SECONDARY FLOW FORMATION OVER LOCALIZED HEAT SOURCE

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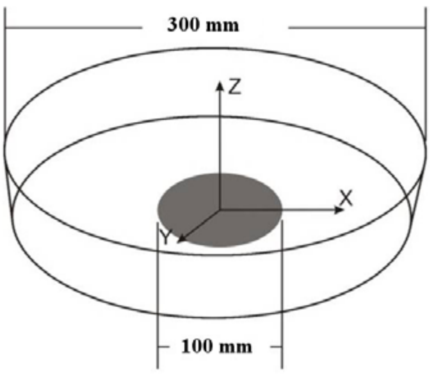
Abstract Formation of secondary flows in a cylindrical fluid layer with a local heating was studied experimentally and numerically. It was shown that secondary structures appear in a temperature boundary layer. The shape of secondary flows essentially depends on the heating. The set of frequencies characterizing the secondary flows generation was obtained by thermocouple measurements. Temperature time series were analyzed by wavelet-analyses for fixed locations over the heater. 2D and 3D models were used for numerical modeling. Numerical results are in a good agreement with experimental measurements.

INTRODUCTION

Secondary flows in the form of horizontal rolls are a common feature of a large variety of flows of different nature and scale. The first studies of horizontal rolls in advective flow were done in connection with stability analysis of Hadley-circulation, ocean circulations and crystal growth [1]. A thin plane layer of fluid with applied horizontal temperature gradient and absence of lateral boundaries was considered. It was found that both a hydrodynamic mechanism (vortex excitation on the boundary of counter-streaming flows) and a convective mechanism (Rayleigh instability in boundary layers characterized by unstable temperature stratification) may lead to advective flow instability. Convective instability can generate two different modes in the form of transverse and longitudinal rolls. Roll vortices are often observed in the atmospheric boundary layer [2]. Depending on their size and strength, rolls play a significant role in transporting momentum, heat and moisture through the atmospheric boundary layer. Examples of such structures can be clearly seen on the satellite images when in locations of warm air ascent so-called "cloud streets" are formed. The formation of these rolls is due to either convective or hydrodynamic instability and is often a result of their combined effect. The problem of horizontal rolls generation in a natural (not mixed) convective flow above a partially heated surface in a closed domain with a free surface was studied in details in [3]. A variety of regimes with longitudinal helical rolls, with transverse rolls and with mixed structures has been observed. The structure of secondary flows is defined by the level of convective supercriticality in the boundary layer (Rayleigh number) and the intensity of the throughflow, defined by the Reynolds number, which depends itself on the heating and size, i.e. on the Rayleigh number. Most of the studied regimes were characterized by the appearance of longitudinal rolls. The next step is investigation of the secondary flow formation in a cylindrical layer, which is very interesting due to many applications to geophysical and technological processes. The main goal of this work is the study the secondary flow formation over localized heat source in a cylindrical layer.

EXPERIMENTAL SETUP

We studied a convective flow in a flat cylindrical vessel placed on a rotating horizontal table. The cylinder radius is R=150 mm. The cylinder is made of acrylic plastic, the fluid is silicone oil, characterized by a high Prandtl number. The layer thickness is constant in all experiments (h=30 mm) and the upper surface is free (Fig.1).



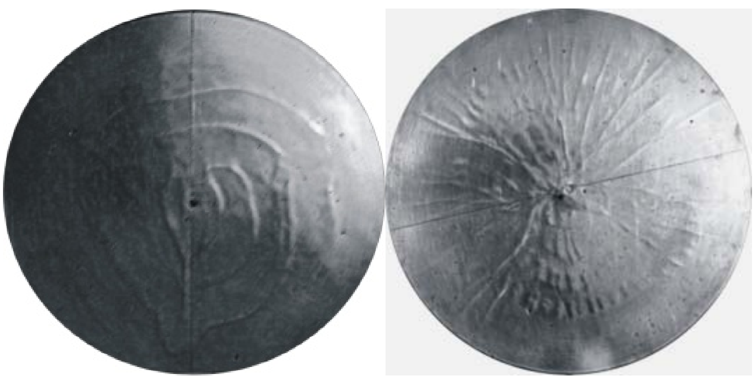


Figure 1. Scheme of experimental setup.

