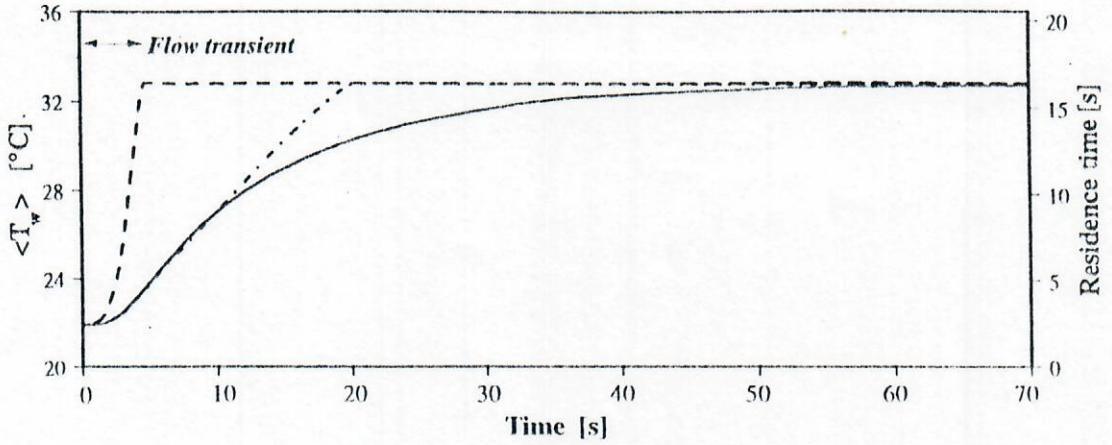


Figure 3. Variation with time of ensemble averaged outer wall temperature, 4 s transient. (***Solid line*** : transient experiment, ***Dashed line*** : steady state exeriment, ***Chain dotted line*** : residence time)

