Laboratory model of tropical cyclone with controlled forcing

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Abstract. The paper presents laboratory model of tropical cyclone with controlled forcing and describes the technology to integrate a measurement system and a supercomputer. Procedures of real-time data acquisition, storing and processing, specifics of PIV and heating control systems integration are described. A series of experiments with laboratory analogue of tropical cyclone using feedback between velocity and a heating is carried out. It is found that imposed temperature difference defines the mean radial velocity and intensity of the vortex. It is shown that the relationship between velocity and heat release is of crucial importance for the cyclonic vortex formation.

1. Introduction
Connection between hydrodynamic and thermodynamic processes is important factor in different natural and technological systems. For example velocity or flow topology variation can lead to increasing or decreasing of heat flux in convective heat transfer, combustion or exothermic chemical reactions processes. Open problem is a link between wind velocity and latent heat release during formation of large-scale atmospheric vortices like tropical cyclones (hurricanes, typhoons) [1, 2]. The problem of tropical cyclogenesis attracts great attention because of multiple human losses and vast economical damage. The main problem is long-term reliable forecast [3]. The quality of prediction of tropical cyclone intensity and track of its motion strongly depends on the choice of mathematical models. Up to now capabilities of numerical modeling are restricted. Most of numerical simulations are carried out using spatial resolution of 2-3 km with parametrization of the subgrid processes. Some effects like the influence of secondary flows with characteristic scale of 1-3 km on heat and mass transfer are either parametrized or neglected. Another serious problem for numerical modeling is a large number of parameters (humidity, compressibility, physical properties of media, and many others). Taking into account that the time of one full-scale 3D run is one week or more, studying the role of all parameters is hardly possible. Limited capabilities of direct numerical modeling of atmospheric flows increase interest to the laboratory modeling of geophysical processes. On the base of approach described in [4] and using of PIV (Particle Image Velocimetry) system it was shown [5, 6, 7] that the structure of laboratory convective vortex is similar to the structure of typical tropical cyclone. Comparison was done with the observational data and results of numerical modeling [8, 9]. Experiments also showed that the characteristics of laboratory cyclonic vortex essentially depend on viscosity which is in a good agreement with numerical studies [10, 11] (for the atmospheric flows turbulent viscosity is used). All these studies prove efficiency of laboratory modeling of atmospheric processes. Presented paper describes approach which integrates measuring
and computational resources for experimental study of formation of laboratory analogue of tropical cyclone [4, 5, 6, 7] with a controlled feedback between flow velocity and heat release. To our knowledge, the only attempt to model of latent heat release in connection with tropical cyclogenesis was done almost fifty years ago [12], where rate of exothermic chemical reaction depended on flow velocity. The new approach has many advantages because of controlled linkage between flow velocity and heating. Realization of controlled feedback between velocity and heating required solution of a number of technical problems such as data acquisition and storing, real-time data processing, integration of PIV and heating control systems.

The paper is structured as follows. In Section II, we describe experimental setup and supercomputer processing of external data. Experimental results are presented in Section III. Discussion and conclusion are given in Section IV.

2. Experimental Setup

2.1. Experimental model

Experimental model is a cylindrical vessel of diameter $D = 300$ mm, and height $H = 40$ mm. The sides and bottom were made of plexiglass with a thickness of 3 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 $d$ 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. Massive heater provides uniform heating which is optimal for vortex excitation. Cylindrical vessel was placed on a rotating horizontal table. Silicon oil PMS-5 (5 cSt at $T = 25^\circ$) is used as working fluid. In all experiments, the depth of the fluid layer $h$ was 30 mm, and the surface of the fluid was open. The room temperature was kept constant by air-conditioning system, and cooling of the fluid was provided mainly by the heat exchange with surrounding air on the free surface and some heat losses through sidewalls. Details of experimental setup, structure and characteristics of the laboratory analogue of tropical cyclone can be found in [6, 7]. The images for PIV processing were obtained using 2D particle image velocimetry (PIV) system Polis and the software package Actual Flow.

Experiment with a feedback requires real-time data processing. In order to solve this problem we use supercomputer for PIV images processing. The variation of number of computational nods allows achieving necessary rate of image processing. Essential feature of the proposed experiment is a linkage between heating and velocity of the fluid. Boundary condition on the heated surface is controlled by copper-constantan thermocouple. Thermocouple is located inside heat exchanger near the surface and is connected with temperature regulator Termodat-17E5. It allows setting required temperature or heating power remotely. Software which controls heating power is linked with the main block providing integration of all parts of experimental system. For each experimental realization we set functional dependence between flow velocity and heating power (or temperature of the heater). Flow characteristics obtained by real-time PIV processing serve as input parameters for the heating system.

