RESPONSE OF TEMPERATURE AND TURBULENCE TO RAMP INCREASES OF FLOW RATE OF WATER IN A HEATED PIPE

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ABSTRACT

In this study, measurements are presented of local temperature and turbulence which were made under conditions of transient turbulent pipe flow. Ramp-up excursions of flow rate are considered. Also presented are numerical simulations of the flow and heat transfer process involved using a number of advanced turbulence models.

INTRODUCTION

Laser Doppler anemometry measurements of ensemble-averaged local velocity and turbulence for fully developed turbulent flow of water in a pipe during imposed mass flow rate transients have been reported recently by Jackson and He [1]. They show that, whereas the mean flow field responds in a rather direct manner to the applied pressure gradient, there are clear delays in the response of turbulence. This is illustrated in Figure 1, where results are presented for a tube of bore 50.4 mm showing the variation of local turbulent kinetic energy with time during a ramp-up transient in which the Reynolds number was caused to increase from 7000 to 45200 in 5 seconds. Also shown, are the corresponding distributions of turbulent kinetic energy obtained from a series of steady-state experiments. It can be seen that in the vicinity of the wall there is a delay of about a second before a measurable response occurs. At the half-radius position, the delay is just over two seconds and on the axis of the flow it is over three seconds. Similar delays occur in the response of turbulent shear stress. That such delays do not depend significantly on ramp-rate was demonstrated by the results of experiments carried out with Reynolds number varying between the above limits for time periods from 2 to 60 seconds. In the near-wall region, there are clear differences between the responses of the components of the root mean square of the turbulent velocity fluctuation. The axial component starts to respond within a fraction of a second of the beginning of the transient and then, almost a second later, the radial and circumferential components start to increase. As a result of the locally increased level of turbulent energy and turbulent shear

enhanced levels of turbulent energy and turbulent stress ensues (see Jackson and He [2]). The associated time scales are clearly revealed by the results, which provide an interesting insight into the turbulence cascade process which takes place continuously in steady turbulent pipe flow, where such time scales are also involved but are not evident.

EXPERIMENTAL STUDY

In the related heat transfer study reported here, ramp-up flow transients were imposed in a long thin-walled, electrically heated pipe of similar bore to that used in the LDA study, using the same flow loop and control system. The heated pipe was preceded by a long, unheated hydrodynamic development section. A novel feature of the study was that the technique of ensemble averaging the results of many identical repeated test runs was employed. The electrical power input was kept at a fixed level and the responses of thermocouples which measured the outer wall temperature of the tube were monitored. A traversable thermocouple probe, capable of responding to the turbulent fluctuation of temperature, was used to measure the variation of local fluid temperature.

Figure 2 shows the variation with time of the ensemble-averaged outer wall temperature for a 5 second ramp-up transient between a starting Reynolds number of 7400 and a final one of 57000. Also shown is the corresponding distribution obtained from a series of steady-state experiments. An initial delay of about two seconds, which later builds up to about 4 seconds, is evident. Only a small fraction of this delay can be attributed to the thermal response of the tube wall. The remainder stems from the thermal response of the viscous sublayer and the delay in the response of near-wall turbulence to the imposed flow transient. Very similar delays were found in other experiments in which the time period of the transient was varied from 2 to 60 seconds.

Figure 3 shows the response of ensemble-averaged local fluid temperature at various radial positions for a 5 second ramp-up transient with the above starting and finishing values of Reynolds number. Again, the corresponding steady-state distributions are shown. The transient responses each involve two stages. The first stage, during which the local fluid temperature changes in a smooth, monotonic manner, covers the period of time during which there is little change of local turbulence. This is followed by a second stage during which the local fluid temperature undergoes a surprising perturbation. Changes in the turbulent thermal diffusion properties of the flow stemming from the build-up of turbulent energy cause the temperature profile shape to change in a manner which can lead to such non-monotonic local variations.

fluctuation. These also exhibit two-stage responses, the second stage of which clearly marks the arrival at the location in question of enhanced turbulent fluctuations of velocity and temperature.

