STUDIES OF THE RESPONSE OF TEMPERATURE TO IMPOSED EXCURSIONS OF FLOW RATE IN A HEATED TUBES

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ABSTRACT

Turbulent flow and heat transfer in tubes has been the subject of many experimental investigations but there are still matters, such as that specified in the title of this abstract which remain to be better understood. Simple flow visualisation techniques in experimental studies have exposed important features of the structure of turbulent boundary layer flow and increasingly sophisticated optical diagnostic techniques have led to further advances enabling the time scales involved in turbulence production, turbulent diffusion, convection and dissipation to be measured. A good picture of the response of turbulence to flow rate excursions has been obtained for unheated tubes. In the present paper, results from some experiments with heated tubes will be described in which the thermal response during such excursions has been studied. The conditions were varied so as to investigate the influence of transient flow on the departure from pseudo-steady heat transfer behaviour. Although, the experiments were carried out some considerable time ago and the results have been published in academic journals concerned with the fundamentals of fluid flow and heat transfer it is possible that the work has not yet come to the notice of nuclear reactor thermal analysts.

1. INTRODUCTION

During the period 1970 to 1990 the corresponding author of this paper directed a comprehensive programme of research at the University of Manchester on buoyancy-influenced heat transfer (see review papers by Jackson et al 1989 [1] and Jackson 2006 [2]). The research included a detailed experimental investigation of mixed convection heat transfer to water in a vertical heated tube of internal diameter 100 mm under conditions of steady flow (Rouai, 1987 [3]). On completing that research the same student went on to perform some exploratory studies of forced convention heat transfer with a fixed heating rate and imposed excursions of flow rate using that tube. These included ramp-up and ramp-down transients between steady initial and final conditions and also repeated sinusoidal excursions of flow rate about a fixed mean level. The tube was arranged vertically with water at 20^0C entering it at the top and flowing downwards. The heat flux of 7.75 kW/m^2 and flow rate limits, 3.5 x 10^3 kg/hr (Re≥13000) and 7.0 x 10^6 kg/hr (Re≥26000) were chosen to ensure that buoyancy influences were negligibly small under the conditions of these transient flow experiments.

Ramp-up and ramp-down flow rate excursions (starting and ending with steady flow) were imposed with time periods ranging from 18 s to 70 s. For the shortest time period of 18 s, strong departure from pseudo-steady heat transfer behaviour was observed with both the ramp-up and ramp-down cases. The thermal response was greatly delayed and continued for a further 20 s beyond the end of the flow rate excursion. For the longest time period of 70 s, pseudo-steady behaviour was approached (the departure from that condition being somewhat greater in the ramp-up case).

The repeated sinusoidal excursions of flow rate between the above-mentioned limits with the same heating rate were imposed for time periods ranging from 20 s to 180 s. For the shortest time period the amplitude of the heat transfer was strongly attenuated compared with the pseudo-steady behaviour and there was a marked phase shift and distortion from a sinusoidal variation. For the longest time period pseudo-steady behaviour was approached.

Detailed explanations of the reasons for the delayed responses in the ramp-type transients and the phase shift, attenuation and distortion in the pulsating transients could not be given at that time because understanding of the turbulence dynamics was still rather limited, although it was clear that delays in the production, dissipation of turbulence and transportation of heat by turbulent diffusion were involved. Therefore, the exploratory study prompted two comprehensive fundamental investigations of turbulence dynamics in a tube with transient flow, firstly without heating (He, 1992 [4]) and then with heating, (Buyukalaca, 1993 [5]), to try to obtain a detailed understanding of the mechanisms involved. These studies were duly reported in a number of conference papers and then in three detailed publications in academic journals. Although the work done has clear relevance to important practical applications, such as nuclear reactor safety, the corresponding author of this paper suspects that it might not yet have come to the notice of those concerned with such matters. Thus, the present paper has been prepared to ensure that the work is known about and can be used to help in enabling the limits to be established beyond which the assumption of pseudo-steady behaviour is no longer applicable in such flow excursions.

2. A STUDY OF TURBULENCE UNDER CONDITIONS OF TRANSIENT FLOW IN AN UNHEATED TUBE

2.1 Ramp-type excursions of flow rate

2.1.1 Overview

In 2000, He and Jackson published a detailed journal paper [6] describing an investigation of fully developed ramp-type transient flow in a tube using water as the working fluid (see also earlier conference papers, [7, 8, 9, 10 and 11]. Linearly increasing or decreasing excursions of flow rate were imposed between steady initial and final values. A three-beam, two-component laser Doppler anemometer utilising frequency trackers was used to make simultaneous measurements of either axial and radial, or axial and circumferential, components of local velocity. Values of ensemble-averaged mean velocity, root-mean-square velocity fluctuation and turbulent shear stress were found from the measurements.