2.2. Supercomputer processing of external data

Remote data processing using external computing system requires organization of data transport network between measuring and computational systems. Another problem is efficient distribution of experimental data on computing nods and return of processed data back to the main experimental computer [13, 14]. Fig. 1 shows scheme of data transport and processing from experimental setup to the Triton supercomputer and back.

Measurement data (image pairs) are stored in a specific folder and transferred to data stream manager. Data stream manager analyzes requests from computational nodes and distributes experimental data. After supercomputer PIV processing, the data (velocity fields) goes back from computational nods to data stream manager for further transport to experimental computer. During the next stage the control software in experimental computer uses this data for changing heating conditions. Data stream manager is highly productive queue server, developed by the authors, which is ready for efficient work with large data packets up to tens of megabytes. This condition is necessary for PIV images transport.
Manager is responsible for control of the sending packets in queues, intermediate storing, distribution among computational nods of supercomputer or other external systems. Using the concept of queues allows separating measuring and computational systems, refusing from synchronization of computational nods and isolating the problem of distribution and collection of data in one subsystem data stream manager. Another advantage of proposed approach is parallelism of data transport from data stream manager to supercomputer. It sufficiently increases efficiency of data transport in case of large distance to supercomputer.

![Figure 1. Scheme of experimental data processing.](image)

As a basic PIV algorithm we chose the one realized in PIVlab software [15] published by BSD license. Initially PIVlab code was written using Matlab and cannot be used directly for calculations on Triton supercomputer, so PIV algorithms were written in C++ and optimized by using Intel libraries (MKL and IPP). Some algorithms were optimized by manual vectorization using SSE and AVX instructions. Implementation of efficient paralleling of data processing using all available cores of computational node was successful at all stages except initial unpacking compressed PNG (portable network graphics) images. Optimization of PIV algorithms and paralleling of data processing decrease time of double-frame PIV processing approximately by 180 times in comparison with original Matlab algorithm. The time of unpacking of images and saving of resulting data is almost constant but the time of processing (efficiency of paralleling) scales linearly and depends on PIV processing settings. In the present study each measurement (double-frame) is processed by four threads.

2.3. Temperature control
The particular feature of the presented experiment is linkage between intensity of the heating and velocity of the flow. This linkage serves as a simple model of latent heat release in a boundary layer of tropical cyclone. Realization of this linkage requires remote control of boundary condition on the heater (heat flux or temperature). Copper-constantan thermocouple is embedded inside the heater and is connected to the temperature regulator Termodat-17E5. Control signal of Termodat-17E5 (high-frequency low voltage impulses with variable duty ratio) comes to a solid-state relay connected in the break of the heater supply circuit. Depending on control signal the coefficient $K_p$ which defines heating power can be varied from 0 to 1 with a step of 0.01. Control of the correct setting of maximal power $P_0$ is provided by voltage and current measurements in the heater coil circuit. As a result instant value of the heating power is a product of $P_0$ and $K_p$, which is a function of flow characteristics. For experiments presented in the paper mean radial velocity $\langle \dot{V}_r \rangle$ is chosen as a flow characteristic which defines heating intensity. The value of $\langle \dot{V}_r \rangle$ is calculated with a required frequency using velocity fields reconstructed by PIV supercomputer processing.
3. Experimental results

Detailed description of the basic flow structure over localized heater in a rotating layer can be found in [5, 6, 7]. Here we present first experiments on modeling of latent heat release using on-line PIV data processing. Modeling of latent heat release requires consideration of initial developing stage of cyclonic vortex when increasing of radial velocity which results in increasing of heat release. For the presented experiments linear dependence of heat flux on instantaneous mean radial velocity \( V_r \) is chosen in the following form \(-P = P_0 V_r / V_{r,st}\), where \( P_0 \) is a maximal heating power, and \( V_{r,st} \) is a mean radial velocity for a quasi-stationary state with fixed heating power equal to \( P_0 \), as in [6].

