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The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Experimental Studies of Geometrical Properties, Vorticity Dynamics and Small-Scale Statistics of Vortex Structures in Rotating Thermal Convection

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Xia, Ke-Qing	Prof Zhong, Jin-Qiang
Post	Professor	Professor
Unit / Department / Institution	Physics Department, The Chinese University of Hong Kong	School of Physics Science and Engineering, Tongji University
Contact Information		
Co-investigator(s) *(with title and institution)*		

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01.01.2016	01.01.2016	
Project Completion date	31.12.2019	15.11.2018	18.12.2018
Duration *(in month)*	48	34.5	
Deadline for Submission of Completion Report		15.11.2019	

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To investigate the geometrical properties of vortex structures in rotating thermal convection. The number and area of the vortex structures and their distribution in the flow will be measured.

2. To study the dynamics of vortices and their interactions in rotating convective turbulence. The horizontal meandering and lifetime of single vortex and the vortex-vortex interaction will be obtained

3. To measure the statistical properties of temperature and velocity fluctuations inside and outside the vortex structures in rotating convection. The spatial distribution of the local heat flux will be calculated to understand the main heat transport path in the system.

4. To investigate the energy cascade in turbulent rotating convection, including the energy dissipation rate, structure function, and the energy and entropy spectra.

5. To understand the mechanism of flow regime transition in rotating thermal convection based on the geometrical and dynamical features of the vortex structures.

5.2 Revised Objectives

Date of approval from the RGC: N/A

Reasons for the change: ______________________________

1.
2.
3. ....

6. Research Outcome

Major findings and research outcome

(maximum 1 page; please make reference to Part C where necessary)

There are a number of findings made in this project. Most importantly, we find that the two-dimensional motion of vortex columns in rotating turbulent flows behave like particles. Specifically, we find that, under moderate rotation rate, the horizontal motion of vortex columns behave like Brownian particles, they initially move ballistically, and then diffusively after certain critical time. Moreover, the transition from ballistic to diffusive behaviors is direct, as predicted by Langevin, without first going through the hydrodynamic memory regime. This is the first time that the "pure Brownian" motion has been observed in a liquid system. In the spatial domain, however, the vortices exhibit organized structures, as if they are performing tethered random motion. Our results imply that vortices actually have inertia-induced memory such that their short term movement can be predicted and their motion can be well described in the framework of Brownian motions. When rotation becomes rapid, the effect of centrifugation becomes significant. In such a case, the vortices move according to their helicity. Near the bottom boundary cyclones are upwelling (warm) vortices while anticyclones are downwelling (cold) ones, and its opposite in the upper half of the cell. Our results show that when centrifugal buoyancy is present the vortices undergo radial motions, i. e. cyclones move radially inward and anticyclones outward. We show that these behaviors can be explained through a Langevin-type stochastic model. Unexpectedly, under even stronger rotation, in the centrifugation-dominant flow regime anomalous outward motion of cyclones are observed. This phenomenon is interpreted as a symmetry breaking of the vorticity field induced by the centrifugal buoyancy. Consequently the cyclones submit to the collective motion dominated by the strong anticyclones. Further studies of this anomalous vortex motion reveal that the vortices self-organize into coherent clusters, in which their velocity fluctuations exhibit scale-free correlations, with the correlation length being about 30% of the cluster length. Scale-free collective motions have been found in many natural systems consisting of large number of large number of objects, such as bird flocks and bacteria swarms. Our study provides new understanding of vortex dynamics and collective motion that are widely present in nature.

Potential for further development of the research and the proposed course of action

(maximum half a page)

There are a number of possible lines of research that one can develop from the wealth of information and knowledge obtained from the present project. During our study, we found that the vortices form or aggregate near the sidewall of the convection cell and their motions resemble the so-called wall mode. We plan to further explore this wall mode in the centrifugation dominant regime. Another interesting line of research worthy of pursuit is the nature of interactions among the vortices in the anomalous regime that lead to the collective their motion within a cluster. The result should shed light on not only vortex dynamics in turbulent flows, but also collective motion in active matter systems.

7. The Layman's Summary

(describe <u>in layman's language</u> the nature, significance and value of the research project, in no more than 200 words)

Convection phenomena exist ubiquitously in geophysical and astrophysical systems, such as in the core and atmosphere of planets and in star. As almost all planets and stars are rotating objects, understanding convection under rotation is therefore essential to our understanding of the many properties of planets and start. Our study reveals that vortices in rotating turbulent flows behaves like particles. Moreove, when the rotation is moderate, the motion of vortices exhibit Brownian-like behavior. When the rotation becomes strong such as the effect of centrifugal force is negligible, the motion of vortices is no longer random but exhibit features of collective motion.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) (**bold** *the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
2017				**Kai Leong Chong,** Yantao Yang, **Shi-Di Huang, Jin-Qiang Zhong,** Richard J. A. M. Stevens, Roberto Verzicco, Detlef Lohse,and **Ke-Qing Xia***	Confined Rayleigh-Bénard, Rotating Rayleigh-Bénard, and Double Diffusive Convection: A Unifying View on Turbulent Transport Enhancement through Coherent Structure Manipulation PHYSICAL REVIEW LETTERS, 119, 064501	Yes 2017	No	Yes	

