Int. J. Heat Mass Transfer. Vol. 36, No. 18, pp. 4487–4491, 1993
Printed in Great Britain

0017–9310/93 $6.00+0.00
Pergamon Press Ltd

Some aspects of free-convective heat transfer in eddy flow through a horizontal tube

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(*Received* 16 *November* 1992)

Abstract—Experimental investigation of unsteady-state free convection in a horizontal cylindrical channel is carried out for the case of non-uniform distribution of heat flux along a channel at a constant temperature on the wall. The averaged temperature field in a gas was investigated on a Mach–Zender interferometer. Hydrodynamic structures were investigated by the smoke visualization technique. Heat fluxes were calculated on the basis of thermocouple measurements. In the case of non-uniform heat flux on the channel wall, the existence of longitudinal large scale hydrodynamic structures has been noted. Longitudinal and lateral Rayleigh numbers varied from 0 to 4×10^9 and from 0.8×10^4 to 1.2×10^5, respectively. Investigations were carried out with air, carbon dioxide and helium flows.

INTRODUCTION

THIS PAPER presents the results of experimental study of free convection in a horizontal cylindrical channel with first- and second-kind boundary conditions on the wall. The works concerned with the study of hydrodynamics and heat transfer in channels [1–5] paid little attention to eddy flow structures and temperature fields under non-uniform boundary conditions. The aim of the present work is to study the distribution of temperature fields, heat fluxes and hydrodynamic flows in a gas and on the tube surface under non-uniform boundary conditions.

APPARATUS AND INVESTIGATION TECHNIQUES

To investigate the dynamics of the temperature field development in a horizontal cylindrical channel with second-kind boundary conditions on the wall, a set-up was employed depicted in Fig. 1. A 400 mm long tube with an inner diameter of 30 mm was covered on the outside with a 20 mm thick insulating layer of glass wool. The tube was heated by electric current supplied through contacts at the tube ends. The current strength in the tube amounted to 225, 325 and 420 A, which corresponded to the mean specific heat generation equal to 4960, 9910 and 17 100 W m^{-2}, respectively.

In experiments with helium and carbon dioxide, the tube end-faces were closed by plane-parallel glass plates which made the measurements practically interference-free and which allowed the channel to be hermetically sealed.

Investigation of the temperature field development in a channel under first-kind boundary conditions were carried out on a set-up depicted in Fig. 2. Water from a thermostat was continually pumped through a gap formed by the double wall of a glass tube. The characteristic difference of temperatures between the inlet and exit pipes of the reservoir amounted to 0.5°C at the thermostat water temperature equal to 70–90°C. This allowed one to regard the channel wall temperature to be constant.

Investigation of temperature fields was conducted on a Mach–Zender interferometer. The block-diagram of the experiment is presented in Fig. 3. A homogeneous beam of light was formed by a collimating system from mercury bulb radiation. When the tube end-faces were closed by plane-parallel plates, the

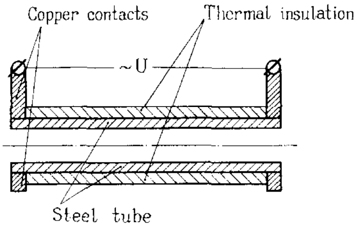

FIG. 1. Schematic of a set-up for studying a temperature field in a horizontal tube under second-kind boundary conditions.

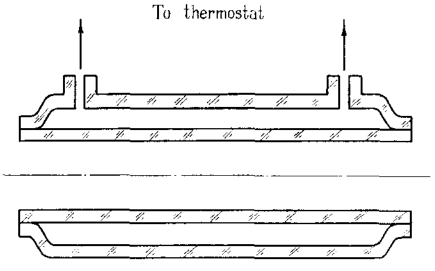

FIG. 2. Schematic of a set-up for studying a temperature field in a horizontal tube under first-kind boundary conditions.

NOMENCLATURE

k	number of interference fringe
n_0	refractive index of gas
T	gas temperature [°C]
T_{min}	minimal gas temperature [°C]
T_w	tube wall temperature [°C]
T_a	ambient temperature [°C]
z	tube length [m].