Being the first really detailed study of ramp-type transient turbulent flow, the investigation yielded new information and valuable insight into certain fundamental aspects of the turbulence dynamics. Some striking features were evident in the response of the turbulence

field to the imposed excursions of flow rate. Three different delays were identified: a delay in the response of turbulence production; a delay in turbulence energy redistribution among its three components; and a delay associated with the propagation of turbulence radially. The last of these was the most pronounced under the conditions of the study.

The first response of turbulence was found to occur in the region near the wall where the turbulence production peaks. The axial component of turbulence responded earlier than the other two components and was found to build up faster. The response propagated towards the centre of the pipe through the action of turbulent diffusion at a speed which depended on the Reynolds number at the start of the flow rate excursion. In the core region, the three components of turbulence energy responded in a similar manner. Turbulence intensity was reduced in the case of accelerating flow and increased in decelerating flow.

2.1.2 Some details of the experimental investigation

Flow loop and test section

The experiments reported were carried out using a test section which was a tube of inside diameter 50.8 mm and length 9 m in which fully developed flow was achieved. A closed circuit flow arrangement was employed. The water was driven through the test section by the constant head difference between two tanks. Flow control was achieved by adjusting the resistance using a pneumatically operated, computer-controlled valve situated downstream of the test section. A turbine flow meter placed in series with the flow control valve was used to measure the flow rate.

The test section consisted of a long length of polyvinyl chloride tube followed by a 2 m length of precision bore glass tube (wall thickness 2 mm). Both were very smooth internally and the inside diameters were carefully matched so that the junction between them was flush. Fully developed flow was achieved at the transparent section. Five carefully prepared pressure tappings were installed at equal intervals along the test section and the pressure differences between the tappings were measured using a decision differential pressure transducer.

Laser Doppler anemometer

The laser Doppler anemometer system enabled simultaneous measurements to be made of both axial and radial, or axial and circumferential, components of the velocity field. The forward scatter mode of operation was employed. An arrangement of the beams was chosen which gave the velocity components in the directions $\pm 45^{o}$ to the axis of the pipe. The glass section of tube was surrounded by a transparent box of square cross section filled with water. This helped to overcome difficulties due to the curvature of the wall.

Flow control and data acquisition systems

The flow control and data acquisition system utilized two personal computers and a Microvax computer system. PCI modules were used for interfacing the computers with the experiment. These made digital to analogue and analogue to digital conversions and incorporated standard clock, trigger signal and other special functions.

Flow control was achieved using one of the personal computers in conjunction with an electronic position controller and a pneumatic activator. A prescribed flow rate was converted to a valve-opening signal in the computer and sent to the electronic position controller. The latter then drove the pneumatic activator to operate the valve until the demanded opening had been achieved. Very accurate flow control with excellent repeatability was achieved using this system.

The flow rate passing through the test section was measured by the turbine flow meter, the electrical output signal from which was of square-wave form with a frequency proportional to flow rate.

Two data sampling schemes were available. Using the first one, up to eight channels of data could be sampled at high speed (utilizing a personal computer and the Microvax computer). The data collected were sent directly to the Microvax computer which had a large memory for data storage and performed data processing at high speed. In the second scheme, data could be sampled using a personal computer with the use of the sample-and-hold technique to ensure that information sampled from different channels corresponded to exactly the same point in time.

Experimental conditions

In the main experimental program of the study, ramp-up experiments were performed in which the ramp rate was varied by imposing excursions of flow rate during which the bulk velocity increased linearly with time from an initial value of $0.138\,\mathrm{ms}^{-1}$ to a final value of $0.891\,\mathrm{ms}^{-1}$ in periods of time which ranged from 2 s to 90 s. Thus, the initial and final Reynolds numbers were constant (at the values 7000 and 45 200) but the dimensionless ramp rate parameter increased systematically from 0.34 (pseudo-steady flow) to 15.3 (unsteady turbulent flow). Corresponding experiments were performed in which ramp-down excursions of flow rate were imposed. Bulk velocity decreased from 0.891 ms^{-1} to 0.138 ms^{-1} over periods of time which ranged from 45 s to 2 s. The initial and final Reynolds numbers Re_0 were constant (at the values 45200 and 7000) and the dimensionless ramp rate parameter varied systematically in the range -0.021 to -0.46. As a ramp-down excursion of flow rate proceeded, the velocity and time scales reduced and delays in the response of turbulence became progressively longer. Therefore, greater departures from pseudo-steady conditions developed.

