INTERNATIONAL CONFERENCE ON RAYLEIGH-BÉNARD TURBULENCE

December 10-14, 2012, Hong Kong

Program

Organizer:

Department of Physics, The Chinese University of Hong Kong

Sponsors:

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Chung Chi College and Institute of Theoretical Physics,
The Chinese University of Hong Kong

香港中文大學
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Keynote Speakers:

Guenter Ahlers, University of California, Santa Barbara, USA

Roberto Benzi, University of Rome "Tor Vergata", Italy

Friedrich Busse, University of Bayreuth, Germany

Francesca Chillà, École Normale Supérieure de Lyon, France

Charles Doering, University of Michigan, USA

Hantao Ji, Princeton University, USA

Gerd Pfister, Kiel University, Germany

Olga Shishkina, German Aerospace Center (DLR), Germany

Richard Stevens, Johns Hopkins University, USA

Scientific Committee:

Detlef Lohse, University of Twente, The Netherlands

Roberto Verzicco, University of Rome "Tor Vergata", Italy

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Penger Tong, The Hong Kong University of Science and Technology

Liqiu Wang, The University of Hong Kong

Yu Zhou, The Hong Kong Polytechnic University

Program

Venue: Lecture Theatre L2, 1/F., Science Centre, The Chinese University of Hong Kong

Date / Time	Dec 10 (Mon)	Dec 11 (Tue)	Dec 12 (Wed)	Dec 13 (Thu)	Dec 14 (Fri)
08:50 – 09:00	**Opening**				
Chair	*K.-Q. Xia*	*R. Verzicco*	*E. Bodenschatz*	*J. Schumacher*	*Z. S. She*
09:00 – 09:40	**G. Ahlers**	**R. Benzi**	**H. T. Ji**	**R. Stevens**	**F. Busse**
09:40 – 10:10	**R. Verzicco**	**B. Eckhardt**	**K. L. Chan**	**H. Clercx**	**J. Schumacher**
10:10 – 10:30	**D. Funfschilling**	**Q. Zhou**	**S. Huisman**	**R. Ni**	**K. Chang**
10:30 – 11:00	*Tea Break*				
Chair	*B. Eckhardt*	*U. Hansen*	*H. Clercx*	*E. Ching*	*F. Toschi*
11:00 – 11:30	**E. Bodenschatz**	**D. Lohse**	**P. Tong**	**Z. S. She**	**E. S. C. Ching**
11:30 – 11:50	**R. Kunnen**	**E. van der Poel**	**E. Brown**	**J. Chen**	**S. Q. Zhou**
11:50 – 12:10	**S. Horn**	**J. Salort**	*Lunch* (12:00 – 13:00)	**Y. X. Huang**	**J. Q. Zhong**
12:10 – 12:30	**J. Scheel**	**E. Rusaouën**		**C. Resagk**	**N. Shi**
12:30 – 14:00	*Lunch*			*Lunch*	*Lunch* (12:30 – 13:30)
Chair	*R. Benzi*	*R. du Puits*	*Boat Tour and Discussion*	*K. L. Chan*	*D. Lohse*
14:00 – 14:40	**F. Chillà**	**G. Pfister**		**O. Shishkina**	**C. Doering** (13:30 – 14:10)
14:40 – 15:10	**L. Skrbek**	**F. Toschi**		**U. Hansen**	**Closing Remarks** (14:10 –)
15:10 – 15:30	**K. Petschel**	**D. van Gils**		**C. Sun**	
15:30 – 16:00	*Tea Break*			*Tea Break*	
Chair	*P. Tong*	*A. Davaille*		*E. Brown*	
16:00 – 16:30	**R. du Puits**	**M. Verma**		**A. Davaille**	
16:30 – 16:50	**R. Kaiser**	**A. Sergent**		**R. Ostilla Mónico**	
16:50 – 17:10	**S. Wagner**	**M. Kaczorowski**		**S. D. Huang**	
17:10 – 17:30	**Y. C. Xie**	**X. Z. He**		**M. Winkler**	
18:00 – 20:00	*Dinner Reception (SCR Clubhouse)*		*Banquet*	*Seafood Dinner (Sai Kung)*	

December 10, Monday

08:20 – 08:50	**Registration** (Room G25A, G/F., Science Centre North Block, CUHK)
08:50 – 09:00	**Opening**
Chair: Ke-Qing Xia (The Chinese University of Hong Kong)	
09:00 – 09:40	**Guenter Ahlers** (University of California, Santa Barbara): *Transition to the Ultimate State in Turbulent Rayleigh-Bénard Convection*
09:40 – 10:10	**Roberto Verzicco** (University of Rome "Tor Vergata"): *Sidewall Effects in Rayleigh-Bénard Convection*
10:10 – 10:30	**Denis Funfschilling** (LRGP CNRS, Université de Lorraine): *Measurement of the Temperature Field in a Rayleigh-Bénard Turbulent Convection Cell by Laser Induced Fluorescence*
10:30 – 11:00	*Tea Break*
Chair: Bruno Eckhardt (Philipps-Universität Marburg)	
11:00 – 11:30	**Eberhard Bodenschatz** (Max Planck Institute for Dynamics and Self-Organization): *Logarithmic Temperature Profiles in Turbulent Rayleigh-Bénard Convection*
11:30 – 11:50	**Rudie Kunnen** (Eindhoven University of Technology): *Flow Structure in $\Gamma = ½$ Turbulent Rotating Rayleigh-Bénard Convection*
11:50 – 12:10	**Susanne Horn** (German Aerospace Center (DLR)): *Non-Oberbeck-Boussinesq Effects in Rotating Rayleigh-Bénard Convection*
12:10 – 12:30	**Janet Scheel** (Occidental College): *Spatial Dependence of Boundary Layers in Simulations of Rayleigh-Bénard Convection*
12:30 – 14:00	*Lunch*
Chair: Roberto Benzi (University of Rome "Tor Vergata")	
14:00 – 14:40	**Francesca Chillà** (École Normale Supérieure de Lyon): *Flow Regimes in a Convective Channel*
14:40 – 15:10	**Ladislav Skrbek** (Charles University): *Experimental Investigation of Cryogenic Turbulent Rayleigh-Benard Convection at Very High Rayleigh Numbers*
15:10 – 15:30	**Klaus Petschel** (Westfälische Wilhelms-Universität Münster): *Dissipation Layers in Rayleigh-Bénard Convection: A Unifying View*
15:30 – 16:00	*Tea Break*
Chair: Penger Tong (Hong Kong University of Science and Technology)	
16:00 – 16:30	**Ronald du Puits** (Ilmenau University of Technology): *Boundary Layer Visualization in Turbulent Rayleigh-Bénard Convection in Air*
16:30 – 16:50	**Robert Kaiser** (Ilmenau University of Technology): *Two-dimensional Heat Flux Distribution on the Heating Plate of a Rectangular Rayleigh-Bénard Convection Cell*
16:50 – 17:10	**Sebastian Wagner** (German Aerospace Center (DLR)): *Numerical Investigation of Geometry Effects in Rayleigh-Bénard Convection*
17:10 – 17:30	**Yi-Chao Xie** (The Chinese University of Hong Kong): *Coupling and Dynamics of the Large-scale Circulation in Two-layer Turbulent Rayleigh-Bénard Convection*
18:00 – 19:30	*Dinner Reception (SCR Clubhouse)*

December 11, Tuesday

Chair: Roberto Verzicco (University of Rome "Tor Vergata")	
09:00 – 09:40	**Roberto Benzi** (University of Rome "Tor Vergata"): *Polymers in Rayleigh Bénard Turbulence*
09:40 – 10:10	**Bruno Eckhardt** (Philipps-Universität Marburg): *Rayleigh-Bénard Convection in the Asymptotic Suction Boundary Layer*
10:10 – 10:30	**Quan Zhou** (Shanghai University): *Experimental Investigation of Longitudinal Space-time Correlations of the Velocity Field in Turbulent Rayleigh-Bénard Convection*
10:30 – 11:00	*Tea Break*
Chair: Ulrich Hansen (Westfaelische-Wilhelms-Universitat Muenster)	
11:00 – 11:30	**Detlef Lohse** (University of Twente): *Logarithmic Temperature Profiles in the Ultimate Regime of Thermal Convection*
11:30 – 11:50	**Erwin van der Poel** (University of Twente): *Logarithmic Temperature Profiles in Rayleigh-Bénard Convection*
11:50 – 12:10	**Julien Salort** (Ecole Normale Supérieure de Lyon): *Local Temperature Measurements at High Rayleigh Numbers*
12:10 – 12:30	**Eleonore Rusaouën** (Ecole Normale Supérieure de Lyon): *Comparison between Rough and Smooth Plates within the Same Rayleigh-Bénard Cell*
12:30 – 14:00	*Lunch*
Chair: Ronald du Puits (Ilmenau University of Technology)	
14:00 – 14:40	**Gerd Pfister** (Kiel University): *Scenarios in Taylor-Couette Flow*
14:40 – 15:10	**Federico Toschi** (Eindhoven University of Technology): *On the Ultimate State of Rayleigh–Bénard Convection*
15:10 – 15:30	**Dennis van Gils** (University of Twente): *The Importance of Bubble Deformability for Strong Drag Reduction in Bubbly Turbulent Taylor-Couette Flow*
15:30 – 16:00	*Tea Break*
Chair: Anne Davaille (Laboratoire FAST, CNRS / Univ. Paris-Sud)	
16:00 – 16:30	**Mahendra Verma** (I. I. T. Kanpur): *Flow Reversals in Turbulent Convection via Vortex Reconnections*
16:30 – 16:50	**Anne Sergent** (LIMSI - CNRS): *Fourier and POD Analysis of the LSC Reversal in Rectangular Rayleigh-Bénard Cell*
16:50 – 17:10	**Matthias Kaczorowski** (The Chinese University of Hong Kong): *On the Challenges of Numerically Investigating Small-scale Statistics in the Bulk of Turbulent Rayleigh-Bénard Convection*
17:10 – 17:30	**Xiaozhou He** (Max Planck Institute for Dynamics and Self-Organization): *Temperature Statistics of Turbulent Rayleigh-Bénard Convection for Rayleigh Numbers up to 10^{15}*

