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EFFECT OF WALL HEAT FLUX ON THE LONGITUDINAL VELOCITY & TEMPERATURE FIELDS IN INITIALLY FULLY DEVELOPED FLOW OF AIR IN A PIPE

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SUMMARY Measurements of longitudinal velocity and temperature fluctuations are reported for different wall heat fluxes in a pipe. At a flow Reynolds number of 55226, the heat flux ranged from 200 to 1300 Wm^{-2} resulting in temperature differences between the pipe wall and centre of the flow of up to 68°C. The pipe was vertical in order to retain axisymmetry under the influence of buoyancy forces. Measurements were performed at 63 pipe diameters from the pipe inlet where the flow is fully developed in the absence of heating. Only the last 35 diameters were heated. Results are reported for the effect of heat flux on the mean velocity and temperature distributions, the turbulence intensity, the temperature fluctuation intensity, the cross-correlation between velocity and temperature as well as the effect on the corresponding spectral values. In addition, measurements of the coherence were performed.

NOTATION

a	,	radius of pipe;
c_p	,	specific heat;
$E_1(f)$	,	fraction of energy of $\overline{u^2}$ associated with f;
f	,	frequency, Hz;
q''_w	,	wall heat flux ;
r	,	radial coordinate ;
Re	,	Reynolds number based on pipe diameter and bulk velocity;
T	,	temperature at r;
T_c	,	temperature at centreline
T_w	,	wall temperature ;
u	,	longitudinal velocity fluctuation;
U	,	local mean velocity
U_c	,	mean velocity at centreline of pipe
U_τ	,	friction velocity ;
y^+	,	non-dimensional distance from wall = $y\, U_\tau/\nu$;
$\overline{}$	,	denotes time averaging;
$\vert\;\vert$	,	absolute value
γ^2	,	coherence = $\vert\overline{u(f)\ \theta(f)}\vert^2 / [(\overline{u^2(f)}\ \overline{\theta^2(f)})]$
$\Gamma(f)$	,	fraction of energy of $\overline{\theta^2}$ associated with f ;
θ	,	temperature fluctuation ;

1 INTRODUCTION

The advent of direct numerical simulation of turbulent velocity and temperature fields using sub-grid scale modelling has brought with it the need for reliable spectral data for testing of computed results against measured ones. Numerical simulation for heated channel flows by Grötzbach and Schumann (1977) indicated temperature fluctuation intensities to be up to 20% larger than those reported for pipe flow by Bremhorst and Bullock (1973). Furthermore, computed spectra of the longitudinal velocity fluctuation, u, and the temperature fluctuation, θ, by Grötzbach (1979), showed significantly different trends to those reported by Bremhorst and Bullock (1970) for pipe flow end Fulachier and Dumas (1976) for boundary layer flow. The numerically predicted spectra did, however, agree with the measured spectra reported by Zaric (1975) for channel flow. Since channel, pipe and boundary layer flows behave similarly everywhere except far from the wall, it is of interest to establish whether the θ spectrum contains more high frequency energy relative to that at low frequencies when compared with the u spectrum as found by Bremhorst and Bullock (1970) and Fulachier and Dumas (1976) or vice versa as shown by Grötzbach (1977) and Zaric (1975).

Since the computed results were for incompressible flow where the temperature field had no influence on the velocity field, it is necessary to note the temperature levels used by the various experimentalists. Bremhorst and Bullock (1970 and 1973) used a temperature difference between the heated wall and the minimum across the flow section of 9.1°C, Fulachier and Dumas (1976) a difference of 21-22°C and Zaric (1975) a difference of about 50°C. The latter is a particularly large temperature difference which gives rise to considerable buoyancy effects in the flow. These can be expected to change the u spectrum as can be seen from the spectra measured by Zaric (1975) under isothermal and non-isothermal flow conditions. Unfortunately, the change is only minor and hence insufficient in order to explain the difference between the results of the latter and the other investigators.