COMPUTATIONAL STUDY

The interpretation of these unusual results, thought to be the first of their kind reported in the literature, has been greatly assisted by a computational study in which a number of advanced turbulence models have been used to simulate the flow and heat transfer process involved (including transient conduction within the pipe wall). Figures 5 and 6 show local turbulent kinetic energy and temperature variations computed using the low Reynolds number, k-e turbulence model of Launder and Sharma [3]. These computational results capture most of the features evident in the experimental results very well indeed. Furthermore, they provide information concerning the inner wall and near-wall temperature behaviour not available from our measurements.

CONCLUSIONS

The outer wall temperature responds to an imposed flow rate transient with an initial delay of about two seconds. This is mainly due to the thermal response of the viscous sublayer and the delay in the response of near-wall turbulence to the imposed flow transient. Changes in the turbulent thermal diffusion properties of the flow stemming from the build-up of turbulent energy cause the distrubution of mean fluid temperature and RMS turbulent temperature fluctuation to exhibit two-stage responses. The low Reynolds number, k-e turbulence model of Launder and Sharma captures most of the features evident in the experimental results.

REFERENCES

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[3] Launder, B.E. and Sharma, B.I. "Application of the energy-dissipation model of turbulence to the calculations of flow near a spinning disc", *Letters, Heat and Mass Transfer*, Vol. 1, pp. 131-138, 1974.

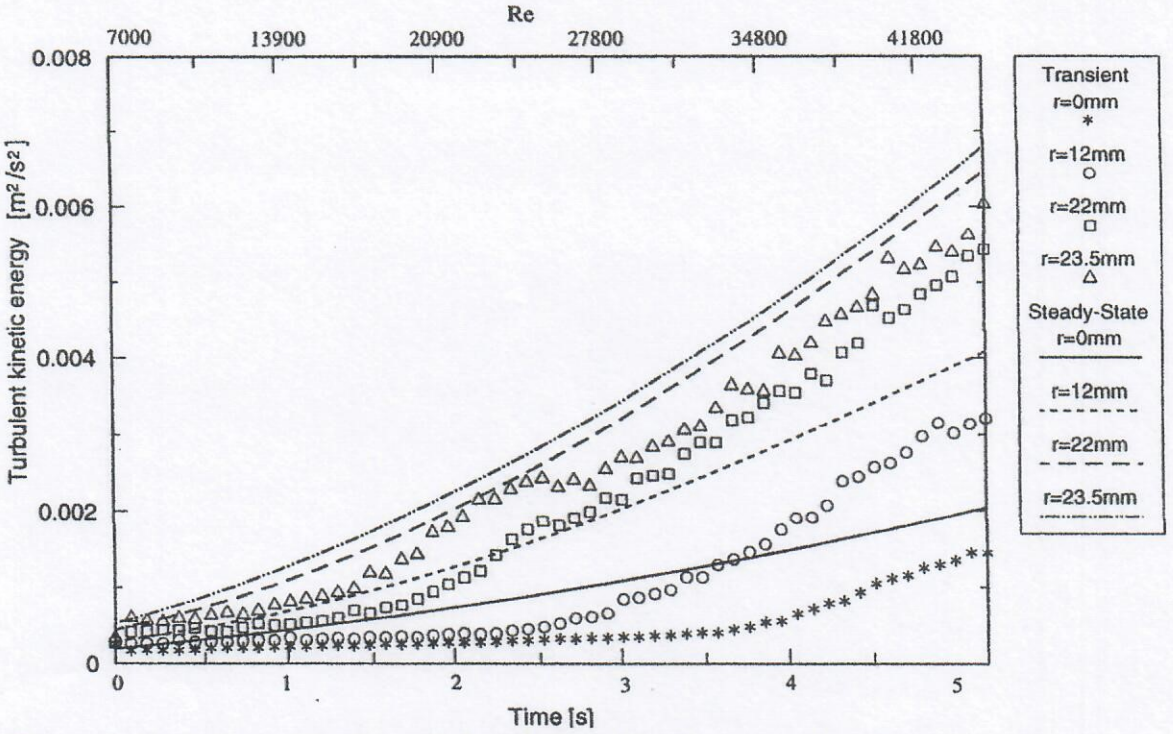


Figure 1. Variation with time of of turbulent kinetic energy in a 5 second transient.