December 12, Wednesday

Chair: Eberhard Bodenschatz (Max Planck Institute for Dynamics and Self-Organization)	
09:00 – 09:40	**Hantao Ji** (Princeton University): *Stability of Quasi-Keplerian Flow in Taylor-Couette Devices at Large Reynolds Numbers*
09:40 – 10:10	**Kwing Lam Chan** (Hong Kong University of Science and Technology): *Compressible Turbulent Convection in Outer Planets*
10:10 – 10:30	**Sander Huisman** (University of Twente): *Statistics in Turbulent Taylor-Couette Flow with Independently Rotating Cylinders*
10:30 – 11:00	*Tea Break*
Chair: Herman Clercx (Eindhoven University of Technology)	
11:00 – 11:30	**Penger Tong** (Hong Kong University of Science and Technology): *Turbulent Rayleigh-Bénard Convection in a Horizontal Cylinder*
11:30 – 11:50	**Eric Brown** (University of California, Merced): *Geometry-dependence of Large-scale Circulation Dynamics*
12:00 – 13:00	*Lunch*
14:00 – 17:30	*Boat Tour and Discussion*
18:30 – 20:30	*Banquet*

December 13, Thursday

Chair: Joerg Schumacher (Ilmenau University of Technology)	
09:00 – 09:40	**Richard Stevens** (Johns Hopkins University): *Rotating Rayleigh-Bénard Turbulence*
09:40 – 10:10	**Herman Clercx** (Eindhoven University of Technology): *Lagrangian Statistics of Particles in Rotating Turbulent Convection*
10:10 – 10:30	**Rui Ni** (The Chinese University of Hong Kong): *Measured Small-scale Quantities in Turbulent Rayleigh-Bénard Convection with Polymer Additives*
10:30 – 11:00	*Tea Break*
Chair: Emily S.C. Ching (The Chinese University of Hong Kong)	
11:00 – 11:30	**Zhen-Su She** (Peking University): *Theory for Velocity and Temperature Distribution inside a RBC Cell*
11:30 – 11:50	**Jun Chen** (Peking University): *The Prandtl Number Dependence of Heat Transport in Turbulent Rayleigh-Bénard Convection*
11:50 – 12:10	**Yongxiang Huang** (Shanghai University): *Generalized Autocorrelation Function in Rayleigh-Bénard Convection*
12:10 – 12:30	**Christian Resagk** (Ilmenau University of Technology): *Large Scale Structures in the Velocity Field of Boundary Layer in Rayleigh-Bènard Convection Measured with PIV*
12:30 – 14:00	*Lunch*
Chair: Kwing Lam Chan (Hong Kong University of Science and Technology)	
14:00 – 14:40	**Olga Shishkina** (German Aerospace Center (DLR)): *The Influence of Confined Geometry and Interior Walls on Heat Transport and Boundary Layer Structures in Turbulent Thermal Convection*
14:40 – 15:10	**Ulrich Hansen** (Westfaelische-Wilhelms-Universitat Muenster): *Convection under Stress-free Boundaries- Reversals without Corner-effects*
15:10 – 15:30	**Chao Sun** (University of Twente): *Optimal Taylor-Couette Turbulence*
15:30 – 16:00	*Tea Break*
Chair: Eric Brown (University of California, Merced)	
16:00 – 16:30	**Anne Davaille** (Laboratoire FAST, CNRS / Univ. Paris-Sud): *Anatomy of Thermal Plumes in Strongly Temperature-dependent Viscosity Fluids at High Prandtl and Rayleigh Numbers: Local Heating Versus Uniform Rayleigh-Bénard Configuration*
16:30 – 16:50	**Rodolfo Ostilla Mónico** (University of Twente): *Transition to the Ultimate Regime in Turbulent Taylor-Couette Flow: Numerical Simulations*
16:50 – 17:10	**Shi-Di Huang** (The Chinese University of Hong Kong): *Confinement Induced Enhancement of Flow Reversals and Heat Transport in Turbulent Rayleigh-Bénard Convection*
17:10 – 17:30	**Michael Winkler** (University of Potsdam): *Rayleigh-Bénard Convection in Thin Liquid Films – An Experimental Study*
18:30 – 20:30	*Seafood Dinner (Sai Kung)*

December 14, Friday

Chair: Zhen-Su She (Peking University)	
09:00 – 09:40	**Friedrich Busse** (University of Bayreuth): *Coherent Structures of Large Scale Natural Convection*
09:40 – 10:10	**Joerg Schumacher** (Ilmenau University of Technology): *Self-aggregation of Moist Convection in a Conditionally Unstable Environment*
10:10 – 10:30	**Kelken Chang** (Michigan Technological University): *Development of Supersaturation in Rayleigh-Bénard Convection*
10:30 – 11:00	*Tea Break*
Chair: Federico Toschi (Eindhoven University of Technology)	
11:00 – 11:30	**Emily S. C. Ching** (The Chinese University of Hong Kong): *Validity of the Bolgiano-Obukhov Phenomenology in Turbulent Thermal Convection*
11:30 – 11:50	**Sheng-Qi Zhou** (South China Sea Institute of Oceanology, CAS): *Characterizations of Double Diffusive Convection Steps and Heat Budget in the Deep Arctic Ocean*
11:50 – 12:10	**Jin-Qiang Zhong** (TongJi University): *Compositional Buoyancy Driven Convection during Sea-ice Solidification*
12:10 – 12:30	**Nan Shi** (Ilmenau University of Technology): *The Boundary Layer Structure in Turbulent Rayleigh-Bénard Convection for Different Prandtl Numbers*
12:30 – 13:30	*Lunch*
Chair: Detlef Lohse (University of Twente)	
13:30 – 14:10	**Charles Doering** (University of Michigan): *Rigorous Results for Heat Transport in High Rayleigh Number Convection*
14:10 –	**Closing Remarks**

Abstracts

December 10, 09:00 – 09:40

Transition to the Ultimate State in Turbulent Rayleigh-Bénard Convection

Guenter Ahlers[1,2], Xiaozhou He[1], Dennis van Gils[1], and Eberhard Bodenschatz[1]

[1] *Max-Planck Institute for Dynamics and Self-Organization, Göttingen, Germany*
[2] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*

It is expected theoretically[1,2] that the physical processes involved in heat transport by turbulent Rayleigh-Bénard convection will change fundamentally when the Rayleigh number Ra exceeds Ra^*, with $Ra^* = \mathcal{O}(10^{14})$. Although a transition in the Nusselt number Nu as a function of Ra was found[3] near $Ra_t \simeq 10^{11}$, this value is in our view too low to correspond to Ra^*.

The present talk will review efforts to extend the experimentally explored Ra range. The experiments were carried out in a new facility for the study of RBC at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany. Measurements of Nu(Ra), and of the turbulent rms fluctuation velocity as expressed by a Reynolds number Re(Ra), were made over the Rayleigh-number range $10^{12} \leq Ra \leq 10^{15}$ [4,5,6]. We used gaseous SF6 as the fluid and pressures up to 19 bars with two cylindrical samples known as High Pressure Convection Facilities (HPCFs), both with a diameter of $D = 1.1$ m, and one each with a height of $L = 2.2$ (HPCF-II)[4,5] and 1.1 m (HPCF-IV)[6]. The HPCFs were located in a large pressure vessel known as the "Uboot of Göttingen" [7].

The measurements for HPCF-II revealed a transition in Nu(Ra) and Re(Ra) which extended over a range of Ra, from $Ra_1^* \simeq 2\times10^{13}$ to $Ra_2^* \simeq 5\times10^{14}$. Recently the transition was observed as well in measurements of the temperature T_c at the sample center, which revealed a small shift away from the mean temperature T_m of the top and bottom plates[8]. Also for HPCF-IV a transition was found[6] in Nu(Ra), starting at the same $Ra_1^* \simeq 2\times10^{13}$; but the Ra range was limited to $Ra \simeq 2\times10^{14}$ and Ra_2^* thus could not be reached. With HPCF-II and for $Ra > Ra_2^*$ we found $Nu \propto Ra^{0.373\pm0.004}$ and $Re \propto Ra^{0.50}$, consistent with the predictions of Grossmann and Lohse[2] for an ultimate (asymptotic) state of RBC.

[1] R.H. Kraichnan, Phys. Fluids **5**, 1374 (1962).
[2] S. Grossmann and D. Lohse, Phys. Fluids **23**, 045108 (2011); and Phys. Fluids, in press.
[3] X. Chavanne, F. Chilla, B. Castaing, B. Hebral, B. Chabaud, and J. Chaussy, Phys, Rev. Lett. **79**, 3648 (1997).
[4] X. He, D. Funfschilling, H. Nobach, E. Bodenschatz and G. Ahlers, Phys. Rev. Lett. **108**, 024502 (2012).
[5] G. Ahlers, X. He, D. Funfschilling, and E. Bodenschatz, New J. Phys. **14**, 103012 (2012).
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[8] G. Ahlers, E. Bodenschatz, D. Funfschilling, S. Grossmann, X. He, D. Lohse, R.J.A.M. Stevens, and R. Verzicco, Phys. Rev. Lett. **109**, 114501 (2012).

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December 10, 09:40 – 10:10

Sidewall Effects in Rayleigh-Bénard Convection

Richard J.A.M. Stevens[1], **Roberto Verzicco**[1,2] and Detlef Lohse[1]

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[2] *DII, Universitá degli studi di Roma 'Tor Vergata', Roma, Italy*

We investigate the influence of the temperature boundary conditions at the sidewall on the heat transport in Rayleigh-Bénard (RB) convection through direct numerical simulations. For relatively low Rayleigh numbers *Ra* the heat transport is higher when the sidewall is isothermal, kept at a temperature $T_c + \Delta/2$ (where Δ is the temperature difference between the horizontal plates and T_c the temperature of the cold plate), than when the sidewall is adiabatic. The reason is that in the former case part of the heat current avoids the thermal resistance of the fluid layer by escaping through the sidewall that acts as a shortcircuit. For higher *Ra* the bulk becomes more isothermal and this reduces the heat current through the sidewall, therefore the heat flux in a cell with a isothermal sidewall converges to the value obtained with an adiabatic sidewall for high *Ra*.