According to the chosen dependence between radial velocity and heat flux it is expected that in case of monotonic increase of radial velocity a quasi-stationary state as in the case of constant heating power will be achieved. Intense processes of heat and mass transfer take place in the boundary layer of tropical cyclone, so 2D PIV measurements are done approximately in the middle of radial inflow at \( z = 5 \) mm. The final size of the interrogation area was \( 16 \times 16 \) pixels, which allows obtaining \( 113 \times 110 \) velocity vectors in the field of measurements. Only velocity vectors located over heating area are used for calculation of \( V_r \) (about two thousand vectors). Three series of measurements are carried out. The only difference between them is the angular velocity \( \Omega \). Now let us describe the course of the experiments. At first the solid-body rotation of the fluid layer is achieved. Then for initiation of radial motion the heating is switched on (approximately 30% of a maximal value) for a short time (30 seconds). After that linear dependence between heating power and mean radial velocity is assigned.

![Figure 2](image)

**Figure 2.** a – Normalized dependences of heating power \( P \) (black lines) and temperature difference \( \Delta T \) (grey lines); b – temporal evolution of the mean square radial velocity; 1 – \( \Omega = 0.08 \) rad/s, 2 – \( \Omega = 0.11 \) rad/s, 3 – \( \Omega = 0.17 \) rad/s.

At first we analyze the temporal evolution of heating power \( P \) and \( \Delta T \) which is imposed temperature difference between temperature of the fluid (measured in the middle of the layer, near periphery), and temperature of the heater. There is important distinction between the role of heat release and horizontal temperature difference. The main source that leads to the formation of concentrated cyclonic vortex is radial inflow which transports additional angular momentum to the center. In our case the radial inflow is driven mainly by convection, which depends on \( \Delta T \), so for the vortex development it is necessary that heat release leads to increasing of \( \Delta T \). It is possible that large-scale flow effectively removes released heat by advection from the center to the periphery. In that case \( \Delta T \) becomes constant or decreases, and this is the end of the cyclonic vortex intensification stage. Figure 2 shows temporal evolution of the heating power and horizontal temperature difference for the three experiments. Note that due to substantial level of fluctuations which are natural for convective flows with localized heating [16, 17, 18] we calculate and present in Fig. 2 (and others) a moving average of flow characteristics. For the comparison between time variation of \( P \) and \( \Delta T \) they are normalized by their maximum values achieved for \( \Omega = 0.17 \) rad/s (\( P_{\text{max}} = 55.6W, \Delta T_{\text{max}} = 21.4^\circ \)). Short-time initial heating explains non-zero starting values of \( \Delta T \). We can see in Fig. 2 that up to some moment heating power which is proportional to the mean radial velocity leads to the increase in \( \Delta T \) which by-turn increases radial inflow. This is developing stage of the cyclonic vortex. Finally, when most of the heating power is removed from the heater by flow circulation, \( \Delta T \) achieves its maximum value, and
vortex development is stopped. It is interesting that unlike [5, 6, 7], where heat flux was constant, here the achieved heating power, which is proportional to the mean radial velocity, is highest for the relatively fast rotation rate. It proves that linkage between flow circulation and heat release is of primary importance for the vortex development.

Important characteristics of the cyclonic vortex are energies of radial and azimuthal flows. For the presented experiments they increase with increasing of \( \Omega \) (Fig. 2 and Fig. 3). Comparison between mean square velocities of radial and azimuthal flows \( \langle V_r^2 \rangle \) and \( \langle V_a^2 \rangle \) show that for \( \Omega = 0.08 \text{ rad/s} \) energy of radial flow is higher than that of azimuthal flow. For \( \Omega = 0.11 \text{ rad/s} \) they are comparable, and for \( \Omega = 0.17 \text{ rad/s} \) azimuthal flow is much more intense. For \( \Omega = 0.17 \text{ rad/s} \) there is monotonic increase of \( \langle V_a^2 \rangle \), when both \( \Delta T \) and \( P \) decrease. It can be explained by specifics of the presented experiment. The cooling of the fluid is provided by the heat release to the relatively cold air at the open surface. It depends on the temperature of the fluid and during the non-stationary stage of experiment the overall heat flux is not zero and mean temperature of the fluid increases. It leads to the change of physical properties of the fluid that concerns mainly kinematic viscosity. Decrease in kinematic viscosity has influence on the processes in the boundary layer and increases \( \langle V_a^2 \rangle \). Taking into account the described kinematic viscosity \( \nu_0 \), variation \( \langle V_a^2 \rangle \) can be corrected:

\[
\langle V_a^2 \rangle_{\text{corr}} = \langle V_a^2 \rangle \cdot (\nu/\nu_0)^2
\]

where \( \nu_0 \) is the initial value of kinematic viscosity. It is evident that temporal evolution of \( \langle V_a^2 \rangle_{\text{corr}} \) is similar to \( \Delta T \) variation (Fig. 3). This strong correlation makes it possible to control the intensity of the cyclonic vortex by variation of \( \Delta T \). The last interesting observation concerns similarity of the dynamics of maximum values of radial and azimuthal velocities. Temporal evolution of normalized values of \( V_{r,\text{max}} \) and \( V_{a,\text{max}} \) is presented in Fig. 3. We can see that despite large quantitative differences the temporal evolution is definitely similar and it can be a ground for a simple mathematical model, which would describe the vortex formation in a presented system.