Greek symbol

λ	probing radiation wavelength [μm].

light was produced by a one-mode helium–neon laser. The use of a laser as a light source somewhat decreased the quality of interference pictures because of the presence of speckle-structures in the beam.

To obtain quantitative data on the development of temperature fields averaged over the tube length, the following procedure was employed. Before the start of the experiment, the interferometer at room temperature was tuned to an infinitely wide band whereupon the heating of the tube by electric current or the pumping of water through the gap were started. Simultaneously, a camera was switched on to record the process.

The recovery of the two-dimensional distribution of the average temperature over the tube length was performed by the following formula obtained in ref. [5]:

$$T_k = \frac{(n_0-1)P_a T_0 T_a z}{(n_0-1)P_a T_0 z - k\lambda P_0 T_a} \qquad (1)$$

where $T_0 = 0$°C, T_a is the ambient air temperature, z is the length of the tube, P_a is the atmospheric pressure at the time of experiment, $P_0 = 101\,325$ Pa.

The distribution of heat flux along the tube length was investigated with the help of a number of thermocouples installed along the channel wall. Thermocouple measurements showed that the heat flux distribution along the tube length is nonuniform and has a characteristic parabolic profile. In order to investigate the structure of hydrodynamic flows existing in the tube at the given heat flux profile, a set-up was used depicted in Fig. 4. A nichrome wire was wound with a variable step onto a 400 mm long quartz tube having an inner diameter of 30 mm. The step was determined experimentally for producing the required heat flux profile. To study the free-convective flow structure in a tube, the 'laser knife' method was used.

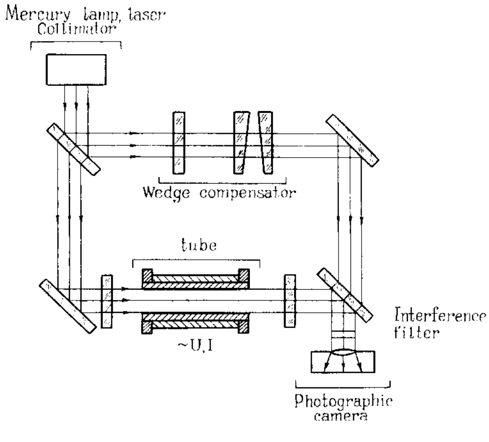

FIG. 3. Schematic of the experiment for studying a temperature field on a Mach–Zender interferometer.

RESULTS OF MEASUREMENTS

Interferograms and graphs of the two-dimensional distribution of the dimensionless mean temperature $(T_w - T)/T_w$ are presented in Fig. 5. The graphs were plotted by the method of cubic spline-approximation. The temperature data were obtained by processing the interferograms by formula (1). In this case, the tube wall temperature T_w was determined from the interference band adjacent to the wall.

Analysis of the interferogram presented in Fig. 5(c) shows that the mean gas temperature maximum is located in the upper flow region and exceeds the mean channel wall temperature. Heat flux calculations based on thermocouple measurements indicate that the heat flux was non-uniform along the tube length (Fig. 6). Its distribution in the longitudinal cross section represents a parabolic profile with a characteristic maximum at the tube centre. This is due to the presence of radiative heat losses through the tube endfaces and heat removal through the massive copper contacts. Investigations have shown that at a constant wall temperature no second extremum originates along the tube length, whereas the structure of free convective flows is similar to that studied in ref [6]. In this case, the flow is two-dimensional and consists of two vortices symmetric about the vertical axis. The

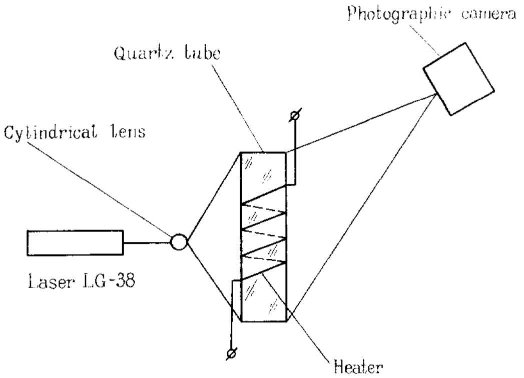

FIG. 4. Schematic of a facility for flow visualization.