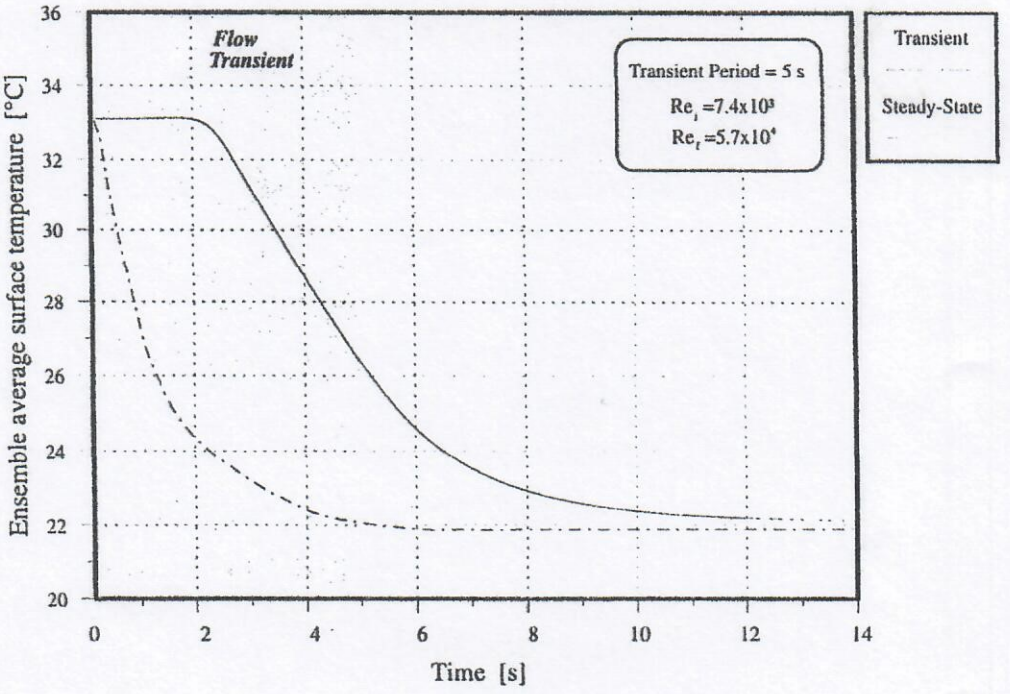


Figure 2. Variation with time of ensemble averaged surface temperature in a 5 second transient.

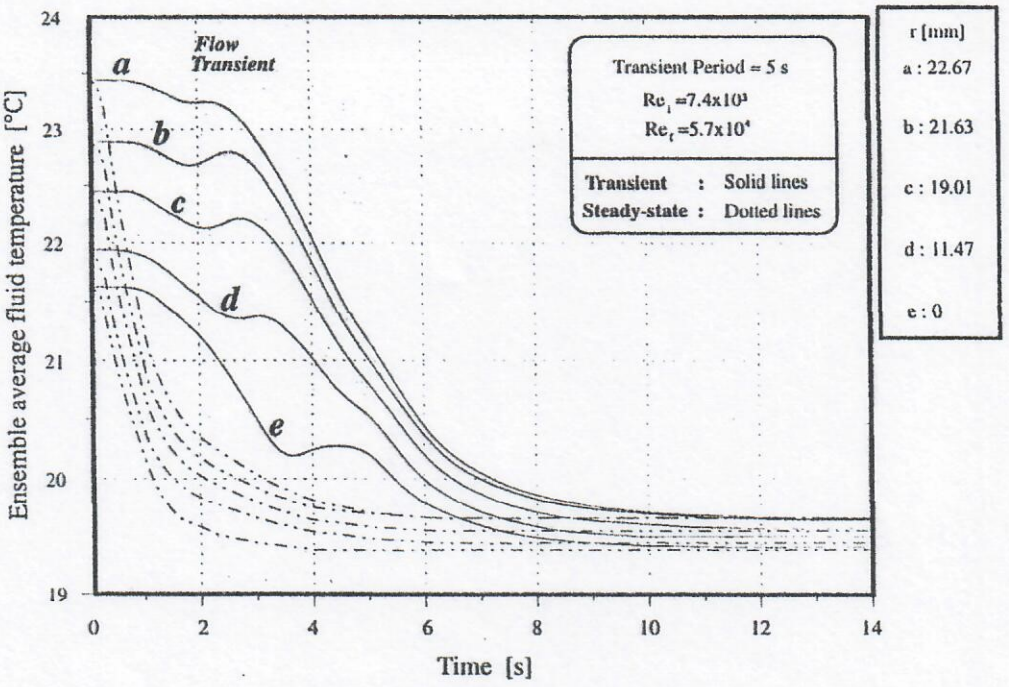


Figure 3. Variation with time of ensemble averaged fluid temperature in a 5 second transient.