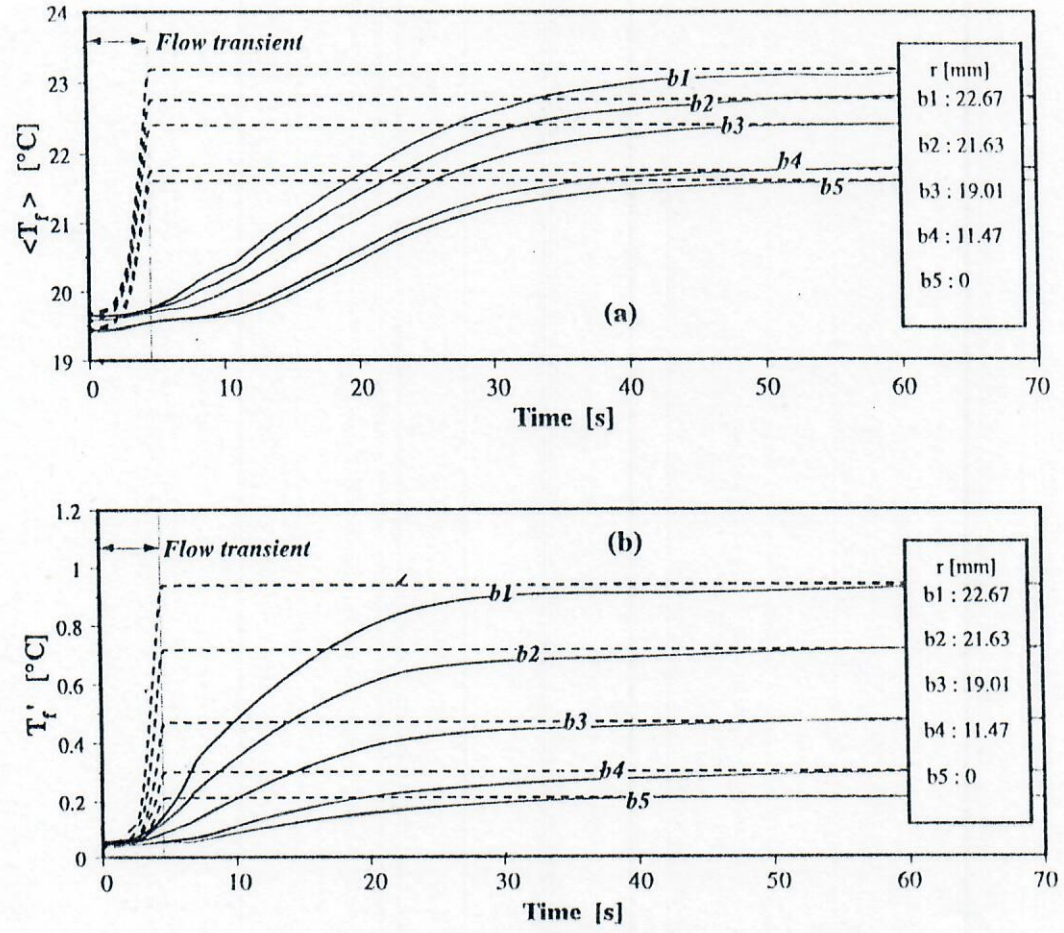


Figure 4. Variation with time of (a) ensemble averaged and (b) RMS fluid temperature fluctuation, 4 s transient. (***Solid line*** : transient experiments, ***Dashed line*** : steady state experiments)

The 20 and 60 Second Time Period Experiments

Results for longer time periods (20 s and 60 s) are shown in Figures 5 to 8. The pattern of behaviour is similar to that in the 4 second case. However, some differences can be seen in terms of the time scales involved. In the longer time period experiments, the initial delay in response of outer wall temperature is almost the same as in the 4 second time period case. However, the "slow-down" in response of local fluid temperature occurs later.

DISCUSSION

A number of matters need to be considered when interpreting results from heated pipe flow experiments with imposed excursions of flow rate. These are : the residence time of fluid in the heated pipe, the storage of heat in the tube wall, and the transient response of turbulence during and after the flow excursion. These are discussed separately below;

The rise of temperature of fluid as it flows downstream depends on the time taken for it to travel from the start of heating to the location in question, the so called "residence time". The variation of residence time has been computed for each of the experiments reported here and is shown in Figures 3, 5 and 7. As can be seen, it varies both during and after the imposed flow transients. Figure 9 shows residence times all for the transients considered here. When a flow excursion is imposed, residence time starts to increase and as a consequence fluid temperature rises. There is an associated rise of wall temperature.

Although the tube used in this study was thin, its thermal capacity nevertheless played a significant role in controlling the rate at which heat was released to the fluid. As the flow rate decreases in a ramp-down transient, fluid temperature increases and consequently so does wall temperature. Part of the energy generated is used to raise the temperature of the wall. Thus, the heat flux released into the fluid is less than that in the steady state. This can be seen in Figure 10, in which the variation of heat flux for flow excursions of various time period are shown. These have been calculated using the measured variations of outer wall. For a flow transient of time period 4 s, the heat flux value was reduced by up to 42%. The corresponding maximum reduction in the case of the 60 second time period transient was about 22%.

We turn next to the response of turbulence during and after an imposed flow transient. In the study of He (1992) measurements made in the case of ramp-down flow excursions showed that, turbulence in the near-wall region reduced almost immediately in response to the excursion. However, further away from the wall the response of turbulence exhibited delays which increased with radial position. The delay in reduction of turbulence was independent of the time period of the flow excursion and increased as the initial flow rate was reduced. At the centre of the tube, an enhanced level of turbulence persisted for about two seconds after the end of the flow excursion for an initial Reynolds number of 4.5×10^3.

Response of Outer Wall Temperature

The most striking feature of the response of ensemble-averaged outer wall temperature to a ramp-down flow excursion is the fact that it is much slower than for the ramp-up case. As indicated previously, the variation of outer wall temperature is linked to that of local fluid temperature but there is a delay associated with the time needed for diffusion of heat across the viscous sublayer and conduction through the wall. The time scale for the response of outside wall temperature to an imposed variation of temperature on the inside surface can be readily estimated and is about 0.2 s. In the case of the ramp-down transients under consideration here, the time scale for thermal diffusion across the viscous sublayer, based on its thickness at the start of the imposed flow transient is about 0.025 s. This