If the sidewall temperature deviates from $T_c + \Delta/2$, however, the heat transport attains a different value at the bottom and top plates and both are different from the reference adiabatic sidewall value. In this case the difference does not decrease with *Ra* thus indicating that the ambient temperature of the experimental apparatus might play a role on the heat transfer.

Similar behaviours are observed when only the sidewall strips closest to the horizontal plates are kept isothermal the reason being that in those regions there is the maximum temperature difference between the fluid and the sidewall. This suggests that the use of thermal shields outside the fluid sample should be particularly cautious if spurious heat currents are to be avoided.

When the sidewall is considered with its physical properties (thickness, thermal conductivity and heat capacity) the problem becomes one of conjugate heat transfer and different behaviours are possible depending on the sidewall properties and the temperature boundary condition on its 'dry' side. It has been observed that in this case the sidewall does not affect only the heat transfer but it can trigger a different mean flow state or change the level of temperature fluctuations in the flow.

References

[1] X. Chavanne, F. Chillà, B. Chabaud, B. Castaing & B. Hebral (2001) Turbulent Rayleigh-Bénard convection in gaseous and liquid He. *Phys. of Fluids* **13**, 1300
[2] Niemela, J. J., Skrbek., L., Sreenivasan, R. R. & Donnely, R. J. (2000) Turbulent convection at very high Rayleigh numbers. *Nature* **404**, 837–841.
[3] Ahlers, G., Funfshilling, D. & Bodenshatz, E., (2009) Transition in heat transport by turbulent convection at Rayleigh numbers up to 10(15). *New J. Phys.*, **11**, 123001.
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[5] Ahlers, G., Grossmann, S. & Lohse, D. (2009) Heat transfer and large scale dynamics in turbulent Rayleigh-Bénard convection. *Rev. Mod. Phys.*, **81**, 503.
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December 10, 10:10 – 10:30

Measurement of the Temperature Field in a Rayleigh-Bénard Turbulent Convection Cell by Laser Induced Fluorescence

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Introduction

Several non-invasive or invasive experimental techniques have been used to study Rayleigh-Bénard convection. The shadowgraph technique [1] locates the plumes and determines their shapes but do not give information on the temperature of the plumes itself. Thermochromic liquid crystals [2] measure the temperature fields, but the range of use is quite limited, what restricts the use of this technique to some special conditions. In our work, the temperature field is measured by LIF (laser induced fluorescence) technique over a large range of temperature differences. The LIF technique is non invasive and has the advantages to be able to be combine with other techniques like Particle Tracking Velocimetry.

Experimental Set-Up and Measurements Technique

The cell is a cylindrical cell of 10 cm diameter and aspect ratio 1. The side walls are in Lexan, the bottom plate is in oxygen free copper and the top plate is in sapphire to allow a good optical access from the top. Distilled water is used as fluid. The LIF is a temperature measurement technique developed among others by some of us [3, 4, 5]. It consists of using a fluorescent dye diluted in the water and illuminated by a laser. By measuring the intensity of the fluorescence light by intensified cameras and by prior calibration, a temperature field can be measured by the relation [4]: $I_f(\lambda) = K_{opt}(\lambda) K_{spec}(\lambda) V_C I_0 C e^{\frac{\beta(\lambda)}{T}}$ where K_{opt} is an optical constant, K_{spec} is a constant depending on the properties of the tracer, I_0 the laser excitation intensity, C the concentration of the tracer, T, the absolute temperature and V_c the collection volume of the fluorescence photons, β is the temperature sensitivity coefficient.

The advantages of these technique is to be non-invasive, not limited to a small temperature range, to measure the temperature field in a full plane and to be able to be completed by other optical measurements techniques like PIV or Particle Tracking Velocimetry.

Results

The temperature field is first measured around a single plume generated by a small resistance. These measurements allow us to observe how fast a rising plume loses his heat with the time. Then the temperature field of the large scale circulation is measured by the LIF.

Reference

[1] Funfschilling D., Ahlers G., Plume motion and large-scale circulation in a cylindrical Rayleigh-Bénard cell, *Physical Review Letters*, **92** 194502-1, 2004

[2] Zhou Q., Sun C., Xia K.-Q., Morphological evolution of thermal plumes in turbulent Rayleigh-Bénard convection, *Physical Review Letters*, **98**, 074501, 2007

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[4] Castanet G., Delconte A., Lemoine F., Mees L., Gréhan G., Evaluation of temperature gradients within combusting droplets in linear stream using two colors laser-induced fluorescence *Experiment in Fluids* **39** 431-440, 2005

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December 10, 11:00 – 11:30

Logarithmic Temperature Profiles in Turbulent Rayleigh-Bénard Convection

Eberhard Bodenschatz[1], Xiaozhou He[1], Dennis van Gils[1], and Guenter Ahlers[1,2]

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It had long been thought[1] that the temperature in the interior of a Rayleigh-Bénard convection (RBC) sample, well away from the boundary layers near the top and bottom plate, is either constant or varies slowly and linearly with vertical position. Contrary to this conventional view it was found recently[2] that the temperature profile $\Theta \equiv (T(z)-T_m) / \Delta T$ (T_m is the mean sample temperature and ΔT the applied temperature difference) of a cylindrical sample of aspect ratio $\Gamma \equiv D/L = 0.50$ (D and L are the diameter and height respectively) varies as $\Theta = A*\ln(z/L) + B$ (z is the distance from the bottom or top plate). These findings are based on experimental measurements over the Rayleigh-number range[2,3] for a Prandtl number $\mathrm{Pr} \simeq 0.8$ and on DNS[2] for $\mathrm{Ra} = 2 \times 10^{12}$ and $\mathrm{Pr} = 0.7$. Although a logarithmic variation of A with z/L had been predicted[4] for the ultimate state which prevails for $\mathrm{Ra} \geq 5 \times 10^{15}$, it was found over the entire range studied, *i.e.* also in the classical state of RBC. The logarithmic dependence is reminiscent of the "law of the wall" long known for turbulent shear flows[5,6].

At all Ra studied, the coefficient A decreased in the radial direction as the distance from the side wall increased. Near $\mathrm{Ra} = 10^{15}$ this decrease could be described well[3] by the power law $|A| = 2.0 \times 10^{-4}[L/(R-r)]^{0.68}$ where r is the radial coordinate and R is the sample radius (the apparent divergence at $r = R$ is of course preempted by the existence of a boundary layer near the wall). The Ra dependence of A can be described well by separate logarithmic functions in the classical and the ultimate state[2,3], but a single power law $A = -1.7 * \mathrm{Ra}^{-0.15}$ fits the data equally well[3] over the entire range of Ra that was studied. The exponent -0.15 agrees fairly well with a recent theoretical result[7] of 0.162.

This talk will finish with a brief discussion of future plans to reach even higher values of Ra in the Göttingen RBC facility.

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* Supported by the Max Planck Society, the Volkswagen Stiftung, the DFG SFB963, and NSF grant DMR11-58514.

December 10, 11:30 – 11:50

Flow Structure in Γ = ½ Turbulent Rotating Rayleigh-Bénard Convection

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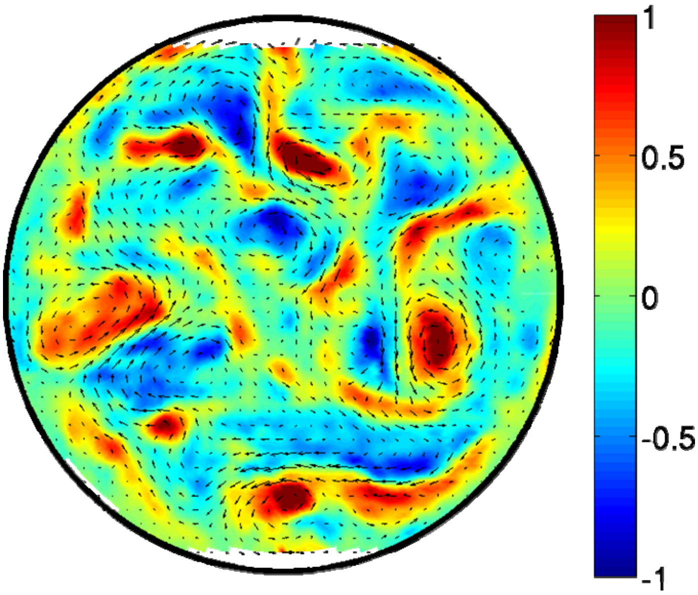
The flow phenomenology of turbulent rotating convection in a cylinder can be divided into two regimes: a large-scale circulation (LSC) for low rotation rates, and an unsteady array of columnar vortices under strong rotation. For cells of diameter-to-height aspect ratio $\Gamma = 1$ the LSC is known to precess against the direction of rotation[1]. The transition is abrupt[2]: at dimensionless rotation rates (inverse Rossby numbers) above the critical value $1/Ro_c$ the LSC is no longer detected. Recently, in an investigation of a $\Gamma = ½$ geometry[3] remarkably different results have been found. Using sidewall temperature probes a *corotating* LSC was detected for low $1/Ro$. The cosine-shaped azimuthal temperature profile typical of an LSC persisted even at rotation rates much higher than $1/Ro_c$.

These remarkable findings have prompted us to perform PIV measurements in a water-filled $\Gamma = ½$ rotating convection cell. We measure flow velocity in a horizontal cross-section of the cell close to the top plate (see the figure) for several rotation rates $0 \leq 1/Ro \leq 15$, covering both flow regimes, at a constant Rayleigh number $Ra = 5.9 \times 10^9$ and Prandtl number $\sigma = 6.4$. From these velocity fields we can extract the dynamics of the LSC; several methods are compared. In the vortex-dominated regime we apply the Q vortex detection criterion and study the clustering of vortices.