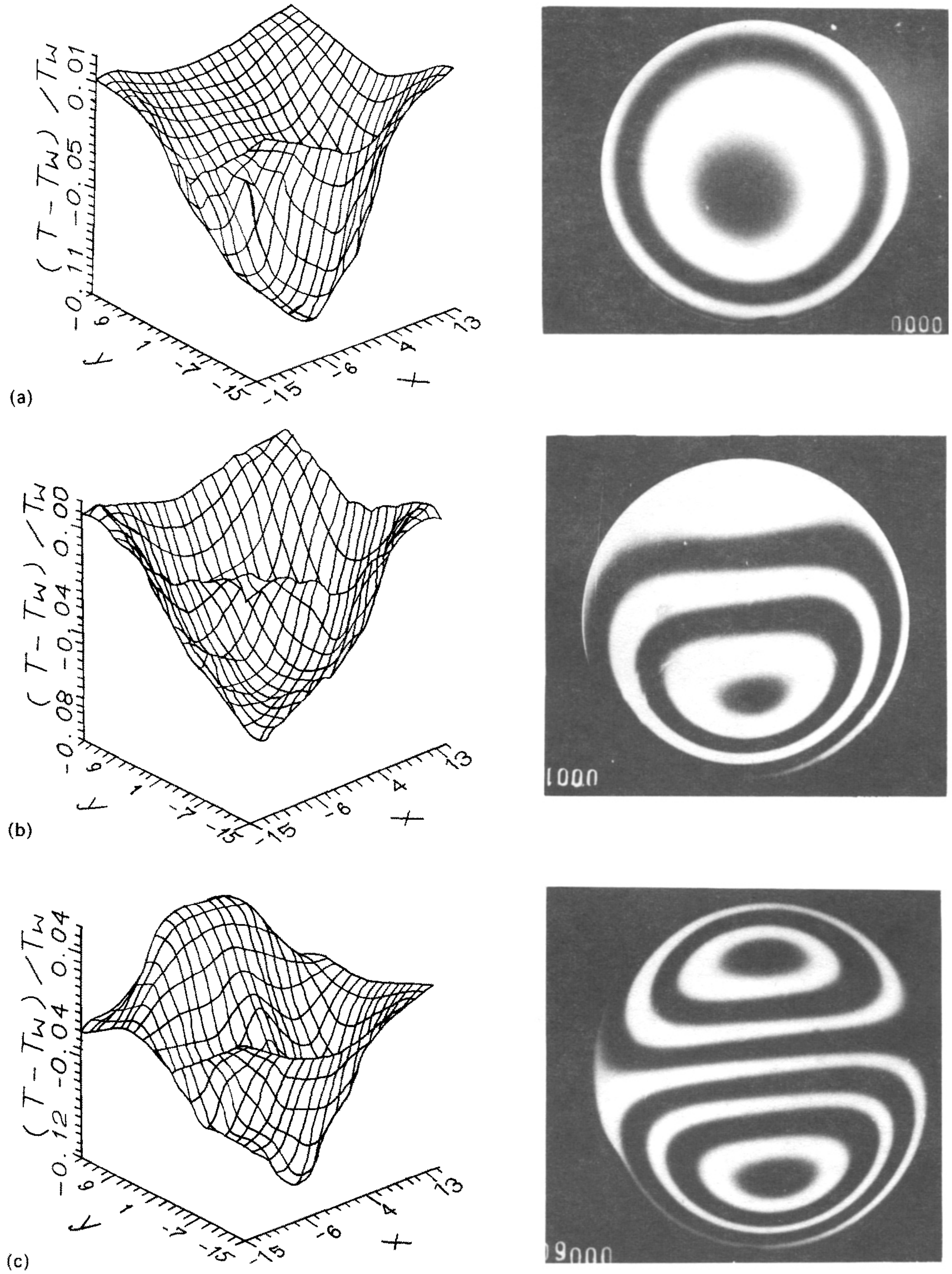

FIG. 5. (a) Interferogram and associated dimensionless mean temperature distribution at time $t = 0.5$ s from the start of heating. (b) Interferogram and associated dimensionless mean temperature distribution at time $t = 30$ s from the start of heating.

interferograms of averaged temperature fields are similar to those depicted in Figs. 5(a) and (b) with one temperature minimum in the lower one third part of the tube.