During the seventies significant developments in the understanding of dynamic hot-wire behaviour under non-isothermal flow conditions took place, Maye (1970), Bremhorst and Gilmore (1978), Højstrup et al (1976) and others. It was shown that for a hot-wire of small length-to-diameter ratio and/or high thermal conductivity, the temperature fluctuation sensitivity of the wire will be frequency dependent due to end conduction. Bremhorst and Bullock (1970) used a temperature sensing wire of tungsten with length-to-diameter ratio of 560, Zaric (1975) used a tungsten wire with a length-to-diameter ratio of about 300 whereas Fulachier and Dumas (1976) used a platinum-rhodium wire with a length-to-diameter ratio of 320. In the first and third cases, multiple wire arrays were used to permit easier separation of velocity and temperature signals but all authors appear to have relied upon static calibration of the wires with no correction for dynamic effects. Bremhorst and Gilmore (1978) have shown that provided the wire length-to-diameter ratio is sufficiently high and its conductivity sufficiently low at a given stream velocity, then the difference between static and dynamic responses is negligible. The experimental conditions used by Fulachier and Dumas (1976) were in fact the most favourable from this point of view whereas those used by Zaric (1975) were the least favourable. Retrospective correction of results without a detailed knowledge of the calibration constants used originally is not possible.

Gilmore (1977) repeated the measurements reported by Bremhorst and Bullock (1970), but using a temperature wire of platinum and 10% rhodium with a length-to-diameter ratio of 600. The effect of this was an increase in the measured temperature fluctuation intensity of about 15% thus bringing the values into close agreement with the computed values by Grötzbach and Schumann (1977). Measured u and θ spectra were, however, quite similar to those reported by Bremhorst and Bullock (1970) and Fulachier and Dumas (1976). In view of this, it only remains to show whether or not even larger temperature differerences than those used by Bremhorst and Bullock (1970) and Fulachier and Dumas (1976) can lead to significant effects on these spectra.

2 EXPERIMENTAL APPARATUS AND INSTRUMENTATION

Measurements were performed in air in a vertical 135.6 mm diameter pipe at 63 pipe diameters from the inlet where the flow is fully developed in the absence of heating. Heating wire wrapped around the outside of the pipe produced a uniform heat flux along the wall. The critical dimensions were 28 tube diameters of unheated flow, 35 tube diameters of heated flow upstream of the traversing station and another four diameters of heated flow downstream of the traversing station. This is the same equipment as used by Bremhorst and Bullock (1970).

Hot-wire anemometers were used as sensors. The wires were the Wollastan type of platinum and 10% rhodium alloy with the two wires being placed parallel to each other and the pipe wall but normal to the flow. The upstream wire of 1.4 mm etched length and 2.5 μm diameter was operated at very low overheat so as to act as a temperature sensor and the other of 5 μm diameter placed 0.5 mm downstream from it was operated at an overheat ratio of 0.4 for adiabatic flow and kept at this value of wire resistance for all measurements. Signals from the two wires were processed on an EAI 681 analogue computer with a method not relying on small signal sensitivities for separation of the velocity and temperature components, and in which only the velocity component of the signal passes through the linearizer. Frequency compensation of the temperature wire for its thermal inertia was used. No corrections were made for wall proximity effects.

3 RESULTS OF MEASUREMENTS

Measurements were performed for a given mass flow equivalent to a Reynolds number based on mean velocity and pipe diameter of 55226 with $U_\tau = 0.311$ m/s under adiabatic flow conditions. For a large part of the heated section this resulted in a linear wall temperature profile and a linear variation of the temperature difference between the wall and the pipe centre with variations in wall heat flux as well as a slight increase in mean velocity with increasing heat flux, Fig. 1. The effect on the radial temperature distribution is negligible in the core of the flow, but becomes pronounced near the wall, Fig. 2, where a significant increase in the gradient of normalized temperature is noted with increasing heat flux. A similar increase is noted in the local mean velocity normalized on the centreline velocity, Fig. 3. At all heat fluxes the flow was symmetric about the pipe centreline. The effect of heat flux on the turbulence level was insignificant except for the point nearest the wall, namely, y/a = 0.9974 which is equivalent to $y^+ = 3.6$ for adiabatic flow. Similarly, the effect on $\sqrt{\theta^2}/(T_w-T_c)$ was minimal except in the wall region where a decrease of up to 10% at the highest heat flow was observed.