Velocity (vectors) and vertical vorticity (colour) in a flow snapshot at $1/Ro = 11.4$. *Many vortices can be identified, with both cyclonic (positive) and anticyclonic (negative) vorticity.*

[*] Visiting student from Université Paris-Sud

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December 10, 11:50 – 12:10

Non-Oberbeck-Boussinesq Effects in Rotating Rayleigh-Bénard Convection

Susanne Horn, Olga Shishkina and Claus Wagner

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We investigate the influence of non-Oberbeck-Boussinesq (NOB) effects in the form of temperature-dependent material properties [1] on rotating Rayleigh-Bénard convection of water ($Pr = 4.38$). For that purpose we performed direct numerical simulations in a cylindrical domain of unity aspect ratio, with a fixed Rayleigh number of $Ra = 10^8$ and various rotation rates, i.e. Rossby numbers, $0.05 \leq Ro \leq 10.0$, and $Ro = \infty$, corresponding to the non-rotating case.

In the non-rotating case NOB effects lead to an asymmetric flow behaviour, the cold plumes from the top plate are more viscous than the warm plumes from the bottom plate, thus move slower and are longer in contact with the bulk medium, consequently heating up. Hence, the temperature in the centre is higher [2]. In the rotating case, the situation is complicated by the generation of Ekman and Stewartson boundary layers [3], and the consequences of the Taylor-Proudman effect. Columnar vortex structures develop, making fully three-dimensional mixing less efficient and resulting in a persisting temperature gradient over the height of the cell [4]. Under NOB conditions, this leads to a decreasing centre temperature with increasing rotation rate.

Furthermore, Ekman pumping enhances the heat transport for $Pr \geq 1$, but the efficiency depends on the size of the columnar vortices, which in turn is determined by the heat diffusivity and the viscosity. For a temperature difference of 40 K, we found that the ratio of the Nusselt number in the rotating case to the one in the non-rotating case is higher than under pure Oberbeck-Boussinesq (OB) conditions. To analyse the influence of NOB effects further, we use the Q-, Δ- and λ_2-criteria [5-7] to quantify the top-bottom asymmetry of the occurring vortical structures.

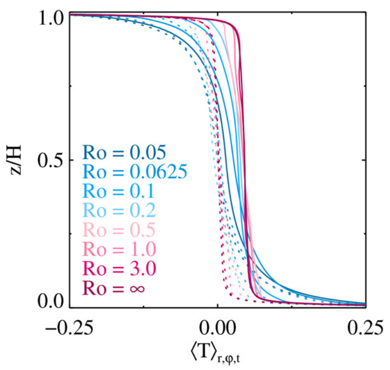

Figure 1: Mean temperature profiles, the dashed lines indicate the OB cases and the solid lines the NOB cases.

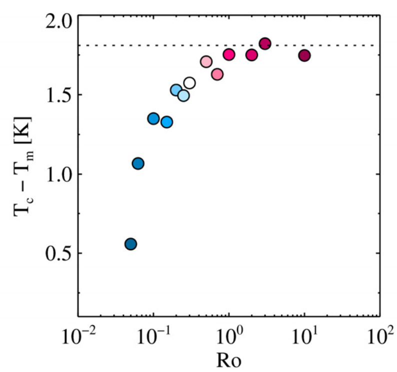

Figure 2: Deviation of the centre temperature T_c from the mean temperature T_m under NOB conditions as function of the Rossby number.

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December 10, 12:10 – 12:30

Spatial Dependence of Boundary Layers in Simulations of Rayleigh-Bénard Convection

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We present results from a systematic study of the thermal and viscous boundary layers obtained from simulations of Rayleigh-Bénard convection in a cylindrical container of aspect ratio (radius to depth) of one. We extract local boundary layers at a variety of locations in the container for Rayleigh numbers between 1×10^5-1×10^9 and for Prandtl numbers from 0.021-0.700. We do find a spatial dependence of boundary layer thickness, but these results depend on the method of finding boundary layer thickness. We find similar results for the scaling of boundary layer thickness with Rayleigh number. This is an extension of our study of boundary layers performed in the center of the cell (J.D. Scheel *et. al*, JFM 2012). We compare our results to others, including the work by Wagner, *et.al*, JFM 2012.

December 10, 14:00 – 14:40

Flow Regimes in a Convective Channel

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Turbulent thermal convection is a common phenomenon encountered in a lot of natural situations as atmosphere of planets, stars and so on. Those phenomena can be hardly approached from experimental point of view and modeling is often necessary. The Rayleigh-Bernard system has been used for long time as the ideal model because of the simplicity of its boundary conditions. The last 20 years have revealed how is difficult to have a unique answer for the Nusselt -Rayleigh curve in the experiments at very high Rayleigh, probably because of a high dependence on the boundary conditions of this system [1]. Recently new models of flow, in which boundary conditions are inexistent or forgotten, have been proposed [2,3,4]. In this case a universal behavior has been recovered and the inertial behaviors $Nu \propto (PrRa)^{1/2}$ have been found. One experimental realization of this kind of flow is a channel connecting two chambers: cold at the top and hot at the bottom. When the channel is vertical a law $Nu \propto (PrRa)^{1/2}$ is observed, showing that the flow and the heat transfer are inertial. In this situation the fluid flows in columns of hot and cold and undergoes reversals. A simple description based on mixing length has been found [5].

When the channel is tilted the breaking of symmetry caused by gravity stops the reversals and separates the flow: hot (cold) fluid always flows along the upper (lower) part of the channel. This leads to a better flowing and so to a general enhancement of the Nusselt number. Additionally turbulence and stratification are in competition, depending on the angle and the applied power, giving a very rich situation in which several flows and so several heat flux regimes can be observed. We will describe and model here 4 typical regimes, obtained in a channel of squared section of 5X5 cm2 and 20 cm of height filled with water at 25°C. We go from laminar (small powers and angles larger than 40°), to intermittent, soft-turbulent and fully turbulent (small angles and high powers) flow.

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December 10, 14:40 – 15:10

Experimental Investigation of Cryogenic Turbulent Rayleigh-Benard Convection at Very High Rayleigh Numbers

P. Urban[1], P. Hanzelka[1], M. Horak[1], T. Kralik[1], M. La Mantia[2] V. Musilova[1] and **L. Skrbek**[2]

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We shall discuss an experimental investigation of heat transfer efficiency in turbulent Rayleigh-Benard convection (RBC) up to very high Rayleigh number, $Ra \leq 10^{15}$, using cryogenic helium gas as a working fluid with well known and *in situ* tuneable properties. Our cylindrical RBC cell of height 0.3 m, diameter 0.3 m is designed to minimize the influence of its structure on the convective flow [1], with the aim of resolving existing contradictions in Nusselt (Nu) versus Rayleigh number (Ra) scaling. For $7.2\text{x}10^6 \leq Ra \leq 10^{11}$ our data are consistent with $Nu{\sim}Ra^{2/7}$. By applying suitable sidewall corrections, we show full agreement among cryogenic experiments in cells of aspect ratio about one for Ra up to about 10^{11} [2], while at higher Ra all these sets of data differ considerably. We claim that distinctly different Nu(Ra) scaling as observed in various high Ra experiments can hardly be explained by the difference in Prandtl number. We discuss other tiny experimental details such as influence of the parasitic heat leak, additional corrections to finite heat conductivity and heat capacity of plates and so called chimney effects that might occur in thermally anchored venting tubes connected to the cell [3]. On approaching $Ra{\sim}10^{11}$, our data display a crossover to $Nu{\sim}Ra^{1/3}$. This scaling holds up to $Ra \leq 10^{15}$ if the mean temperature of the working fluid - cryogenic helium gas - is measured by small sensors directly inside the cell at about half of its height. In contrast, if the mean temperature is determined in a conventional way, as an arithmetic mean of the bottom and top plate temperatures, the $Nu(Ra)/Ra^{1/3}$ displays spurious crossover to steeper scaling that might easily be misinterpreted as a transition to the ultimate Kraichnan regime [4]. Our results, including the latter one, do not mean that this elusive transition does not happen, but suggest strongly that experimental investigation of this issue and observed departures from $Nu{\sim}Ra^{1/3}$ at very high Ra ought to be interpreted with extreme care. Additionally, we discuss statistical analysis of the RBC based on measurements of temperature fluctuations by four small (0.2 mm) Ge sensors placed inside the cell interior, in pairs positioned opposite at half height of the cell 1.5 cm from the sidewall and 2.5 cm vertically apart, calibrated them *in situ*, within 1 mK accuracy, against our primary Lake Shore GR-200A-1500-1.4B Ge temperature sensors. We have calculated and discuss probability density functions, power spectra and structure functions, including their scaling using extended similarity hypothesis. Dependence of Peclet and Reynolds numbers on Ra up to 10^{14} will be presented and discussed.

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December 10, 15:10 – 15:30

Dissipation Layers in Rayleigh-Bénard Convection: A Unifying View

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Turbulent thermal convection, i.e. a buoyancy driven flow within a fluid heated from below and cooled from above, is an ubiquitous physical process observable in various natural systems. As a driving mechanism, convection is a major cause of the dynamics of stars, giant planets, the Earth's mantle and cloud formation.

Theoretical research has focused on the prediction of scaling laws between the control parameters Rayleigh number (Ra) and Prandtl number (Pr) and the output parameters Nusselt number (Nu) and Reynolds number (Re). For such scaling theories, the thermal and viscous boundary layers are typically considered as crucial. However, many natural systems like the ones mentioned above can often be well described by stress-free boundary conditions. It is often argued that viscous boundary layers do not exist, i.e., their thickness is zero. Hence, to extend the existing theories to a wider range of geophysical and astrophysical applications, a generalization of the classical boundary layer definitions is of central interest.