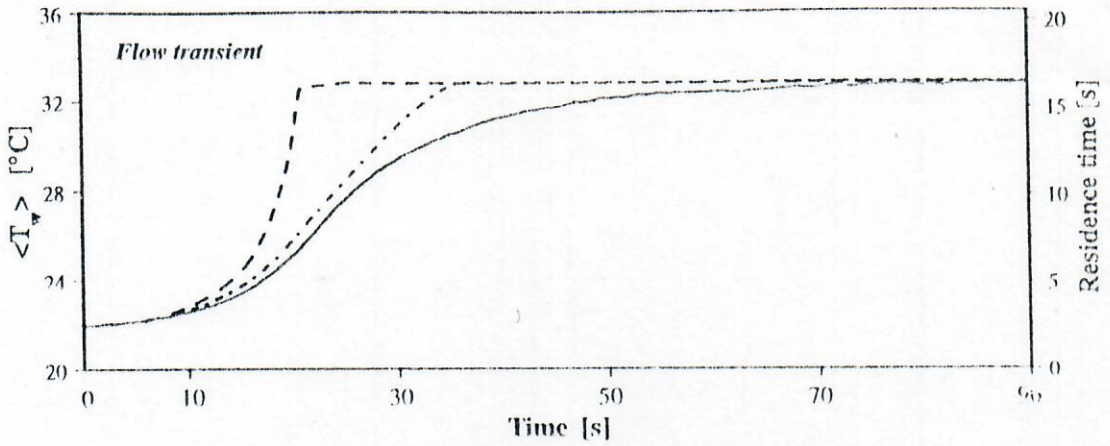


Figure 5. Variation with time of ensemble averaged outer wall temperature, 20 s transient. (***Solid line*** : transient experiment, ***Dashed line*** : steady state experiment, ***Chain dotted line*** : residence time)

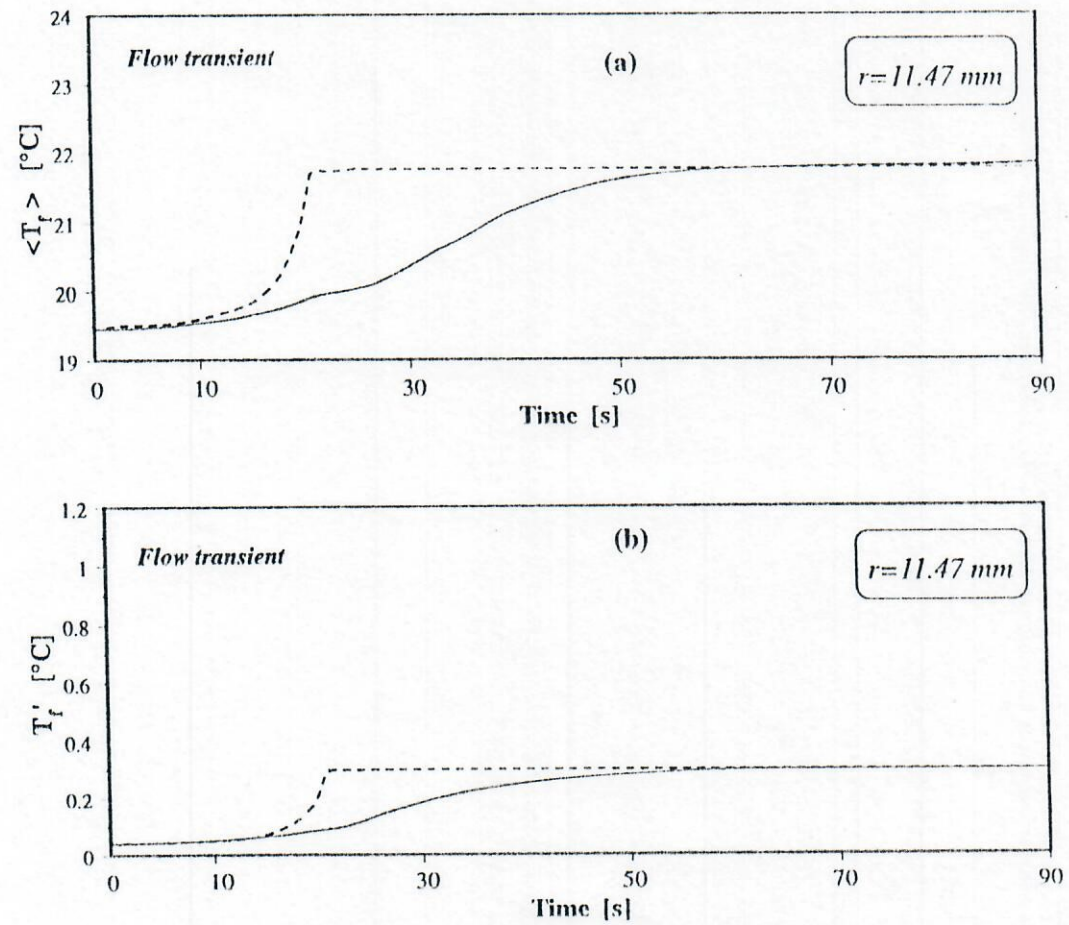


Figure 6. Variation with time of (a) ensemble averaged and (b) RMS fluid temperature fluctuation, 20 s transient. (***Solid line*** : transient experiments, ***Dashed line*** : steady state experiments)