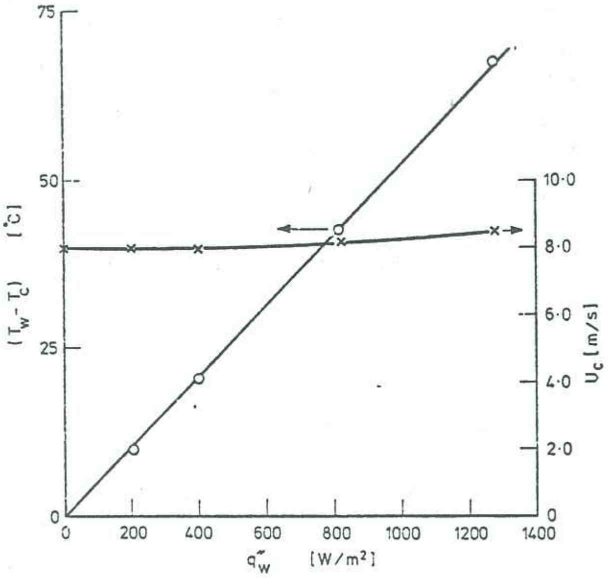

Figure 1 Variation with heat flux of centreline velocity and temperature relative to wall temperature

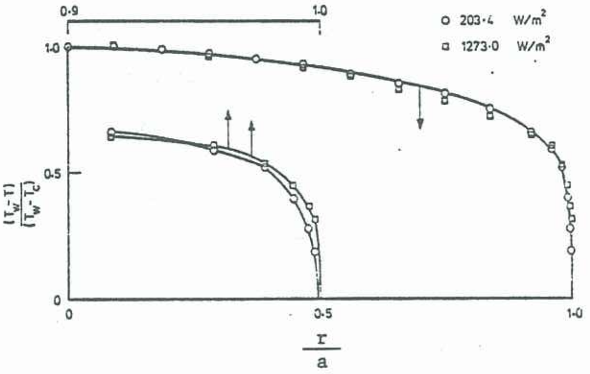

Fig. 2 Radial temperature distribution for different heat fluxes.

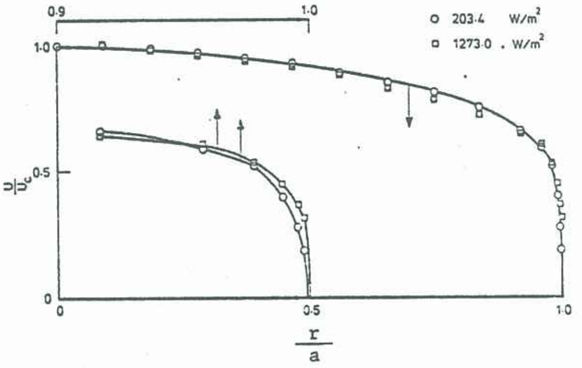

Fig. 3 Radial velocity distribution for different heat fluxes.

A significant result, however, is a marked decrease in the correlation coefficient between u and θ with increasing heat flux, Fig. 4. At higher heat fluxes, buoyancy effects appear to destroy the naturally occurring structure with a consequential decrease in the correlation coefficient. Buoyancy forces have least effect on the correlation coefficient in the wall region where the shear forces are greatest.

Spectral results were obtained for a number of radial positions at different heat fluxes. Signals were processed using a general purpose, cross-spectral analysis program which yielded the power spectra of the fluctuating velocity and temperature signals as well as the cross-spectral magnitude, phase and coherence. To check the quality of signal separation, the u spectrum for low heat input was compared with that for no heat input and found to be identical. Spectra of u and θ at the low heat input were also compared with those of Bremhorst and Bullock (1970) and Gilmore (1977) and found to be identical.