In this talk we discuss a new concept to capture the near-wall flow in Rayleigh-Bénard convection. Based on the kinetic energy budget and the thermal variance balance we define viscous and thermal dissipation layers which are independent of the boundary condition and hence can be used to define boundary layers for thermal convection not only for laboratory experiments but also for a wide range of geophysical and astrophysical applications.

To verify this concept, we present a numerical parameter study in a three-dimensional Rayleigh-Bénard configuration, where the Prandtl number is varied, while the Rayleigh number is fixed at a value of $Ra = 5 \cdot 10^6$ for both no-slip and stress-free boundaries.

We find that the newly defined dissipative layers also exist for stress-free boundaries in close analogy to laboratory no-slip systems. We demonstrate that for the no-slip case the classical boundary layer and the dissipative layer share a number of important features and investigate their behavior for a wide parameter range. This paves the way for an application of the existing scaling theories to many systems found in nature.

December 10, 16:00 – 16:30

Boundary Layer Visualization in Turbulent Rayleigh-Bénard Convection in Air

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The heat transfer throughout the boundary layers at the hot bottom and the cold top plates is the key to understand the global heat transport in turbulent Rayleigh-Bénard convection. Over the last decade the assumption of a basically laminar structure according to the Prandtl/Blasius model has been established as long as the Rayleigh number does not exceed the critical value towards the so-called ultimate regime [1]. Until now this assumption is verified comprehensively neither by experiments nor by numerical simulations. Highly resolved local velocity and temperature measurements at the "Barrel of Ilmenau" [2] as well as very recent numerical simulations [3] focussing particularly on the boundary layers give reason to believe that this physical picture has to be refurbished, especially at low Prandtl numbers $Pr \leq 1$ and high Rayleigh numbers $Ra \geq 10^{10}$.

We performed a set of flow visualizations in turbulent Rayleigh-Bénard (RB) convection in air. In order to fix the mean plane of the mean wind a slender rectangular test cell (2.5 m x 2.5 m x 0.6 m) was installed in our large-scale RB experiment 'Barrel of Ilmenau' (see photo in Fig. 1). The flow in this cell is described by a Rayleigh number $Ra = 1.4 \times 10^{10}$, a Prandtl number $Pr = 0.7$ and aspect ratios $\Gamma_x = 1$ and $\Gamma_z = 0.26$. We were mainly interested in the boundary layer flow at the bottom plate and we illuminated a plane light of about 7 cm in height and 0.1 cm in depth over the full length of the plate. The light was generated by a 2,000 mW Laser in combination with a beam expander according to the sketch in Fig. 1. In order to make the air flow visible we added cold-atomized droplets of Di-Ethyl-Hexyl-Sebacat (DEHS) with a size of about 1 μm. Using a Canon EOS 600 D camera movies with a resolution of 1920 x 1080 pixels and a frame rate of 30 frames/s as well as highly resolved single pictures with 5184 x 3456 pixels but shorter exposure time have been captured.

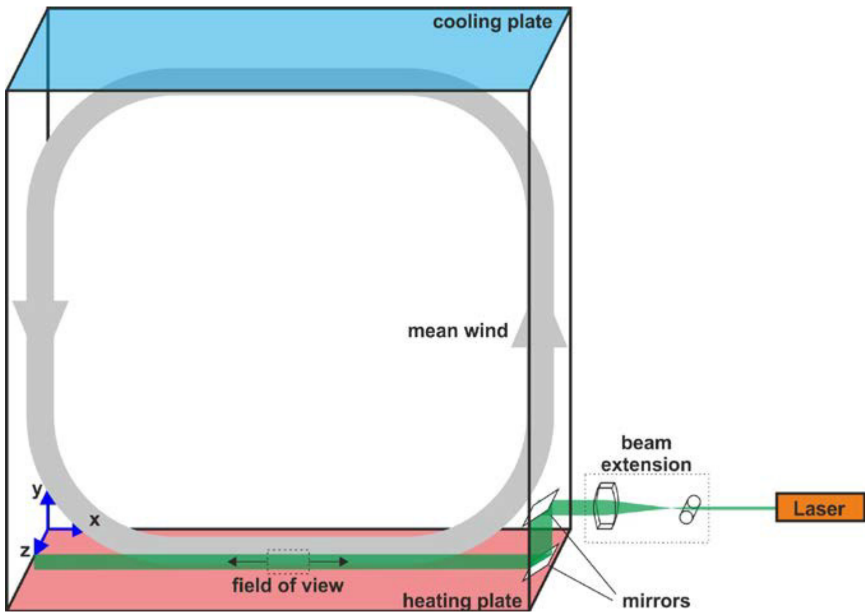

Figure 1: Set-up of the boundary layer visualization in turbulent Rayleigh-Bénard convection. The rectangular test cell with the dimensions of 2.50 m x 2.50 m x 0.60 m is embedded in the large scale experiment "Barrel of Ilmenau" using its heating and cooling plates with uniform temperature as bottom and top bound. The photo on the right shows the rectangular test cell.

In Fig. 2 one snapshot of a movie of the boundary layer captured above the centre of the heating plate is shown. The large-scale circulation above the plate surface is from left to right as indicated in Fig.1. The scale on the left hand side of the figure represents the wall-normal distance z in units of millimetres, z = 0 mm corresponds to the surface of the plate.

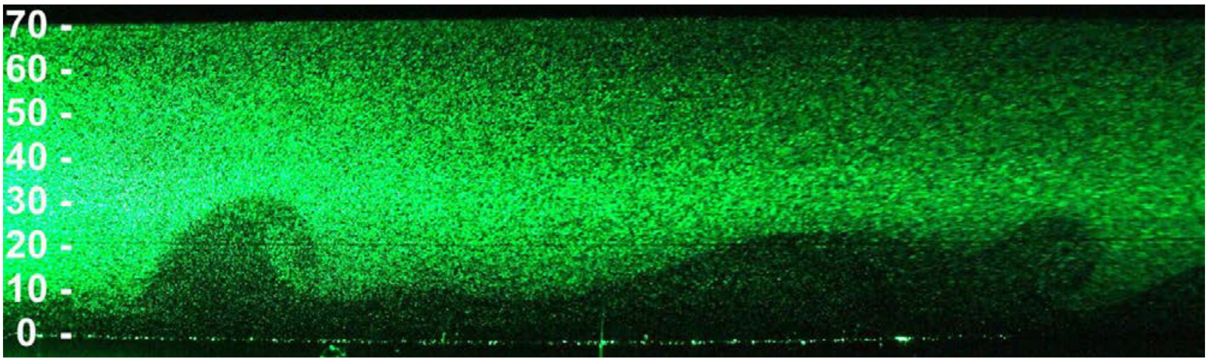

Figure 2: Boundary layer in turbulent Rayleigh-Bènard convection in air at Ra = 1.4 x 10^{10}*. The mean flow is from left to right. The scale on the left hand side is the distance z from the heating plate in units of millimeter, z = 0 mm corresponds to the surface of the plate.*

The picture shows the wavy structure of the viscous boundary layer with a mean (time-averaged) thickness of δ_v = 7.5 mm. It illustrates how thermal plumes evolve as buoyancy driven boundary layer instabilities and how they interact with the mean wind. In the movies that we wish to present in our talk it becomes clearer that the laminar region of the boundary layer is very thin and limited only to a small region very close to the surface of the plate.

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December 10, 16:30 – 16:50

Two-dimensional Heat Flux Distribution on the Heating Plate of a Rectangular Rayleigh-Bénard Convection Cell

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Thermal convection is an omnipresent mechanism in nature and industry whereas its complexity is still a great challenge for scientists. A common model system to study natural thermal convection is the Rayleigh-Bénard setup. The flow inside such a Rayleigh-Bénard convection cell is driven by a temperature difference between the top and the bottom plate, while the heat loss throughout the sidewall is suppressed (adiabatic sidewall). A lot of effort has been taken to measure the global heat transport at high *Ra* (dimensionless temperature difference between top and bottom) spanning a wide *Pr* range (=kinematic viscosity/thermal diffusivity), an overview is given in[1]. However, it is still unclear how it is locally distributed at the horizontal plates and how this distribution depends on the aspect ratio Γ ($\Gamma = D/H$ = diameter/height). We will report two-dimensional measurements of the local heat transport at the surface of the heating plate. Therefore we have assembled a thin layer of a well-known thermal resistance $r_{th}[K/Wm^{-2}]$ at the heating plate. While the heating plate is temperature controlled, the temperature T_r at the top surface of the layer is investigated using a infrared camera, which was first used by[2]. The local heat flux can be computed according to $\dot{q} = (T_r - T_h)/r_{th}$. We perform first measurements between $1.4 \cdot 10^{10} \le Ra \le 5.5 \cdot 10^{10}$ in the barrel of Ilmenau with a small rectangular sample 2.5*m* x 0.65*m* x 2.5*m* inside to confine the large scale circulation. In this parameter space a strong horizontal dependency of the thermal boundary layer thickness has been observed indicating the non-uniformly distributed heat flux[3]. For the first time, infrared thermography could be applied successfully in highly turbulent Rayleigh-Bénard convection and the results of [3] could be confirmed.

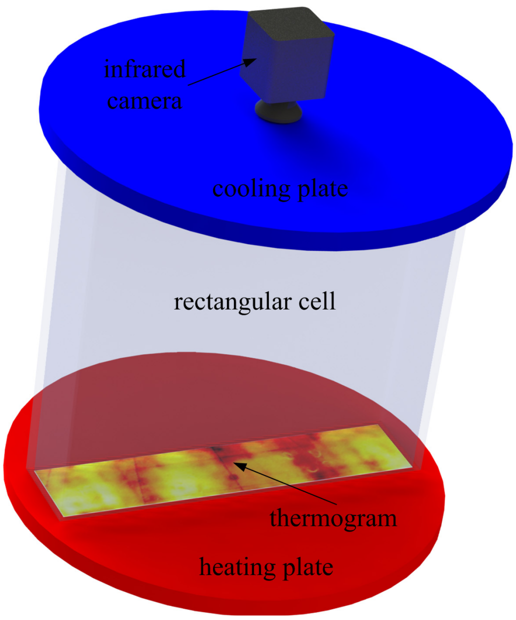

Figure 1: Schematic of the measurement setup

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Numerical Investigation of Geometry Effects in Rayleigh-Bénard Convection

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Direct numerical simulations (DNS) of Rayleigh-Bénard convection have been performed in two types of containers, namely a rectangular sample with equal height H and length L and variable depth W/H between 0.1 and 1, and a cylinder with equal height and diameter. The Prandtl number was chosen as *Pr*=0.786 and the Rayleigh number *Ra* between 10^5 and 10^7, i.e. rather small.