2.1.3 Summary of the results

This fundamental study of the mean flow and turbulence fields in ramp-type excursions of flow rate yielded useful new information concerning transient turbulent flow and valuable insight into certain fundamental aspects of the turbulence dynamics. The main conclusions arrived were:

(a) In fast ramp-type excursions of flows the acceleration (deceleration) of the flow was initially practically the same throughout the core and the boundary layer regions and the velocity gradient became steeper in a very thin region near the wall.

(b) A particularly interesting feature of the response of turbulence to imposed ramp-type excursions of flow rate was the occurrence of various delays. Three were identified as: a delay in the response of turbulence production, a delay in turbulence energy redistribution among its three components and a delay associated with the propagation of additional turbulence radially. As a result of these delays turbulence intensity was attenuated in accelerating flow and increased in decelerating flow.

(c) On imposing a ramp-up flow excursion, the mean velocity field started to respond first. The velocity gradient increased in a region very near the wall, the extent of which gradually grew with time. Until this region overlayed the region where turbulence production peaked, there was little increase of turbulence. Therefore there was a delay in the response of turbulence production.

(d) In the wall region, the responses of the various components of turbulence were different. The axial component responded to an imposed transient with only a short delay whereas the radial and circumferential components each exhibited distinct two stage responses with a longer delay which did not depend on the radial position. The difference in response reflected the process of redistribution of turbulent energy between the components through the action of pressure strain.

(e) The additional turbulent energy generated near the wall propagated outwards at a speed which was mainly dependent on the conditions prevailing when the additional structure was generated. It increased with the increase of the starting Reynolds number of the transient, but was not affected by the imposed acceleration of the flow except in the case of very fast transients. In this case, turbulence generated later could overtake that generated earlier in the course of propagating outwards and then a reduced delay was experienced.

(f) As a result of the time needed for propagation, the development of turbulence at positions away from the wall region exhibited a two-stage variation. During the early part of a transient, normal turbulent stresses responded slowly. The delay stage ended with the arrival of additional turbulence originating from the wall region. Then the developing stage began. The response of each of the normal turbulent stresses in the core region was similar. The time scale for the process of the redistribution of turbulent energy between the three components was much smaller in this region than that for the propagation of turbulence.

(g) In the wall region, the response of the turbulent shear stress was similar to that of the radial and circumferential normal stresses. In the core region, the delay in its response was similar to those of the normal stresses. However, the shear stress remained unchanged during the delay.

(h) Inertia played an important role in the momentum balance even when the imposed excursion of flow rate was slow and little effect of the transient was seen on the mean flow and turbulence fields. The direct effect of inertia on the mean flow field was only felt in the early stages of faster transients.

(i) The appropriate dimensionless groups for similarity and scaling in the case of ramp-type transient turbulent flows were identified as the initial and final Reynolds numbers

and a ramp rate parameter. For very fast transients, an alternative parameter was proposed based on the delay in the response of turbulence production rather than the time scale for turbulence propagation.

2.2 Pulsating flow in with sinusoidal variation of flow rate about a steady mean level

2.2.1 Overview

In 2009 He and Jackson [12] published a detailed study of pulsating turbulent flow in a tube (see also associated conference papers [13] and [14]). Measurements of instantaneous velocity were again made using Laser Doppler anemometry. Local values of ensemble-averaged axial velocity, and radial and axial components of root-mean-square turbulent velocity fluctuation were obtained. The frequency ω of the imposed pulsation of flow rate was varied systematically over a wide range covering inner scale dimensionless frequency $\omega\nu/U_\tau^2$ (in which ν is kinematic viscosity and U_τ is friction velocity) from 0.004 to 004. In terms of outer scale frequency $\omega D/U_\tau$ the corresponding values ranged from 1.8 to18. In addition, effects of changing the mean flow rate and the amplitude of flow rate pulsation were studied.

Radial distributions of the amplitude of the modulation of ensemble-averaged axial velocity and axial and radial components of RMS turbulent fluctuation, and their phase shifts relative to the imposed flow pulsation, were reported for conditions which included the *low*, *intermediate* and *high frequency* ranges. These added to and reinforced the information available on pulsating flow from the extensive experimental work already reported in the literature.

2.2.2 Experimental details

The experimental facility and measurement equipment used in the investigation was the same as that used earlier the study of ramp type transient flow. Data reduction was again based on ensemble averaging, in this case of the results from numerous successive flow pulsations.

In the majority of the experiments, the Reynolds number based on the time mean value of the flow rate was 7000 and the amplitude (peak to mean) was 20% of the mean value. The time period of the pulsation was varied systematically from 2 to 20 seconds covering a range of non-dimensional frequency parameter. Experiments with higher values of mean Reynolds number (10500 and 14000) and a higher value of the ratio of flow rate amplitude to mean ratio (47%) were also conducted.