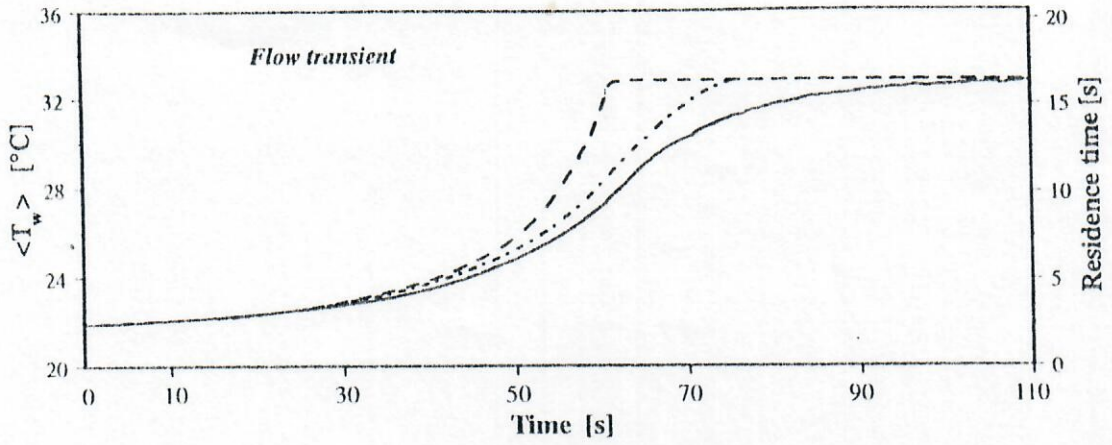


Figure 7. Variation with time of ensemble averaged outer wall temperature, 60 s transient. (***Solid line*** : transient experiment, ***Dashed line*** : steady state exeriment, ***Chain dotted line*** : residence time)

