The characteristics of steady-state convective cyclonic vortex

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Abstract

Experimental study of the steady-state cyclonic vortex from isolated heat source in a rotating fluid layer is described. The structure of laboratory cyclonic vortex is similar to the typical structure of tropical cyclones from observational data and numerical modelling including secondary flows in the boundary layer. Different constraints of the steady-state hurricane-like vortex were studied. The three main dimensional parameters that define the vortex structure for a fixed geometry - heating flux, rotation rate and viscosity were varied independently. It was shown that viscosity is one of the main parameters that define steady-state vortex structure. Along with the experiment a numerical simulation in a similar geometry was performed. For numerical simulation we used CFD package FlowVision. Numerical results showed good agreement with experimental data and proved efficiency of the use of numerical modeling.

1 Introduction

The phenomenon of vortex generation is found in a wide range of flows of different nature and scales. Synoptic vortices, such as cyclones and anticyclones, play a major role in the formation of weather conditions over the large areas. And secondary flows in the hurricane boundary layers may have a considerable effect on the heat and mass transfer between the water and the air [1]. Despite decades of research the problem of the intense large-scale atmospheric vortices generation is unsolved and attracts close attention from many scientific groups. The complexity of the problem forces researchers to study cyclones formation step by step using laboratory experiments as well as numerical modeling.

The main reason of the vortices formation in the atmosphere and ocean is interaction between Coriolis force and mass forces caused by the local temperature inhomogeneity. In this way laboratory model of hurricane-like vortex was proposed and studied in [2, 3, 4]. They considered rotating layer of fluid with the localized heater in the bottom. Local velocity measurements showed that the general structure of mean radial and azimuthal flows in a proposed model is similar to the typical structure of a hurricane and proved that chosen configuration is very promising for a studying of hurricane-like vortices. The studies were done with the use of the buoyant probe for measurement of cyclonic rotation in a central part and many questions were left open for further studies.

In the current study, like [2, 3, 4], we consider steady-state hurricane-like vortex using a modern experimental technique and numerical simulation. For a fixed geometry there are only three main dimensional parameters that define the vortex structure - heating flux, rotation rate and viscosity. Independent controlled variation of these parameters gives possibility to analyse the influence of each dimensional parameter on the cyclonic vortex structure and to define government nondimensional parameters.

In addition to laboratory modeling the numerical calculations using CFD package Flow Vision were conducted. Despite of experiment numerical modeling provides an opportunity to get information about instantaneous velocity and temperature distribution throughout the volume. The geometrical dimensions of the computational domain and the values of the control parameters selected in accordance with the experimental regimes. Numerical results showed good agreement with experimental data. Using numerical modeling instant velocity and temperature distribution were obtained.

2 Experimental Setup

The formation of cyclonic vortex was studied in a cylindrical vessel of diameter 300 mm, and height 40 mm (Fig. 1, a). The sides and bottom were made of Plexiglas with a thickness 3 mm and 20 mm respectively. There was no cover or additional heat insulation at the sidewalls. The heater is a brass cylindrical plate mounted flush with the bottom. The diameter of the plate is 104 mm, and its thickness is 10 mm. The brass plate is heated by an electrical coil placed on the lower side of the disc. For studying the influence of the heating on the flow structure the series of experiments was carried out. For different experimental realizations the heating power was varied from 17 Wt to 78 Wt. For each realization the heating power was constant and controlled by Termodat system. Cylindrical vessel was placed on a rotating horizontal table (Fig. 1, b). The table provides uniform rotation in the angular velocity range $0.04 \leq \Omega \leq 0.30\ s^{-1}$. In the present study the angular velocity was varied from $\Omega = 0.07$ s^{-1} to $\Omega = 0.17$ s^{-1}. Silicon oils with different values of kinematic viscosity, PMS-20, PMS-10, PMS-5 and PMS-3 (25, 10, 5 and 3 cSt at T = 25 ^{0}C) were used as working fluids. In all experiments, the depth of the fluid layer was 30 mm and the surface of the fluid was always open. The room temperature is kept constant by air-conditioning system, and cooling of the fluid is provided mainly by the heat exchange with surrounding air on the free surface and some heat losses through sidewalls. For low values of kinematic viscosity it takes about 2 hours to obtain a steady-state regime. Temperature inside the fluid layer was measured by copper-constantan thermocouples.