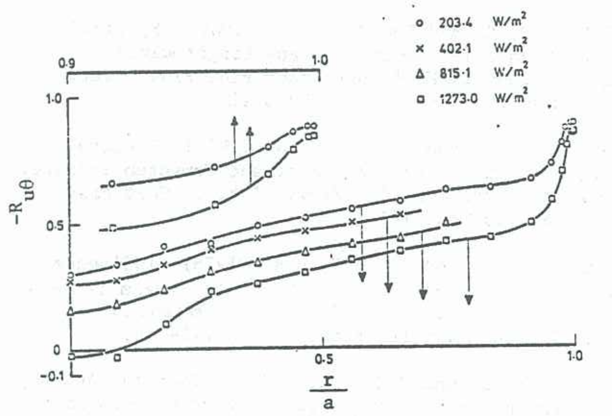

Fig. 4 Correlation coefficient, $R_{u\theta}$, dependence on heat flux.

Figs. 5 compare spectra at different positions in the flow for different heat inputs. Clearly, buoyancy effects are broadband in nature and appear to add energy in the mid and high frequency range of the u spectrum with increasing heat input, but leave the θ spectrum completely unaltered. Comparison of u and θ spectra at the low heat input, Fig. 5(a), shows the same trend as previously published data, Bremhorst and Bullock (1970) and Fulachier and Dumas (1970), that is, the θ spectrum commences to fall off at higher frequencies than that of u. At the high heat input, this is no longer the case, Fig. 5(b).

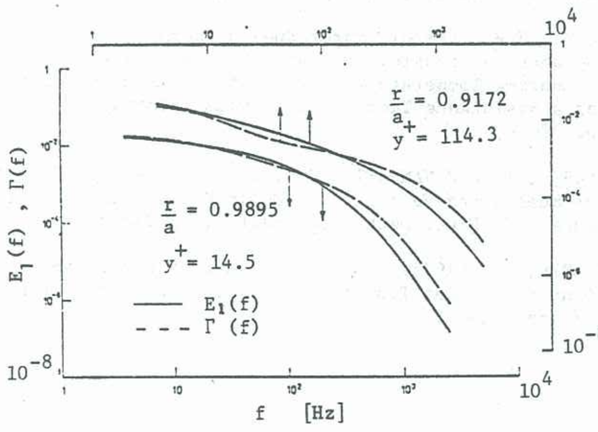

Fig. 5(a) u and θ spectra at $q''_w = 203.4$ W/m^2

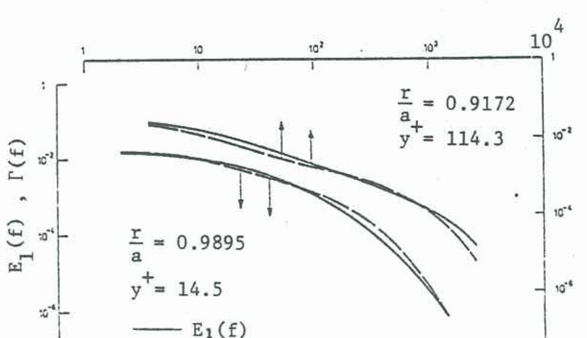

Fig. 5(b) u and θ spectra at $q''_w = 1273.0$ W/m^2

The effect of heat flux was found to be more marked in the cross-spectrum amplitude and phase of θ relative to u, Figs. 6, but by far the most obvious effect is on the coherence, Fig. 7. As is to be expected from the total correlation coefficient $R_{u\theta}$ of Fig. 4, the effect of heat flux is more pronounced away from the wall. Below about 100 Hz where the phase is 180°, the magnitude of the spectral cross-correlation coefficient, $R_{u\theta}(f)$, is identically equal to $\gamma(f)$. This frequency range also corresponds to the energy containing part of the spectrum for which $R_{u\theta}(f)$ is in the range 0.95–0.98 in the near wall region but away from the wall a rapid fall-off in this correlation is observed.