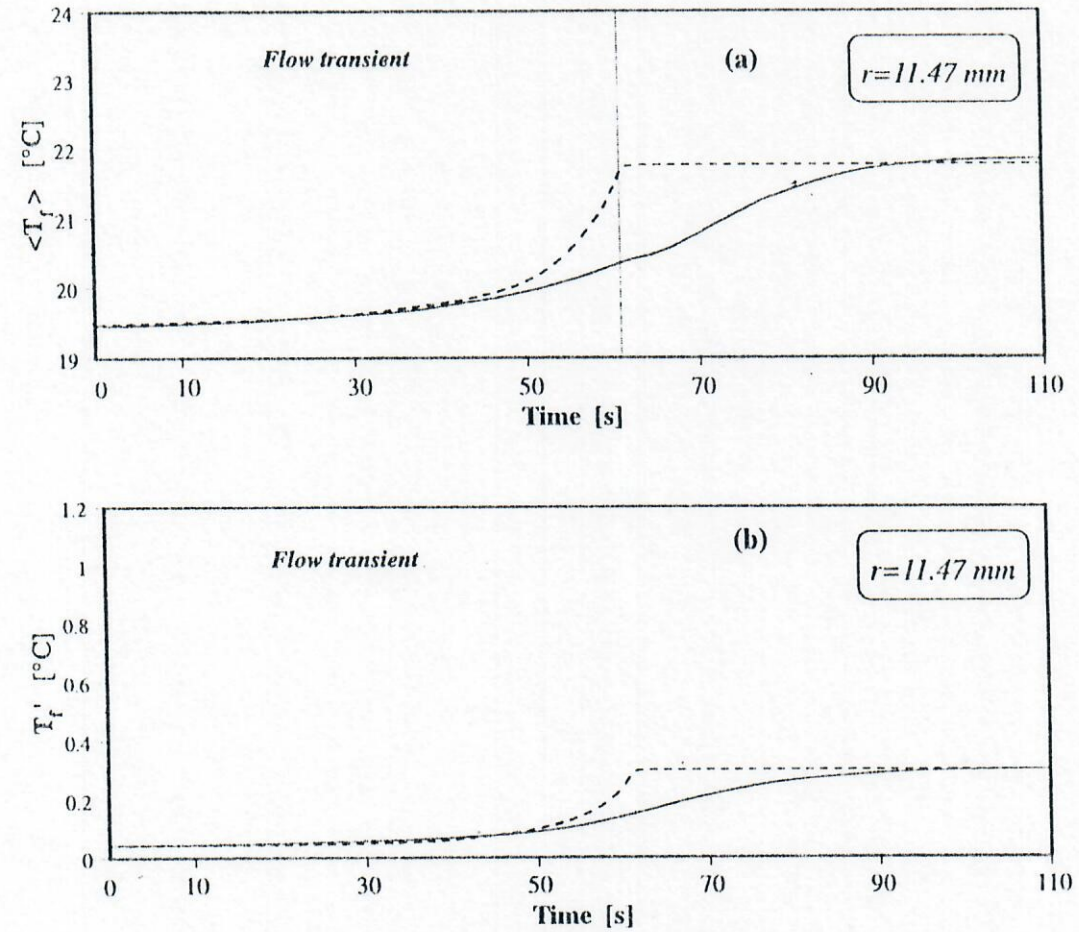


Figure 8. Variation with time of (a) ensemble averaged and (b) RMS fluid temperature fluctuation, 60 s transient. (***Solid line*** **:** transient experiments, ***Dashed line*** **:** steady state experiments)

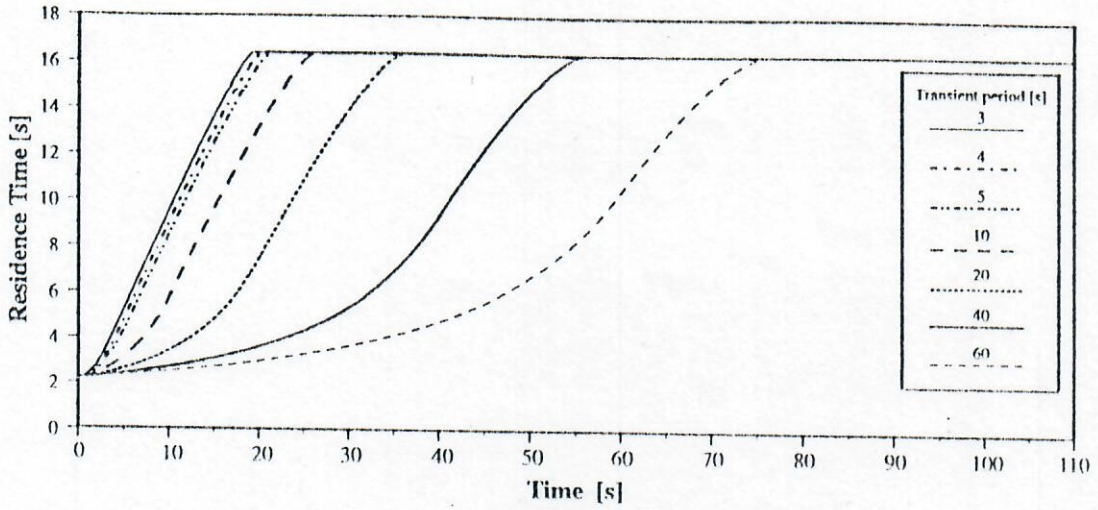


Figure 9. Variation of residence time for several flow excursion time periods.

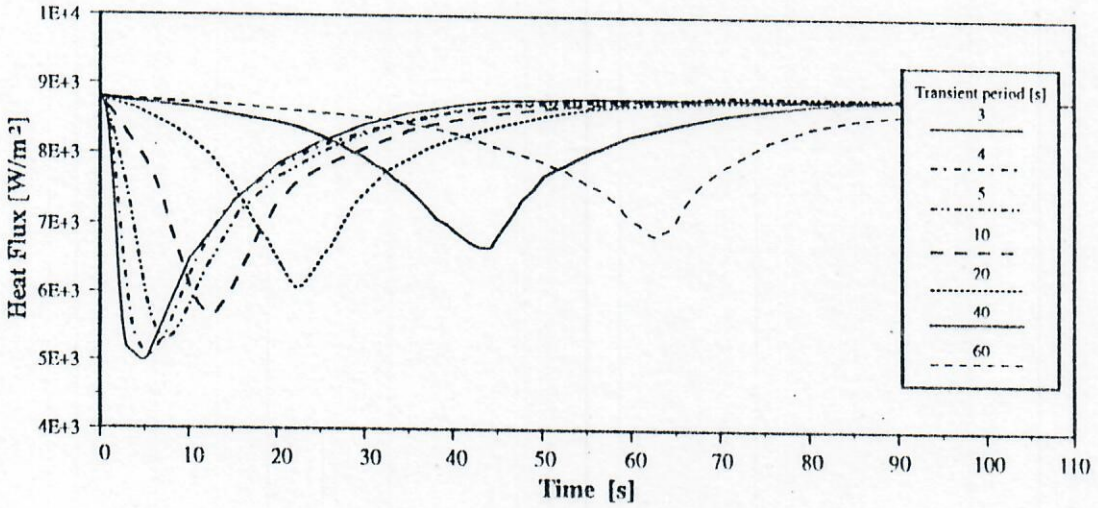


Figure 10. Variation with time of heat flux for several flow excursion time periods.