The velocity field measurements were made with a 2D particle image velocimetry (PIV) system Polis (Fig.1, b). The system included a dual pulsed Nd-YaG laser (1), a control unit, a digital CCD camera (3), placed in a rotating frame, and a computer. The synchronization of the operation of the laser and the CCD camera, the measurement, and the processing of the results were performed using the software

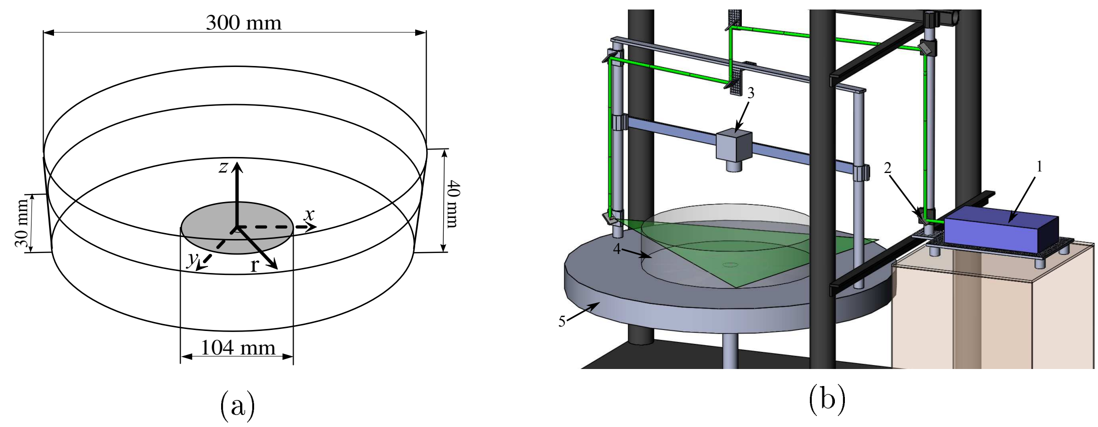


Figure 1: Experimental setup: (a) Dimensions and location of the coordinate system, (b) - Measurement system

package Actual Flow. All data were obtained in rotating coordinate system using optical mirrors (2). Optical mirrors rout laser beam (4) from fixed laser to rotating vessel. Cylindrical vessel works as a lens and narrow horizontal light sheet (5) from the periphery to the center but all area of our interest in the central part of the vessel was illuminated. Also we need to note that due to strong optical distortions we did not make PIV measurements in a close proximity to the heater at height less than 2 mm. All PIV measurements were done for horizontal crosssections at different heights. Even variation of the three main dimensional parameters (heating, viscosity, rotation) leads to the many experimental realizations (62 in our case). So for the most of regimes the measurements were done only at three heights, near the bottom (z = 3 mm), in the central horizontal crosssection (z = 15 mm), and near the upper surface (z = 27 mm). It allowed us to study the flow structure in the boundary layers and in the bulk of the flow. Iteration algorithms and decreasing of the size of the interrogation windows from 32×32 to 16×16 pixels provided a dynamic range of approximately 500. The main subject of this study is cyclonic vortex over the heating area, so for keeping high spatial resolution the most of the PIV measurements were made only in a central part of the layer at different horizontal cross-sections.

3 Dependence of the cyclonic vortex structure on the main parameters

In this chapter we describe the general structure of large-scale radial flow and formation of the cyclonic motion in the central part of the vessel. The heat flux in the central part of the bottom initiates the intensive upward motion above the heater. Warm fluid cools at the free surface and moves toward the periphery where the cooled fluid moves downward along the side wall. After some time, large-scale advective flow occupies the whole vessel(Fig. 2, vertical cross-section). Structure and specifics of flows in the case of non-rotating cylindrical layer are described in details in [5].