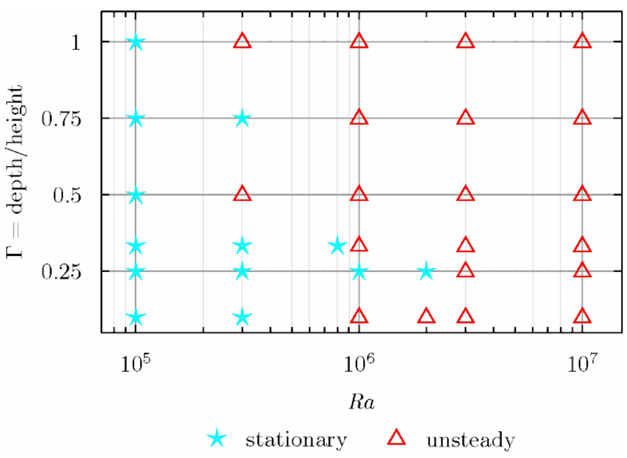

Figure 1: Type of the equilibrium in dependence of the aspect ratio and Ra for Pr=0.786.

To study the influence of the geometry, different aspects have been investigated. First of all the Nusselt number *Nu* and the Reynolds number *Re* (based on the volume- and time- averaged kinetic energy) and their time-dependence have been studied. The latter allows characterising the transition from a stationary equilibrium to an unsteady one, which occurs in the considered *Ra*-interval. The results for the rectangular geometry are depicted in Figure 1. It might be expected that the transition occurs in case of a smaller aspect ratio for higher *Ra, b*ut it becomes obvious that more complex processes take place for very thin domains. For example one observes the unsteady equilibrium for aspect ratio W/H=0.1 and a stationary one for W/H=0.25. Possible explanations are nearness of the opposite boundary layers near the vertical walls and a change in the global flow structure.

To further analyse it, the method introduced by Brown & Ahlers (JFM 568, 2006) was adapted to rectangular geometries. It reveals that indeed *Ra* and the aspect ratio influence the global flow and its dynamics. The general tendency is that for small *Ra* and small aspect ratio the flow is organized parallel to the vertical walls. If both quantities are increased, the flow structure is rather diagonal. This change between the flow structures has a strong influence on *Nu* and *Re* as depicted in Figure 2 for *Nu* in a cube and a cylinder with equal diameter and height. In case of the cube a drop in the reduced *Nu* occurs around *Ra*=10^6, which is not present in case of the cylinder. It is connected to the mentioned change in the global flow, which takes place around this *Ra*. The latter might also be an explanation for the differences in *Nu* between cube and cylinder, which were obtained for higher *Ra* (Kaczorowski & Xia, submitted to JFM, 2012).

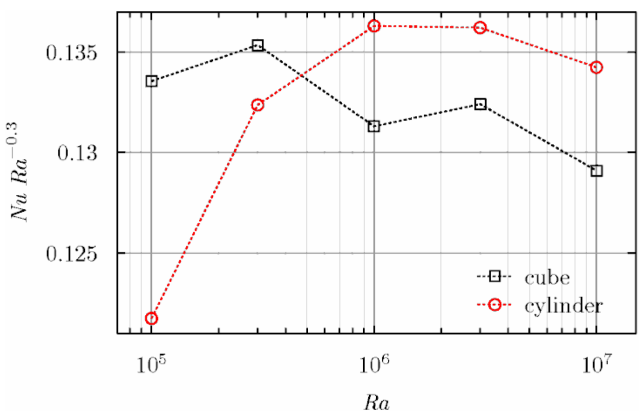

Figure 2: Comparison of the reduced Nusselt number for cube and cylinder with equal diameter and height for Pr=0.786.

December 10, 17:10 – 17:30

Coupling and Dynamics of the Large-scale Circulation in Two-layer Turbulent Rayleigh-Bénard Convection

Yi-Chao Xie and Ke-Qing Xia

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We present experimental studies of the coupling and dynamics of the large-scale circulation (LSC) in two-layer turbulent Rayleigh-Bénard convection. Using two immiscible working fluids, water above fluorinert electronic liquid FC-77, the dynamics of the LSC was studied in each of the fluid layers. The aspect ratio of each fluid layer was one. It is found that there are two LSCs, one in the water layer and the other in the FC77 layer. The coupling states of the two LSCs can be classified into three different regimes according to the relative phase difference of the two LSCs, namely, thermal coupling (the LSCs at the interface are in opposite direction), viscous coupling (the LSCs at the interface are in the same direction) and transition state. It is found that thermal coupling is the preferred way of coupling and that the global heat transfer efficiency of this state is larger than that of the viscous coupling. It is found that with the increase of the flow strength δ of the LSC at the water (FC77), the flow strength of the FC77 (water) layer also increases. Further analysis showed that the flow strength of water layer becomes smaller when the LSC in the FC77 layer rotates faster azimuthally. On the other hand, the flow strength of FC77 layer becomes larger when the azimuthal rotation of LSC in water layer is fast. This indicates that the influence of one layer on the other is not symmetric.

December 11, 09:00 – 09:40

Polymers in Rayleigh Bénard Turbulence

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We discuss recent numerical results concerning the effects of flexible polymers in Rayleigh Bénard convenction. We show that polymer effects can be represented by a space dependent viscosity similar to what it is observed in wall bounded turbulence. Using the Blasius-Prandtl equations we are able to compute the change in the Nusselt number due to the space dependent viscosity.

December 11, 09:40 – 10:10

Rayleigh-Bénard Convection in the Asymptotic Suction Boundary Layer

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JM Burgers Centrum, TU Delft, The Netherlands

The aysmptotic suction boundary layer is a parallel version of a boundary layer, obtained by adding a steady cross flow to a parallel shear flow. When a temperature gradient is superimposed the laminar flow develops thermal and shear boundary layers, both of exponential form. As a step towards establishing this flow as a model for the interaction between thermal and velocity boundary layers, we perform a linear stability analysis. We find that the transition is strongly subcritical even for moderate Reynolds numbers. The lower branch state remains well confined within the boundary layers, but the upper branch state reaches surprinsingly high into the neutral region.

December 11, 10:10 – 10:30

Experimental Investigation of Longitudinal Space-time Correlations of the Velocity Field in Turbulent Rayleigh-Bénard Convection

Quan Zhou

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We report an experimental investigation of the longitudinal space-time cross-correlation function of the velocity field, $C(r,\tau)$, in a cylindrical turbulent Rayleigh-Bénard convection cell using the particle image velocimetry (PIV) technique. We show that while the Taylor's frozen-flow hypothesis does not hold in turbulent thermal convection, the recent elliptic model advanced for turbulent shear flows \cite[]{he06pre} is valid for the present velocity field for all over the cell, i.e., the isocorrelation contours of the measured $C(r,\tau)$ have a shape of elliptical curves and hence $C(r,\tau)$ can be related to $C(r_E,0)$ via $r_E^2=(r-U\tau)^2+V^2\tau^2$ with U and V being two characteristic velocities. We further show that the fitted U is proportional to the mean velocity of the flow, but the values of V are larger than the theoretical predictions. Specifically, we focus on two representative regions in the cell: the region near the cell sidewall and the cell's central region. It is found that U and V are approximately the same near the sidewall, while $U\simeq0$ at cell center.

December 11, 11:00 – 11:30

Logarithmic Temperature Profiles in the Ultimate Regime of Thermal Convection*

Siegfried Grossmann and **Detlef Lohse**

Physics of Fluids Group, University of Twente, The Netherlands

We report on the theory of logarithmic temperature profiles in very strongly developed thermal convection in the geometry of a Rayleigh-Bénard cell with aspect ratio $\Gamma = 1$ and discuss the degree of agreement with the recently measured profiles in the ultimate state of very large Rayleigh number flow. The parameters of the log-profile are calculated and compared with the measure ones. Their physical interpretation as well as their dependence on the radial position are discussed.

* S. Grossmann and D. Lohse, Phys. Fluids, in press (2012).

December 11, 11:30 – 11:50

Logarithmic Temperature Profiles in Rayleigh-Bénard Convection

Erwin P. van der Poel, Rodolfo Ostilla, Siegfried Grossmann and Detlef Lohse

Physics of Fluids Group, University of Twente, The Netherlands

Recently, Ahlers et al. [1] experimentally and numerically found logarithmic temperature profiles not only in the ultimate regime of turbulence, but also in the “classical regime” for Rayleigh numbers as low as 1e10. In this talk we will try to rationalize this surprising behavior, based on a novel viewpoint of plume-driven flow.

[1] Ahlers, G., Bodenschatz, E., Funfschilling, D., Grossmann, S., He, S., Lohse. D., Stevens, R.J.A.M. & Verzicco, R., PRL 109, 114501 (2012).

December 11, 11:50 – 12:10

Local Temperature Measurements at High Rayleigh Numbers

J. Salort, O. Liot , E. Rusaouën, F. Seychelles, B. Castaing and F. Chillà

Laboratoire de Physique, ENS Lyon

Although there have been many experimental and theoretical studies in the last couple of decades, the physics of Rayleigh-Bénard system at very high Rayleigh numbers is still not fully understood [1]. In particular, the discrepancies in the global heat transfer measurements obtained in various experimental setups (eg. Chavanne, *et al.* 1997 *versus* Niemela, *et al.* 2000 *versus* Ahlers *et al.* 2009) lack a satisfactory interpretation. To understand these apparent contradictions, it is interesting to get a picture of the flow features (eg. spatial structure, local temperature fluctuations, velocity fluctuations, turbulent heat-flux statistics, lagrangian statistics) to characterize these different regimes [2,3].