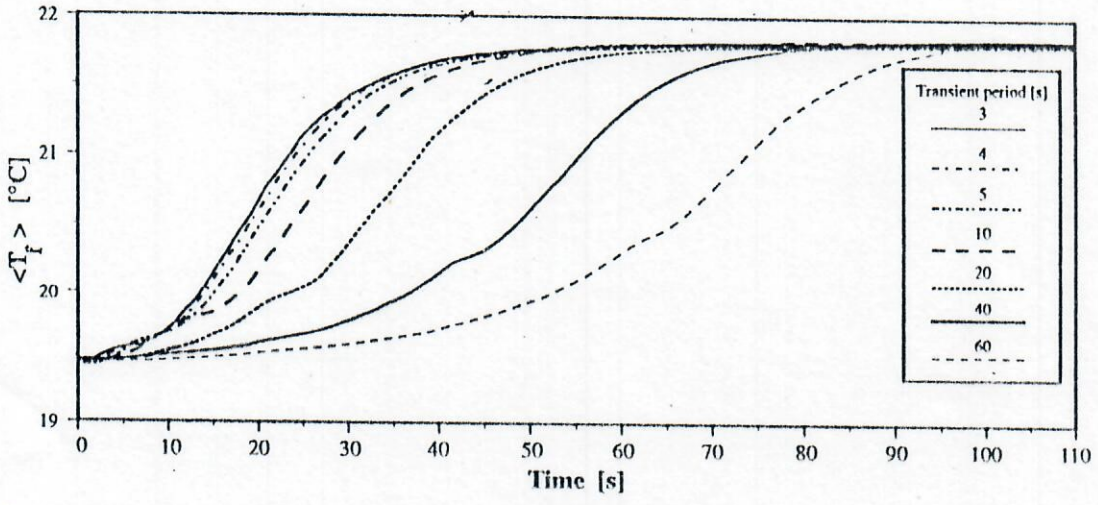


Figure 11. Variation with time of fluid temperature at r=11.47 mm for several flow excursion time periods.

compares with 0.9 s for the ramp-up case. Thus, the initial delay in the response of outer wall temperature is less than one second.

Response of Local Fluid Temperature

In the case of ramp-down transients it is the extended residence time (Figures 3, 5 and 7) and the variation of heat flux (Figure 10) which together determine the response of the fluid temperature (Figure 11). The delay in the response of turbulence is of secondary importance. As noted earlier, there is a "slow-down period". In the core fluid, this coincides with the occurrence of the peak reduction in wall heat flux and can be directly attributed to that influence.

Comparison of the response of fluid temperature (Figure 11) with the variation of residence time (Figure 9) clearly reveals that fluid temperature reaches its final steady value after the residence time has already settled to a constant value. This can be explained by the heat flux varying with time which itself is tied to the response of fluid temperature and wall temperature.

Response of RMS Temperature Fluctuation

As the initial flow rate in the ramp-down experiments is high, turbulence in the near wall region responds rapidly to the imposed flow transient and during this time there is only a slight variation of fluid temperature. A consequence of this is that no perturbation in the response of RMS temperature fluctuation will occur.

CONCLUSIONS

The most striking feature of the present study of transient turbulent flow in a heated pipe is that the response of temperature is extremely slow. It continues for a long time after the end of imposed flow excursion. Consequently, there are big differences between the transient values and the corresponding steady state ones. For the shortest time period experiment, most of the rise of temperature occurs after the excursion.

Local fluid temperature and RMS temperature fluctuation exhibit a three stage pattern of behaviour. There is a "slow-down" period between the initial rise and the final asymptotic approach to the steady state condition. The response of fluid temperature can be explained in terms of "residence time" and variation of heat flux. The "slow-down" period coincides with peak reduction of heat flux.

The variation of wall temperature is linked to that of fluid temperature. However, there is a short delay in its response due to the time needed for diffusion of heat across the viscous sublayer and conduction through the wall.

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