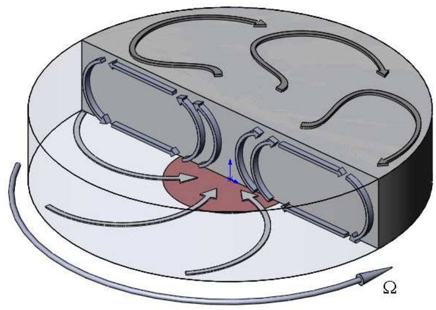
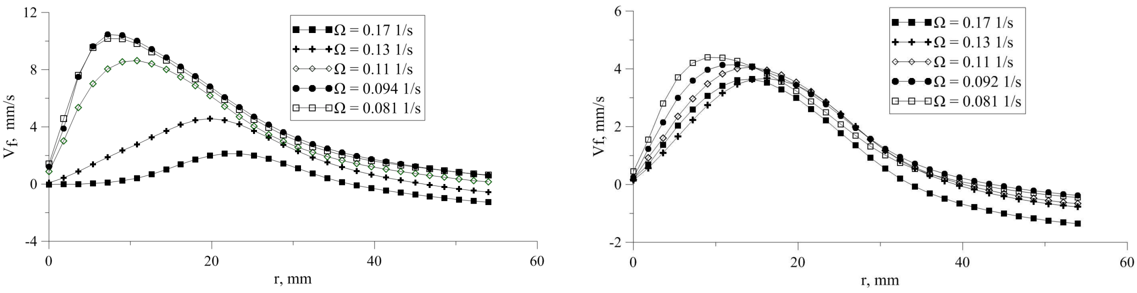


Figure 2: The structure of main flow in a rotating frame

In rotating case large-scale radial circulation leads to the angular momentum transport and angular momentum exchange on the solid boundaries. Convergent flow in the lower layer brings fluid parcels with large values of angular momentum from periphery to the center and produces cyclonic motion (Fig.2, lower horizontal cross-section). In the upper layer situation is the opposite - divergent flow takes fluid with low values of angular momentum to the periphery resulting in anticyclonic motion (Fig.2, upper horizontal cross-section).
The main motivation of investigation is to separate the role of the three main parameters of the problem - heating, rotation and viscosity, and analyze the influence of each dimensional parameter on the cyclonic vortex structure. In details research was described in [6]. Here the main results of this work are presented.
Relative motion in our system is driven by localized heating so the clear understanding how the increase of the heating changes the flow structure is very important. As is expected the increase of the heating produce more intensive meridional circulation. Meridional circulation provides angular momentum transport in the lower layer and magnitude of azimuthal velocity also increases with the heating. Structure of the cyclonic vortex changes with the heating, it becomes more uniform over depth. The shape of the vortex is conical for the weak heating and becomes cylindrical (in the central part) in the developed state.
Another important parameter is the rotation rate. In our case the rotation is the source of angular momentum so the faster we rotate the layer the more intensive vortex we potentially may produce. From the other side rotation suppresses convection which is the main source of the meridional circulation that brings extra angular momentum to the center and produces cyclonic vortex. It means that for the fixed rotation rate increasing of the heating leads to increasing of cyclonic vortex intensity but for the fixed heating there is the optimal rotation rate that provides the most intensive cyclonic vortex. Spatially and time averaged azimuthal velocity profiles for the fixed heating and different rotation rates in the middle of the layer (z = 15mm) for the two working fluid (PMS-5 and PMS-10) are presented in Fig. 3 . There is remarkable change of the flow structure with a relatively small variation of the rotation rate. Maximum of azimuthal flow moves to the periphery and decrease with the rotation rate growth, it means that convective cell moves from the center and its intensity is declined.
One more parameter that has crucial importance on the cyclonic vortex formation is viscosity. In order to separate effects of viscosity we have made three series of