In the cylindrical channel under the second-kind boundary conditions and with parabolic heat flux distribution along the wall, the longitudinal heat and mass transfer in the tube exerts a substantial effect on heat exchange. In Figs. 7(a) and (b) the results of flow visualization in the longitudinal vertical and horizontal sections of the tube are given. It should be noted that there exist two symmetric nonmixed struc-

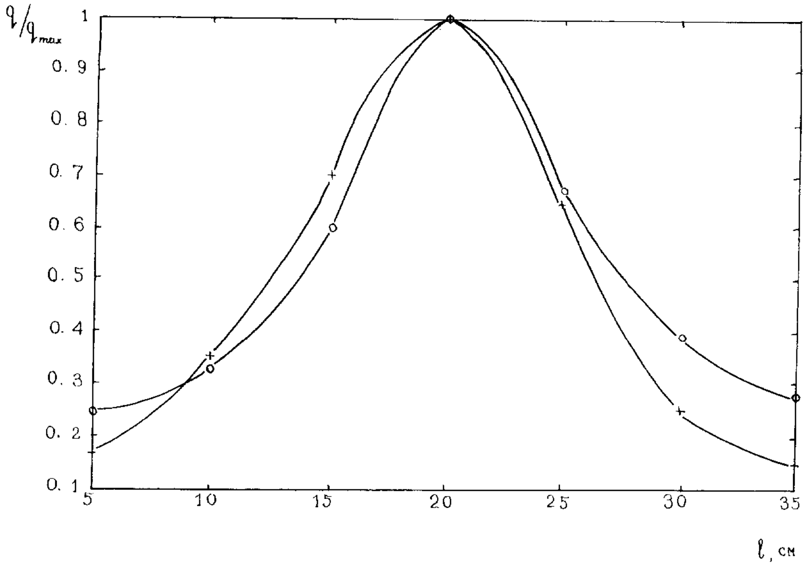

FIG. 6. Dimensionless heat flux distribution along the tube length.

tures in the left and right sides of the tube separated by two torroidal vortices which rotate in opposite directions. In different cross sections of the tube one can observe smaller-scale structures (Fig. 8). The case depicted in Fig. 8(a) corresponds to the tube section at the centre, i.e. in the region of the existence of torroidal vortices. Figures 8(b)–(d) correspond to the distances equal to 1, 6 and 11 cm from the tube centre, respectively. The lateral gas motion turns out to be reduced to a simple four-vortical motion of gas as assumed in ref. [5].

Thus, the existence of longitudinal temperature gradients in a horizontal cylindrical channel under non-uniform first- or second-kind boundary conditions on the wall leads to the origination of rather complex three-dimensional circulating flows in a tube which substantially influence the process of free-convective heat exchange.

The presence of end-face windows that limit gas influx into the interior of the tube did not change the qualitative picture of the temperature field distribution within the tube, but only somewhat lowered the longitudinal and transverse temperature gradients in the gas.

The study of the hydrodynamic flow structures in a channel was carried out in different heating regimes. The range of variation of the transverse Rayleigh numbers based on the characteristic difference of aver-