Rayleigh numbers above 10^{12} requires large infrastructures (cryogenic helium or pressurized sulfur hexafluoride) that are out of reach for many laboratories. In our group, we are working on alternative systems to understand the physics of thermal flows: convection in a vertical channel and Rayleigh-Bénard cells with a controlled roughness. In these systems, it is possible to obtain the various Nu *versus* Ra scalings that were reported in usual smooth Rayleigh-Bénard cells (close to $Ra^{2/7}$, $Ra^{1/3}$ or $Ra^{1/2}$) [4,5]. Our aim is then to catch the physical differences between those regimes and possibly to compare them to their counterpart in usual smooth Rayleigh-Bénard systems.

To do that, we have completed local temperature fluctuations measurements near the rough plate (either above a roughness or above a groove) or near the smooth plate, temperature field measurements using synthetic Schlieren, velocity field measurements with PIV, lagrangian velocity and temperature measurements with a dedicated instrumented neutrally buoyant particle [6] and the design of a new micromachined turbulent heat-flux sensor. The present talk will more specifically focus on the local temperature results.

References:

[1] F. Chillà and J. Schumacher, "New perspectives in turbulent Rayleigh-Bénard convection", *Eur. Phys. J. E* **35**, 58 (2012)
[2] D. Lohse and K.-Q. Xia, "Small-Scale Properties of Turbulent Rayleigh-Bénard Convection", *Annu. Rev. Fluid Mech.* **42**, 335-364 (2010)
[3] R. Ni, S.-D. Huang and K.-Q. Xia, "Lagrangian acceleration measurements in convective thermal turbulence", *J. Fluid Mech.* **692**, 395-419 (2012)
[4] J.-C. Tisserand, *et al.*, "Comparison between rough and smooth plates within the same Rayleigh-Bénard cell", *Phys. Fluids* **23**, 015105 (2011)
[5] J.-C. Tisserand, *et al.*, "Convection in a vertical channel", *New. J. Phys.* **12**, 075024 (2010)
[6] W. L. Shew, *et al.*, "Instrumented tracer for Lagrangian measurements in Rayleigh-Bénard convection", *Rev. Sci. Instrum.* **78**, 065105 (2007)

December 11, 12:10 – 12:30

Comparison between Rough and Smooth Plates within the Same Rayleigh-Bénard Cell

E. Rusaouën, J. Salort, F. Seychelles, J-C. Tisserand, M. Creyssels, O. Liot, F. Chilla and B. Castaing

Ecole Normale Supérieure de Lyon, 46 allée d'Italie 69364 Lyon

Rayleigh-Bénard convection has been studied for decades but some part of the physics of this problem remains unclear. Usually, this phenomenon is characterized by a local logarithmic slope between the Nusselt number (Nu : dimensionless heat transfer) and the Rayleigh number (Ra). A ongoing issue is the characterization of the influence of the boundary conditions. Several experiments involving roughness have been done all around the world, most of them were symmetric with both hot and cold rough plates (eg. Shen *et al*. 1996, Du and Tong 1998, 2000, Qiu *et al*. 2005). All of this observed a Nusselt enhancement but no change in the power law of (Nu,Ra).

Here we present an asymmetric Rayleigh-Bénard cell: the hot plate is rough whereas the cold plate is kept smooth. Roughness used here are parallelepiped which dimensions are10x10x4mm.

Previously, a similar experiment has been done in the same apparatus using 2 mm high roughness. The results showed a transition in the (Nu,Ra) law. This new regime was characterized by a local logarithmic slope of 1/2. The transition appeared when the height of the thermal boundary layer reached the height of the roughness. A Nusselt improvement larger than expected from the surface increasing due to roughness only, and the independence of both plates were also observed (eg. Tisserand et al 2011).

In order to investigate the dependence of that results on the dimension of the roughness, we use the 10x10x4mm rough plate. In this new case the boundary layer is always smaller than the roughness so we can observe the 1/2 regime but not the transition to it. Moreover another transition from a ½ law at low Rayleigh number to a 1/3 appears at very high Rayleigh. This second 1/3 regime reveals a multiplier coefficient of 1.6 with previous one.

References:

[1] F. Chillà and J. Schumacher, “New perspectives in turbulent Rayleigh-Bénard convection”, *Eur. Phys. J. E* **35** , 58 (2012)

[2] J.-C. Tisserand, *et al.*, “Comparison between rough and smooth plates within the same Rayleigh-Bénard cell”, *Phys. Fluids* **23**, 015105 (2011)

[3] Y.Shen, P.Tong, and K.-Q.Xia, “Turbulent convection over rough surfaces”, *Phys. Rev. Lett.* **76**, 908 (1996)

[4] Y.-B. Du and P. Tong, “Enhanced heat transport in turbulent convection over a rough surface”, *Phys. Rev. Lett.* **81**, 987 (1998)

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December 11, 14:00 – 14:40

Scenarios in Taylor-Couette Flow

Gerd Pfister

University of Kiel, Germany

The flow of a fluid between two concentric independently rotating cylinders is a long lasting physical problem. Already 1890 Couette studied this flow to measure the dynamic viscosity of the fluid. Later Mallock (1896) found in experiments that the rotation of the inner cylinder is not suitable for viscosity measurements because even for low speeds the flow was eddying and unstable. This behavior was treated by G. I. Taylor in 1923 in his landmark work *"Stability of a Viscous Liquid Between Two Rotating Cylinders"* where he quantitatively predicted and experimentally confirmed the existence of flow instability. The new state is called *Taylor vortex flow* today. Since Taylor's work many studies have been done on that problem and still today it is an active field of hydrodynamic stability and turbulence research.

In the talk I will present various scenarios in Taylor-Couette flow where the boundary conditions are varied. In a physical realization the flow is always confined between the two concentric, independently rotating cylinders and top and bottom boundaries. Therefore the aspect ratio, i.e., the ratio between gap height and gap width, provides an essential control parameter of the flow in addition to the Reynolds numbers of inner and outer cylinders and of the axial boundaries.

The scenarios include symmetry breaking, multiplicity of states, and global bifurcation events. In some experiments we observed types of flow states and transition scenarios which are usually suppressed if the Reynolds numbers are increased quasi-statically. By systematic variation of control parameters we were even able to estimate unstable solutions experimentally. Many of the experimental results have been compared quantitatively with numerical simulations.

December 11, 14:40 – 15:10

On the Ultimate State of Rayleigh–Bénard Convection

F. Toschi*, E. Calzavarini, D. Lohse, L.E. Schmidt and R. Verzicco

* *Eindhoven University of Technology, The Netherlands*

I will present results from the numerical investigations of the 'ultimate state of thermal convection' in cylindrical geometry with lateral walls and periodic boundary conditions in the vertical direction. A recent numerical study investigated the ultimate state of thermal convection by removing both horizontal and vertical walls and thus studying an homogenous versions of the Rayleigh–Bénard cell [1]. When all walls are replaced with periodic boundary conditions, the heat transfer scales like $Nu \sim Ra^{1/2}$ and the turbulence intensity as $Re \sim Ra^{1/2}$, where the Rayleigh number Ra indicates the strength of the driving force (for fixed values of Pr, which is the ratio between kinematic viscosity and thermal diffusivity). Experiments however never operate in unbounded domains and it is thus important to understand how confinement might alter the approach to this ultimate regime. In order to clarify this point we performed numerical investigation of Rayleigh–Bénard convection in a cylindrical cell, retaining the lateral walls, but imposing periodicity in the vertical direction [2]. In spite of the lateral confinement and the resulting kinetic boundary layers, we confirm that Nu ~ Re ~ Ra^½ at Pr=1. Further we can show that the system supports solutions composed of modes of exponentially growing vertical velocity and temperature fields, with Ra as the critical parameter determining the properties of these modes. Counter-intuitively, in the low-Ra regime, or for very narrow cylinders, the numerical simulations are susceptible to these solutions, which can dominate the dynamics and lead to very high and unsteady heat transfer. As Ra is increased, interaction between modes stabilizes the system, evidenced by the increasing homogeneity and reduced fluctuations in the root-mean-square velocity and temperature fields. The axially homogenous Rayleigh–Bénard cell can approximation thermal convection in very tall chimneys.

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December 11, 15:10 – 15:30

The Importance of Bubble Deformability for Strong Drag Reduction in Bubbly Turbulent Taylor-Couette Flow

Dennis P. M. van Gils, Daniela Narezo Guzman, Chao Sun, and Detlef Lohse

Physics of Fluids Group, Faculty of Science and Technology, J.M. Burgers Center for Fluid Dynamics, and IMPACT Institute, University of Twente, The Netherlands

Bubbly turbulent Taylor-Couette (TC) flow is globally and locally studied at Reynolds numbers of $Re = 5 \times 10^5$ to 2×10^6 with a stationary outer cylinder and a mean bubble diameter around 1 mm. We measure the drag reduction (DR) based on the global torque as a function of the global gas volume fraction α_{global} over the range 0% to 4%. We observe a moderate DR for $Re = 5.1 \times 10^5$. Significantly stronger DR is achieved for $Re = 1.0 \times 10^6$ and 2.0×10^6, with, remarkably, more than 40% of DR at $Re = 2.0 \times 10^6$ and $\alpha_{global} = 4\%$.

To shed light on the two apparently different regimes of *moderate* DR and *strong* DR, we investigate the local liquid flow velocity and the local bubble statistics, in particular the radial gas concentration profiles and the bubble size distribution, for the two different cases; $Re = 5.1 \times 10^5$ in the moderate DR regime and $Re = 1.0 \times 10^6$ in the strong DR regime, both at $\alpha_{global} = 3 \pm 0.5\%$.

In both cases the bubbles mostly accumulate close to the inner cylinder (IC). Surprisingly, the maximum local gas concentration near the IC for $Re = 1.0 \times 10^6$ is ≈ 2.3 times lower than that for $Re = 5.1 \times 10^5$, in spite of the stronger DR. Evidently, a higher local gas concentration near the inner wall does not guarantee a larger DR.