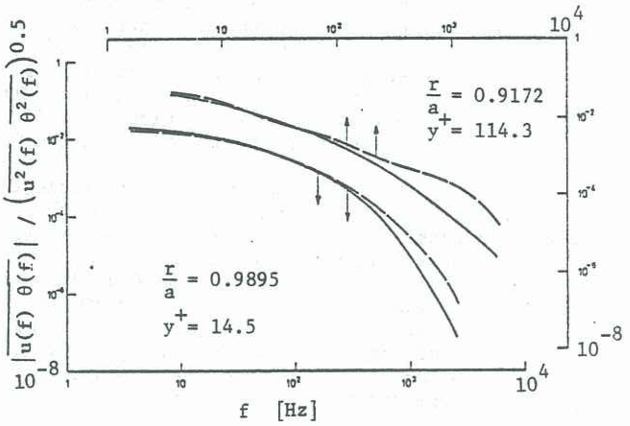

Fig. 6(a) u-θ cross-spectra at two different heat fluxes; —— $q''_w = 203.4$ W/m^2, - - - $q''_w = 1273$ W/m^2.

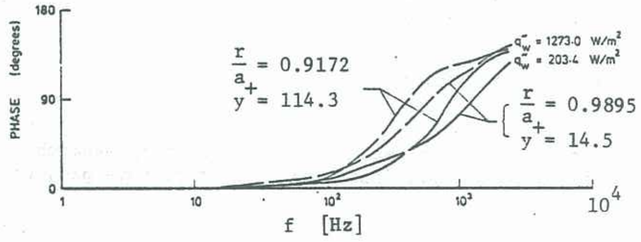

Fig. 6(b) Phase of θ relative to u.

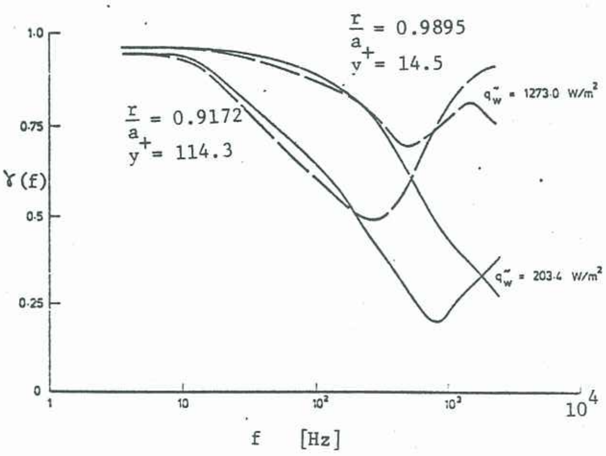

Fig. 7 Effect of heat flux on (coherence)$^{0.5}$.

4 CONCLUDING REMARKS

Hot-wire anemometer measurements in a heated, vertical pipe flow have shown different levels of wall heat flux to have only a minimal effect on mean velocity and mean temperature distributions in the range of heat fluxes and flow Reynolds number used for the experiments. The effect on the intensity of fluctuating velocity and temperature signals was also minimal but the cross-correlation coefficient, $R_{u\theta}$, is significantly affected. This effect is a minimum near the wall in the highly sheared wall layer. Spectra of the longitudinal velocity fluctuation are also sensitive to heat flux but those of the temperature fluctuation are completely insensitive to a change in heat flux. The commencement of the spectral fall-off of the u spectrum is at lower frequencies than that for θ at the low heat flux but this is not so at the high heat flux, giving the impression of added energy in the mid and high frequency range of the u spectrum. It may, therefore, be concluded that the spectral results by Zaric (1975) are indeed due to the high heat flux effects which modify the spectral behaviour of the flow.

The very high spectral cross-correlation coefficients near the wall in the energy containing part of the spectrum, indicate a near perfect similarity between heat and momentum transfer. This also reflects the effects of the organized wall structure which is associated with the lower frequency part of the spectrum. The extreme sensitivity of this structure to the effects of buoyancy is reflected in the coherence which, in the higher frequency part of the spectrum, changes markedly with heat flux.

At higher frequencies the phase angle by which θ leads u is seen to increase rapidly with frequency. Similar measurements in grid turbulence by Yeh and Van Atta (1973) also show non-zero values of phase angle in the higher frequency range of the spectrum adjacent to the energy containing range. Such non-zero and positive phase values are indicative of a strain rate effect which coexists with the convective one found at the lower frequencies.

5 ACKNOWLEDGEMENT

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