2018				**Kai Leong Chong,** Sebastian Wagner, Matthias Kaczorowski,Olga Shishkina, and **Ke-Qing Xia***	Effect of Prandtl number on heat transport enhancement in Rayleigh-Bénard convection under geometrical confinement PHYSICAL REVIEW FLUIDS 3, 013501	Yes 2017	No	Yes	
2018				**Fei Wang, Shi-Di Huang, and Ke-Qing Xia***	Contribution of Surface Thermal Forcing to Mixing in the Ocean Journal of Geophysical Research: Oceans 123, 855–863 https://doi.org/10.1002/2017JC013578	Yes 2017	No	Yes	
2018				**Yi-Chao Xie, Guang-Yu Ding, and Ke-Qing Xia***	Flow Topology Transition via Global Bifurcation in Thermally Driven Turbulence PHYSICAL REVIEW LETTERS 120, 214501 (2018)	No	Yes	Yes	
2018				**Kai Leong Chong*, Guangyu Ding, Ke-Qing Xia***	Multiple-resolution scheme in finite-volume code for active or passive scalar turbulence Journal of Computational Physics 375, 1045–1058	No	Yes	Yes	

2019				**Zi Li Lim, Kai Leong Chong, Guang-Yu Ding and Ke-Qing Xia***	Quasistatic magnetoconvection: heat transport enhancement and boundary layer crossing J. Fluid Mech. (2019), vol. 870, pp. 519-542.	No	Yes	Yes	
		2019		**Kai Leong Chong, Jun-Qiang Shi, Guang-Yu Ding, Shan-Shan Ding, Hao-Yuan Lu, Jin-Qiang Zhong* and Ke-Qing Xia***	Vortices as Brownian Particles in Turbulent Flows Science Advances (under review)	No	Yes	Yes	
		2019		**Shan-Shan Ding, Kai Leong Chong, Jun-Qiang Shi, Guang-Yu Ding, Hao-Yuan Lu, Ke-Qing Xia* and Jin-Qiang Zhong***	Scale-free collective motion of vortices in rotating turbulent flows Physical Review Letters (under review)	No	Yes	Yes	

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Nov. 2017/ Denver	Magnetoconvection and universality of heat transport enhancement	70th Annual Meeting of the APS Division of Fluid Dynamics (APS – American Physical Society)	Yes 2017	No	Yes	

Nov. 2017/ Denver	Passive moist transfer in Rayleigh-Bénard convection	70th Annual Meeting of the APS Division of Fluid Dynamics (APS – American Physical Society)	Yes 2017	No	Yes	
May 2018 Enschede	CONTRIBUTIO N OF SURFACE THERMAL FORCING TO MIXING IN THE OCEAN	INTERNATIONAL CONFERENCE ON RAYLEIGH BÉNARD TURBULENCE	no	Yes	Yes	
May 2018 Enschede	AN EXPERIMENTA L STUDY OF INTERNAL WAVE FIELD IN A STABLY THERMAL STRATIFIED FLUID LAYER	INTERNATIONAL CONFERENCE ON RAYLEIGH BÉNARD TURBULENCE	no	Yes	Yes	
May 2018 Enschede	CLUSTER FORMATION AND BROWNIAN MOTION OF COLUMAR VORTICES IN ROTATING RAYLEIGH-BÉ NARD CONVECTION	INTERNATIONAL CONFERENCE ON RAYLEIGH BÉNARD TURBULENCE	no	Yes	Yes	
May 2018 Enschede	TURBULENT RAYLEIGH-BÉ NARD CONVECTION IN A VERTICAL ANNULUS	INTERNATIONAL CONFERENCE ON RAYLEIGH BÉNARD TURBULENCE	no	Yes	Yes	

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Wang Fei	PhD	2011	2016
Chong Kai Leong	PhD	2014	2018
Lim Zi Li	M.Phil.	2016	2018
Zhang Lu	PhD	2012	2019

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

Mr. Kai-Leong Chong has been awarded the Croucher Postdoctoral Fellowship (2014-2017). His PhD thesis work was support by the present project. Part of the results was published in (Publication #1,2,5,6,7,8).

The Hong Kong PI and the Mainland PI have established collaborations with the Physics of Fluids group of Professor Detlef Lohse of the University of Twente in the Netherlands. The Hong Kong PI has established collaboration with the group of Professor Olga Shishikina at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany. These collaborations have led two publications with the respective groups