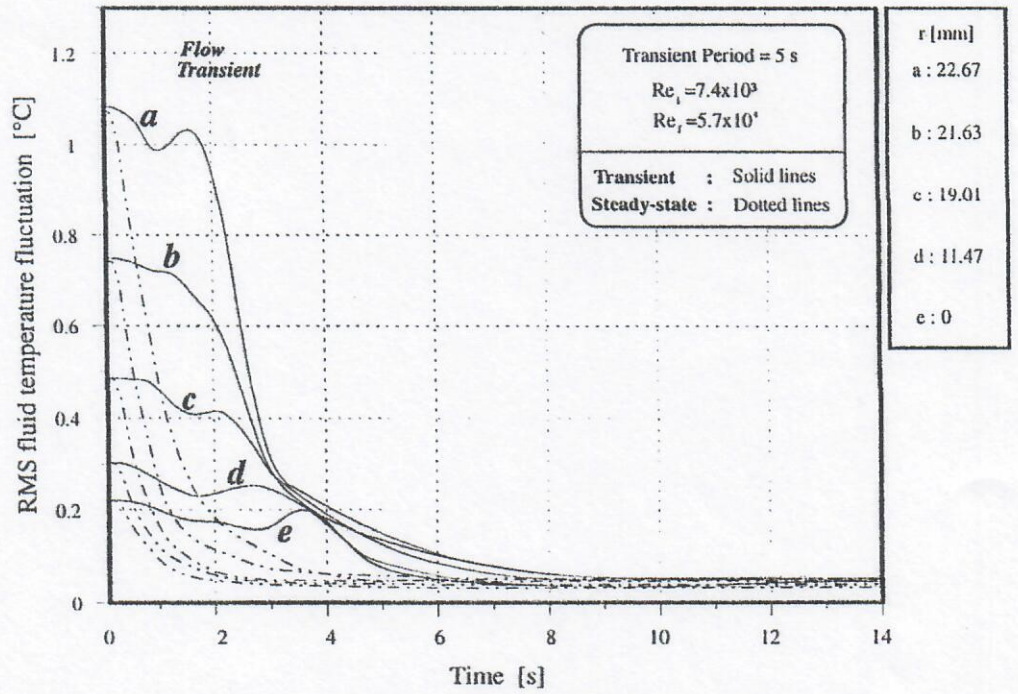


Figure 4. Variation with time of RMS fluid temperature fluctuation in a 5 second transient.