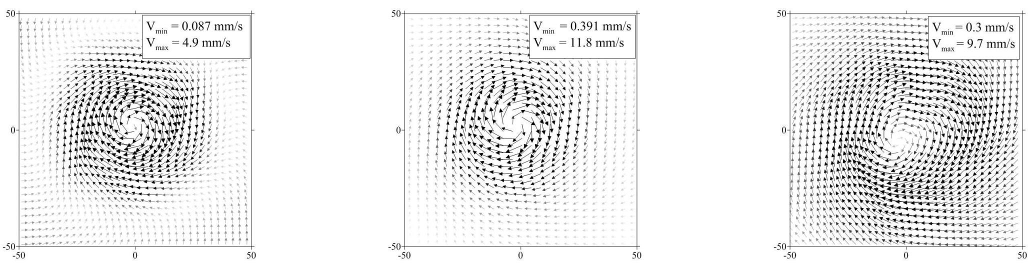


(a) (b)

Figure 3: Mean azimuthal velocity profiles for height z = 15mm for regimes with different rotation rates and fixed heat power P = 17wt: a - PMS-5, b - PMS-10

measurements for fluids with substantially different values of kinematic viscosity for fixed values of heat flux and rotation rate. It means that we consider the rotating layer of fluid with constant energy source and study what would happen with the cyclonic vortex with variation of the physical properties of the fluid.

In (Fig. 4) mean vector fields at z = 15 mm for the fixed value of heating and rotating rate and for fluid with different viscosity are presented. Decrease of kinematic viscosity leads to the remarkable increase of cyclonic vortex intensity. The structure of vortex is also changed. We believe that this result might be very important because spatial or time dependence of turbulent viscosity in the atmospheric flows may lead to the strong variation of the magnitude of the wind velocity and spatial inhomogeneity of temperature and velocity fields.



(a) (b) (c)

Figure 4: Mean vector velocity fields at z = 15 мм, heat power P = 17 Wt, $\Omega = 0.081 s^{-1}$: a - PMS-10, b - PMS-5, c - PMS-3

Along with the experiment a numerical simulation in a similar geometry was performed.For the numerical simulation we used the CFD package Flow Vision. The fluid is assumed to be Newtonian and the flow is considered to be incompressible and laminar. The numerical finite volume code is used to solve the Boussinesq equations for thermal convection. Impermeable and no-slip velocity conditions are applied at the side wall and bottom. The upper boundary was stress-free. The bottom has a localized heat source in the central part defined through a heat flux and the diameter of the heating area was fixed at 100 mm. All numerical runs were done in 3D and the integration domain was a cylindrical cavity, equivalent to the one in the laboratory experiments. Silicon oil PMS-3 was used as a working fluid. The depth of the layer was 3 cm. The spatial resolution was 0.5 mm over the heat area in all

directions. At the periphery, the spatial resolution was decreased up to 1 mm in order to save computational costs.1 mm in all directions.
The structure of the steady-state radial and azimuthal flows (in a rotating frame) for different values of heat flux and rotating rate are shown in Fig. 5. Positive (negative) values of velocity describe convergent and cyclonic (divergent and anticyclonic) motion respectively. To verify the numerical results,the vertical profiles of the mean radial velocity in the place of their maximum (Fig. 6) were compared. One can see that for regimes are shown below the mean velocity profiles have a very good quantitative agreement.