2.2.3 Summary of results

The results of this study showed that the variation with frequency of the amplitude of velocity modulation exhibits a non-monotonic but consistent pattern.

In the case of the higher frequencies, the flow in the core region exhibits a ‘frozen’ behaviour, the amplitude of the velocity modulation being constant. With reduction of pulsation frequency, the extent of this region reduces until eventually ‘freezing’ no longer occurs.

In very high frequency pulsating flows, the maximum amplitude of the velocity modulation occurs at a location near the wall. It moves away from the wall as the frequency of the pulsation reduces and for pulsation of very low frequencies, the maximum amplitude occurs at the centre of the pipe.

The responses of the axial and radial components of rms fluctuating velocity are quite similar in the core region of the flow but are different in the wall region, where the latter exhibits a bigger delay than the former. This difference is associated with turbulence energy re-distribution from the axial component to the other components.

In the core region, the amplitude of modulation of both the axial and radial components of RMS turbulent fluctuation reduces with the increase in the frequency of the flow pulsation, eventually becoming zero as the turbulence field in that region becomes 'frozen'.

The response of turbulence to an imposed pulsation of flow rate initially occurs in the wall region and then propagates into and across the core. Thus there is an additional time delay in the response of the turbulent fluctuation in the core region, which grows with the distance from the wall. It remains more or less the same irrespective of the frequency of the flow pulsation but decreases with increase of mean flow rate.

3. A DETAILED STUDY OF HEAT TRANSFER IN A TUBE UNDER CONDITIONS OF TRANSIENT TURBULENT FLOW

3.1 Overview

This section of the paper is concerned with the response of fluid temperature within a heated pipe to imposed excursions of flow rate and is based on work carried out in the course of the PhD study of Buyukalaca, 1993 [5] which was reported in a detailed journal paper published by Jackson, Buyukalaca and He, 1998 [15], (see also Jackson, Buyukalaca and He [16], Jackson, He and Buyukalaca [17] and Buyukalaca and Jackson, [18]) and Jackson, Buyukalaca and He [19]). The paper describes experiments 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 flow rate range covered in the transient flow experiments.

These transient flow experiments on heat transfer in a tube showed that there was 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 stemmed from the delayed response of turbulence to the imposed excursions of flow rate.

The results provided independent confirmation of ideas concerning the modelling of time scales for the production and diffusion of turbulence in pipe flow developed in the course of the fundamental studies on transient turbulent flow described in Section 2. Ensemble-averaged local fluid temperature also varied in an unusual manner. Instead of falling monotonically with increase of flow rate, as might have been expected, it started to rise at some stage, reached a peak value and then fell again. The release of heat stored in the pipe wall contributed to this behaviour.

3.2 Experimental arrangement

Water at atmospheric pressure was used as the working fluid. It flowed from a header tank downwards through a test section made from stainless steel tube 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 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 length of 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 tube was covered by thermal insulation material of very low thermal conductivity.

The temperature of the heated section 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.

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.

3.3 The experiments

During the imposed excursions of flow rate in the main series of experiments, 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 was varied from 3 to 60 s. All the experiments were carried out with an inlet fluid temperature of 19.1°C and a fixed power input. It was ascertained that with this power input 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. A series of experiments was performed under steady flow conditions 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.

3.4 Summary of the results

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

Wall temperature exhibited a delayed response to imposed excursions of flow rate. This was 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 tube wall.

The responses of RMS fluctuation of outer wall temperature exhibited perturbations having peaks which occurred shortly after the ensemble-averaged outer wall temperature began to respond.

Local ensemble-averaged fluid temperature and RMS fluctuation of fluid temperature both started to respond to the imposition of a flow transient within a fraction of a second at all radial positions. However, they also exhibited perturbations in their variation. The response of local fluid temperature was explained in terms of a re-distribution of temperature, following a delayed response of the turbulence field. This was accompanied by release of heat stored in the tube wall.

Peaks on the curves of RMS fluctuation of local fluid temperature provided evidence concerning the response of turbulence in pipe flow to ramp-type excursions of flow rate which substantiated the ideas obtained from the earlier work with an unheated tube described in Section 2.

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

4. CONCLUDING REMARKS

As indicated earlier the main aim in producing this paper has been to try to ensure that the work described here on forced convection heat transfer in tubes with imposed excursions of flow rate is brought to the notice of engineers and scientists involved in nuclear reactor safety studies so that it can be utilised to enable the limits beyond which pseudo-steady behaviour might be achieved under conditions forced convection with transient flow. The details of the exploratory experimental investigation outlined in Section 1 have not been published but can be obtained from the corresponding author in the form of a short report prepared using the material from Reference 3. The work described in Sections 2, 3 and 4 is described in detail in the open literature (see references 6, 12 and 15).

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