![Figure 3](image)

**Figure 3.** a – Temporal evolution of the mean square azimuthal velocity, thick black line – the mean square azimuthal velocity, thick grey line – corrected mean square azimuthal velocity, thin black line – normalized \( \Delta T \); 1 – \( \Omega = 0.08 \text{ rad/s} \), 2 – \( \Omega = 0.11 \text{ rad/s} \), 3 – \( \Omega = 0.17 \text{ rad/s} \). b – temporal evolution of normalized maxima of radial (grey lines) and azimuthal (black lines) velocity.

4. Discussion and conclusion

In the present study we described laboratory model of tropical cyclone with controlled forcing. Procedures of real-time data acquisition, storing and processing, specifics of integration of PIV and heating control systems were described. A series of experiments with laboratory analogue of tropical cyclone using feedback between velocity and a heating is carried out. To our knowledge this is the first attempt since [12]. It is known that convection and formation of secondary (meridional) circulation is of primary importance for tropical cyclone (TC) formation [1, 2]. We show that for laboratory model of TC the crucial parameter which defines the mean radial velocity and intensity of the vortex is imposed temperature difference \( \Delta T \). Strong dependence of developed vortex intensity on rotation rate was found. It gives a reason to assume that development of real TCs also substantially depend on the intensity of initial vortical disturbance. The similarity between temporal dynamics of
maximum values of radial and azimuthal velocities for different rotation rates despite their large quantitative discrepancies shows that there is some universal feature in the development stage of cyclonic vortex with localized heat flux. It can serve a ground for a simple analytical model of cyclonic vortex dynamics. Finally we can conclude that the linkage between velocity and heat release is of crucial importance for the cyclonic vortex formation. This is just the first step toward the solution of the problem of latent heat release in a complex system such as tropical cyclone. Different functional dependences of heat release on flow characteristics will be studied further.

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References
[1] Emanuel K 2003 Annual Review of Earth and Planetary Sciences 31
[2] Montgomery M T and Smith R K 2017 Annual Review of Fluid Mechanics 49 541–574
[3] Gall R, Franklin J, Marks F, Rappaport E N and Toepfer F 2013 Bulletin of the American Meteorological Society 94 329–343
[4] Bogatyr’ev G P 1990 Soviet Journal of Experimental and Theoretical Physics Letters 51 630
[5] Batalov V, Sukhanovsky A and Frick P 2010 Geophysical and Astrophysical Fluid Dynamics 104 349–368
[6] Sukhanovskii A, Evgrafova A and Popova E 2016b Quarterly Journal of the Royal Meteorological Society 142 2214–2223
[7] Sukhanovskii A, Evgrafova A and Popova E 2017 Dynamics of Atmospheres and Oceans 80 12–28
[8] Zhang J A, Rogers R F, Nolan D S and Marks Jr F D 2011 Monthly Weather Review 139 2523–2535
[9] Smith R K, Montgomery M T and Persing J 2014 Quarterly Journal of the Royal Meteorological Society 140 2638–2649
[10] Zhang J A and Marks F D 2015 Monthly Weather Review 143 3981–3995
[11] Zhang J A, Marks F D, Sippel J A, Rogers R F, Zhang X, Gopalakrishnan S G, Zhang Z and Tallapragada V 2018 Weather and Forecasting 33 317–329
[12] Hadlock R K and Hess S L 1968 Journal of the Atmospheric Sciences 25 161–177
[13] Shchapov V, Masich G and Masich A 2015 Procedia Computer Science 66 515–524 4th International Young Scientist Conference on Computational Science
[14] Shchapov V A, Masich A G and Masich G F 2017 Journal of Systems and Software 127 258 – 265 ISSN 0164-1212
[15] Thielicke W and Stamhuis E 2014 Journal of Open Research Software 2(1) e30
[16] Boubnov B and Van Heijst G 1994 Experiments in fluids 16 155–164
[17] Maza D, Vallone A, Mancini H and Boccaletti S 2000 Physical review letters 85 5567
[18] Sukhanovskii A, Evgrafova A and Popova E 2016a Physica D: Nonlinear Phenomena 316 23–33