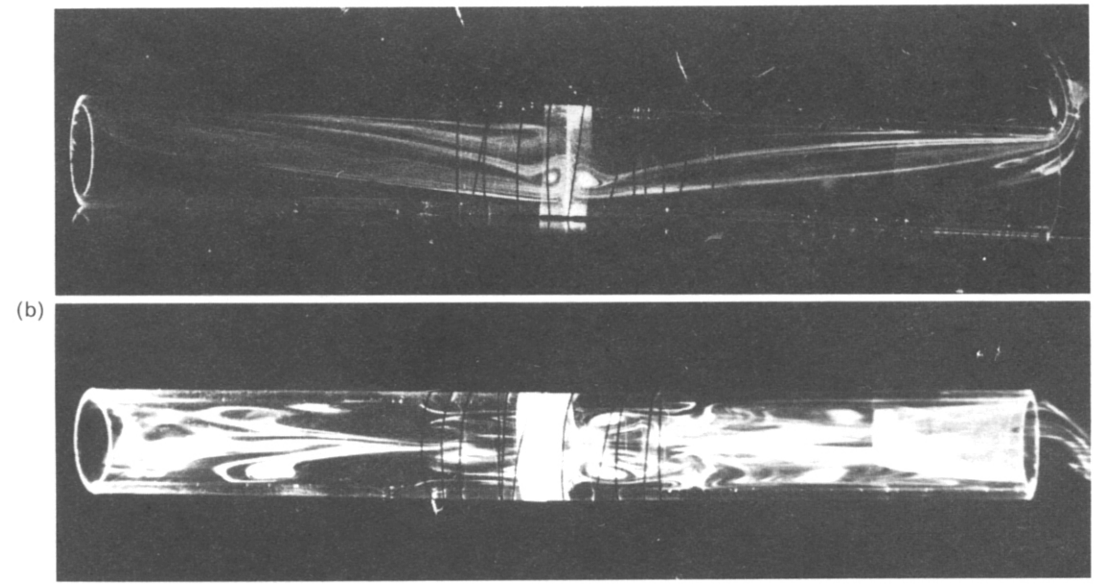

FIG. 7. Flow patterns in longitudinal vertical (a) and horizontal (b) tube sections.

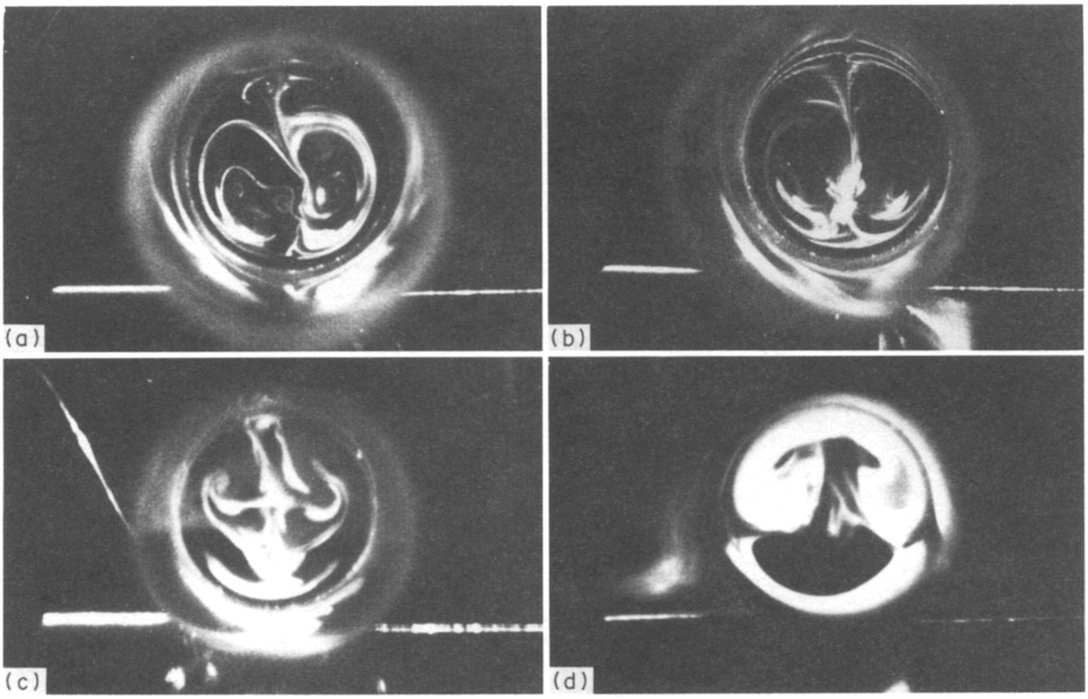

FIG. 8. Flow patterns in tube cross sections: (a) at the centre; (b), (c) and (d) at the distances of 1, 6 and 11 cm from the centre, respectively.

aged temperatures $T_w - T_{min}$ amounted to 0.8×10^4–1.2×10^5. The longitudinal Rayleigh number based on the tube length varied from 0 in the absence of the initial stage of tube heating to the maximum value of 4×10^9.

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