Figure 2. Secondary flows over the heater.

Heater is a copper cylinder of radius 52 mm, installed in the center of the vessel and coinciding with the axes of rotation. The temperature in the layer was measured by copper-constantan thermocouples. For the reconstruction of temperature fields an array of 7 thermocouples mounted on 3-axis translation stage Thorlabs was used. The data from the thermocouples were obtained by an Agilent 34970A data acquisition switch unit with a 16 channel multiplexer module 34902A. Velocity fields were measured by PIV system « Polis ».

RESULTS

When heating is switch on the warm fluid in the center of the vessel is going up and moving to the periphery, that leads to the advective flow formation which occupies the whole layer. The large-scale advective flow in the lower part of the layer leads to the formation of boundary layers with potentially unstable temperature stratification above the heater and makes possible the generation of secondary convective flows. The structure of secondary flows strongly depend on the value of heat flux which was controlled during the experiment. The examples are shown in Fig.2, on the left spiral structures for the weak heating and on the right more complicated system which consist of both spiral transverse rolls and radial convective rolls. The set of frequencies characterizing the secondary flows generation was obtained by thermocouple measurements. Temperature time series were analyzed by wavelet-analyses for fixed locations over the heater. Azimuthal dependence of frequency of temperature fluctuations and its time inhomogeneity was shown.

Experimental studies are supported by direct numerical simulations, which made possible the examination of the regimes inaccessible in the experiment, and enables the detailed investigation of the structure of the convective flow. The problem was numerically realized in 2D and 3D cases using a finite element Fluent CFD software.

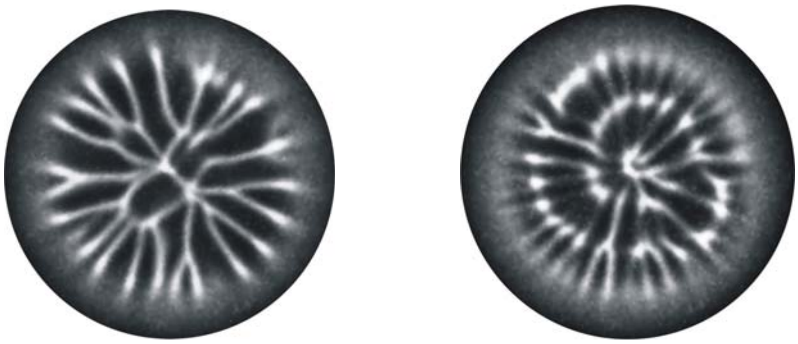


Fig.3. Temporal evolution of the secondary flows.

Evolution of spatial structure of secondary flows is different from scenario observed in [3] where formation of horizontal rolls was studied in a rectangular tank. In our case radial rolls are formed at first and afterwards appears secondary flow in a shape of the ring which is shifted towards the center by main advective flow. After some time the ring shape of this transverse flow is gradually turns into spiral one (Fig.3). The numerical results are in a good agreement with the experimental measurements.

CONCLUSION

Formation of secondary flows in a cylindrical fluid layer with local heating was studied in a laboratory experiment and numerical modeling. It was shown that secondary structures appear in a temperature boundary layer. The shape of secondary flows essentially depends on the heating. The set of frequencies characterizing the secondary flows generation was obtained by thermocouple measurements. Temperature time series were analyzed by wavelet-analyses for fixed locations over the heater. Azimuthal dependence of frequency of temperature fluctuations and its time inhomogeneity was shown. 2D and 3D models were designed for numerical calculations in Fluent CFD software. The secondary flow evolution were studied in details in the frame of 3D model.

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