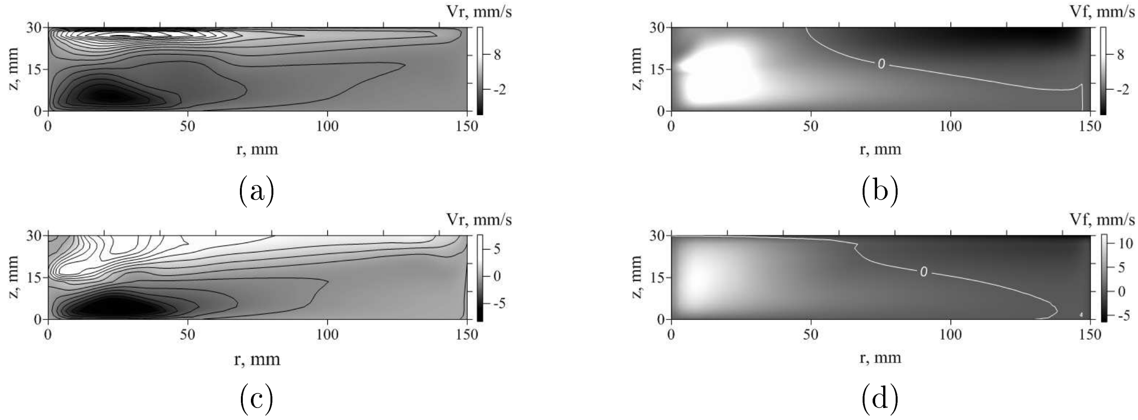


Figure 5: Mean radial (a, c) and azimuthal (b, d) velocity fields obtained from Flow Vision (PMS-3): a, b - P = 26 Wt, $\Omega = 0.081 s^{-1}$, c, d - P = 38 Wt, $\Omega = 0.041 s^{-1}$

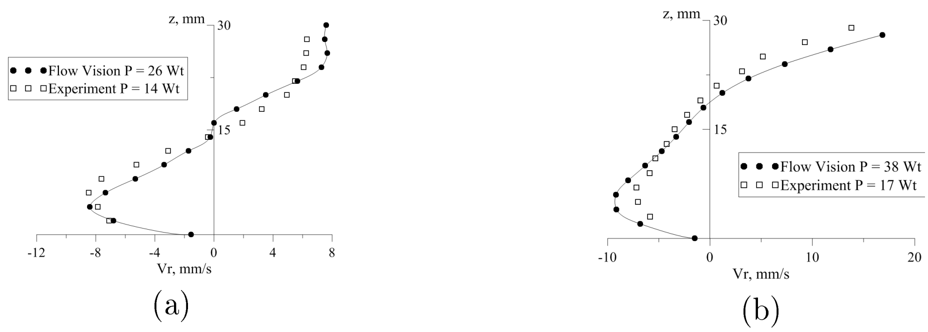
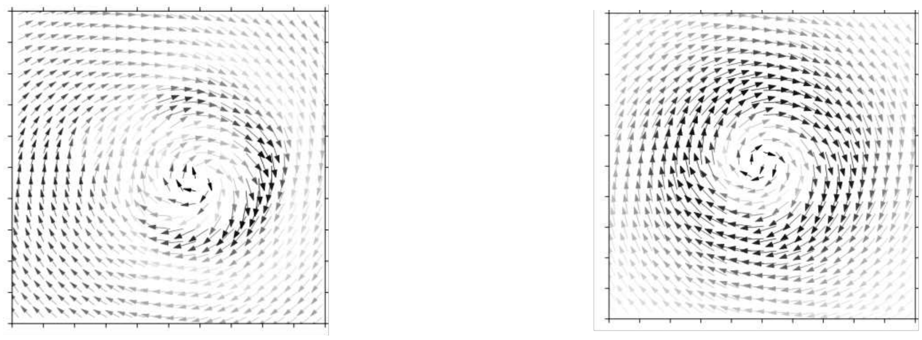


Figure 6: Mean radial velocity profiles (PMS-3): a - P = 14 Wt, $\Omega = 0.081 s^{-1}$, b - P = 17 Wt, $\Omega = 0.041 s^{-1}$

The significant advantage of the numerical simulation is that it gives full information about the 3D distribution of the different flow characteristics, which is hardly achievable experimentally. Instantaneous temperature and velocity fields give us a better understanding of the formation and evolution of the flow. Here instantaneous and mean vector velocity (Fig. 7) fields over a heat source at the height z = 15 mm are presented. One can see that instantaneous and mean velocity fields greatly differ. In this regime cyclonic vortex becomes unstable and start to precess around the center of the vessel. This precession leads to expansion of the vortex on the mean velocity field and to displacement of the azimuthal velocity maximum at the experimental profiles.



(a) (b)

Figure 7: Instantaneous - a and mean - b vector velocity field at z = 15 mm, P = 14 Wt, $\Omega = 0.081 s^{-1}$, PMS-3

Acknowledgements

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