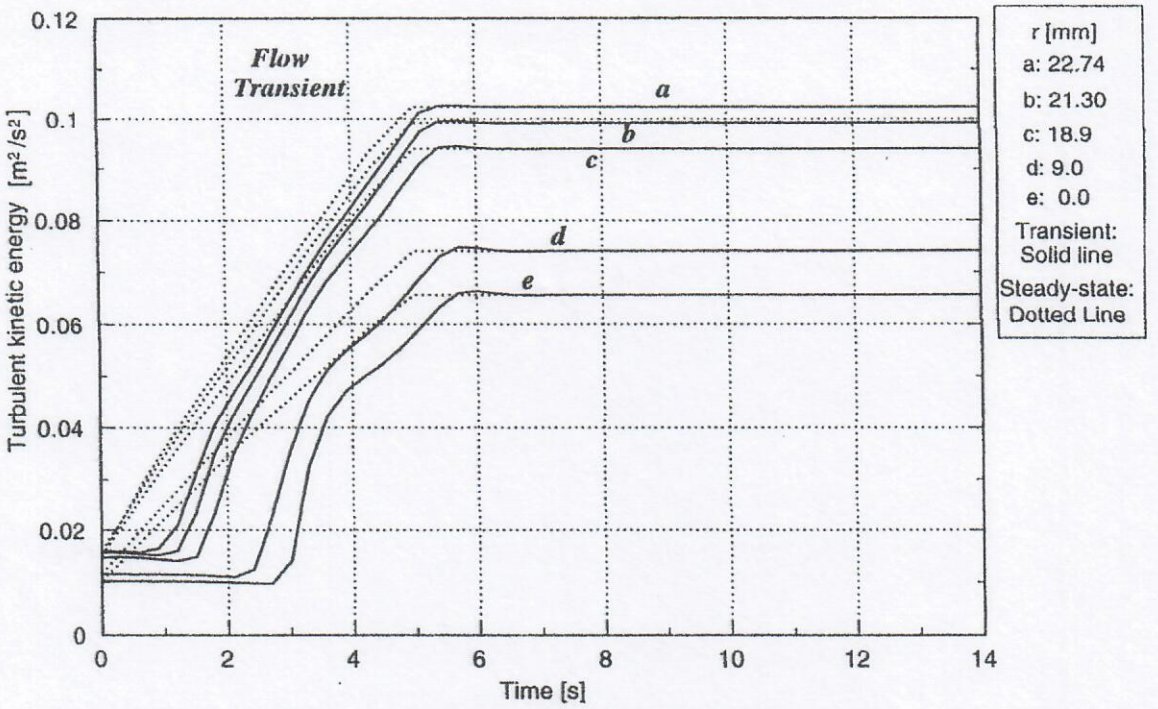


Figure 5. Variation with time of turbulent kinetic energy (From Launder and Sharma model).

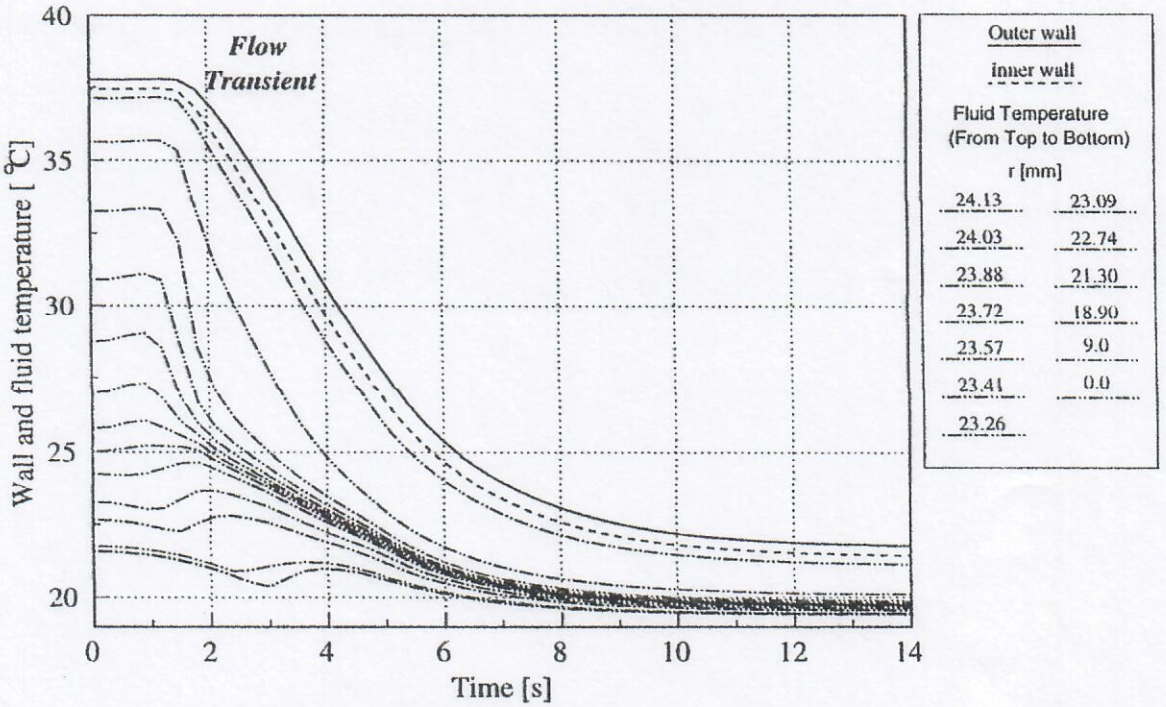


Figure 6. Variation with time of wall and fluid temperature (From Launder and Sharma model).

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