By defining and measuring a local bubble Weber number (We) in the TC gap close to the IC wall, we observe that the crossover from the moderate to the strong DR regime occurs roughly at the crossover $We \sim 1$. In the strong DR regime at $Re = 1.0 \times 10^6$ we find $We > 1$, reaching a value of 9 (+7, -2) when approaching the inner wall, indicating that the bubbles increasingly deform as they draw near the inner wall. In the moderate DR regime at $Re = 5.1 \times 10^5$ we find $We \approx 1$, indicating more rigid bubbles, even though the mean bubble diameter is larger, namely 1.2 (+0.7, -0.1) mm, as compared to the $Re = 1.0 \times 10^6$ case, where it is 0.9 (+0.6, -0.1) mm. We conclude that bubble deformability is a relevant mechanism behind the observed strong DR. These local results match and extend the conclusions from the global flow experiments as found by van den Berg *et al.* (2005) and from the numerical simulations by Lu, Fernandez & Tryggvason (2005).

- van den Berg, T. H., Luther, S., Lathrop, D. P. & Lohse, D. 2005 Drag reduction in bubbly Taylor-Couette turbulence. *Phys. Rev. Lett.* **94**, 044501.
- Lu, J., Fernandez, A. & Tryggvason, G. 2005 The effect of bubbles on the wall drag in a turbulent channel flow. *Phys. Fluids* **17**, 95102.

December 11, 16:00 – 16:30

Flow Reversals in Turbulent Convection via Vortex Reconnections

Mahendra K. Verma

Department of Physics, I. I. T. Kanpur, India

We employ detailed numerical simulations to probe the mechanism of flow reversals in two-dimensional turbulent convection. We show that the reversals occur via a vortex reconnection of two attracting corner rolls having same sign of vorticity, thus leading to major restructuring of the flow (see Fig. 1). Large fluctuations in heat transport are observed during the reversal due to this flow reconfiguration. The flow configurations during the reversals have been analyzed quantitatively using large-scale modes (Fourier). Using these tools, we also show why flow reversals occur for a restricted range of Rayleigh and Prandt numbers. We will also present results on reversals studies in three-dimensional cube and cylinder, and show similarities in these flows.

Reference: M. Chandra and M. K. Verma, Flow reversals in turbulent convection via vortex reconnections, arxiv:1207.4521, 2012.

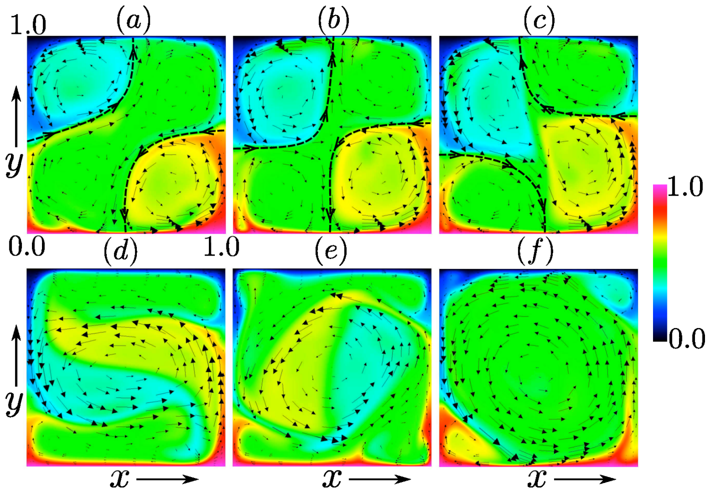

Fig. 1: Velocity and temperature profiles for six snapshots during the reversal: (a,b) Growth of corner rolls; (c) The two corner rolls at the upper-left and bottom-right corners reconnect to form a large single roll. The streamlines, represented by black curves, combine via vortex reconnections; (d,e) The flow reconfigures itself via rotation of the large roll formed after the reconnection. There is a strong nonlinear interaction among the modes (1,1), (2,2), (1,3), and (3,1) during these events; (f) The flow stabilizes to a quasi-steady state configuration.

December 11, 16:30 – 16:50

Fourier and POD Analysis of the LSC Reversal in Rectangular Rayleigh-Bénard Cell

Anne Sergent[1,2] and Bérengère Podvin[1]

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[2] *UPMC Univ Paris 06, 75005, Paris, France*

At high Rayleigh number, a large-scale circulation (LSC) filling the Rayleigh- Bénard cell remains quasi-stationary for long stretches of time, then experiences abrupt flow reversals and reorientations over a short period of time before switching to another quasi-stable configuration. Numerical results of the turbulent thermal convection ($10^7 \leq Ra \leq 10^{10}$) in an air-filled rectangular cavity of large aspect ratios (L = H = 5) are presented. In order to gather data for significant time periods, large eddy simulations are performed. Sudden transitions without any external input have been observed in all studied cases between two LSC which are stable on very long time period. The changes in LSC correspond to a modification of the number of the rolls. The aim of this work is to investigate the physical phenomena occurring during the LSC reversal process. The spatial Fourier transform of the horizontal velocity in the longitudinal direction shows a competition during a short time transition (on order of 100 convective time units) between the first modes containing 2, 3 or 4 rolls placed side by side. The spatio-temporal evolution of the horizontal velocities displayed key features of the reorganization process, such as cessation, transient reorientation of the roll axis and reversal of the rotation direction. By applying POD analysis to the joint temperature and velocity fields, different types of coherent structures are identified. The two most energetic structures consist of a row of 2-D, quasi-stationary rolls, which contain the LSC. The two next most energetic structures form longitudinal roll-like structures which extend over the length of the box and which are predominantly contained in the wall layers. The amplitude of these structures oscillates with a well-defined time scale on the order of 100 time units. Higher-order structures exhibit a lesser spatial coherence. The energy level of the higher-order structures ($n \geq 4$) was found to remain unaffected by the transition process.

December 11, 16:50 – 17:10

On the Challenges of Numerically Investigating Small-scale Statistics in the Bulk of Turbulent Rayleigh-Bénard Convection

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The Rayleigh-Bénard system, which is primarily determined by the Rayleigh and Prandtl number, responds with a certain heat flux, typically given in terms of the Nusselt number, and a Reynolds number as a measure for the momentum transport. One way to test a theoretical model is to compare its prediction for the scaling of these quantities with experimental or numerical results, and hence make an inference on the flow dynamics. This could be considered an indirect or top-down approach which in the absence of globally available measurement data is often used in experimental, but also in numerical investigations.

In the past years the tremendous increase of available computational resources allowed for direct numerical simulations of unprecedented size in terms absolute grid size (high Rayleigh numbers) [1] and averaging time of the simulations [2,3], which allowed DNS to become a widely used tool to help understand previously measured experimental data. The great advantage of DNS is that all desired quantities of the flow are available at all desired positions and therefore allow for a direct or bottom-up approach to test a theory or provide new insight into the dynamics of the flow.

The theoretical model recently proposed by Grossmann-Lohse [4,5] estimates the global Nusselt and Reynolds numbers by estimating the contributions of the dissipation rates to the heat flux from the bulk and the boundary layers. This approach has provided a basis for many studies testing the scaling of various quantities like dissipation rates or turbulent fluctuations in the bulk or the boundary layers [6,7] and has been found to yield a good estimate of the scaling of Nu and Re over a wide range of Ra and Pr. Experimentally there has been evidence that it is reasonable to consider the boundary layers of low to moderate Ra as of Prandlt-Blasius type [7,8] and that the heat flux in the bulk is balanced by the turbulent kinetic energy dissipation rate [9].

Using DNS we investigated the flow in the bulk of turbulent RBC in a cubic geometry [10]. It is essential to achieve sufficient resolution not only in the boundary layers, but also in the bulk of the flow [11]. For insufficiently resolved simulations, the dissipative scales will not obey a scaling δur ~ r2 for the structure function in the dissipative range, resulting in a wrong dissipation rate, which in turn will give a wrong estimate of the Bolgiano length scale, which represents the cross-over from thermal to inertial dominated scales. It is also found that while the dissipation rates in the bulk tend to approach their statistically stationary behaviour, the local heat flux in the core region requires significantly more time to reach its statistically stationary state.

Despite our efforts to integrate the solution as long as possible, the heat flux in the centre of the cell differs significantly from experimental data, not only in its amplitude, but also in its scaling. Since we can rule out that this is due to under-resolution of the simulation, we use this observation to discuss possible problems of a relatively short integration time as compared to experiments and the implications for future DNS.

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December 11, 17:10 – 17:30

Temperature Statistics of Turbulent Rayleigh-Bénard Convection for Rayleigh Numbers up to 10^{15} *

Xiaozhou He[1], Dennis van Gils[1], Eberhard Bodenschatz[1] and Guenter Ahlers[1,2]

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We report on the study of local temperature statistics in turbulent Rayleigh-Bénard convection (RBC) for Rayleigh numbers Ra up to 10^{15} and for a Prandtl number Pr $\simeq$ 0.8. We used two upright cylindrical RBC samples with the same diameter D = 112 cm but different heights L = 112 and 224 cm, corresponding to aspect-ratios $\Gamma \equiv D / L$ = 1.00 and 0.50 respectively.

Near the side wall of the Γ = 1.00 sample, we found the Kolmogorov −5/3 scaling of the temperature power spectrum, $P(f) \sim f^{-5/3}$, at Ra = 1.26 × 10^{14} (see fig.1). It indicates that temperature is a local passive scalar. We also measured temperature space-time cross-correlation functions $C_T(r,\tau)$. Our results extend previous measurements for a lower Ra range and larger Pr $\simeq$ 4.3 [1,2,3]. They confirm the validity of the elliptic approximation (EA) of He and Zhang[4] up to Ra $\simeq$ 10^{14}. Using the EA, we determined an effective Reynolds number in the Γ = 0.50 sample from the classical state to the ultimate state of turbulent RBC [5]. Finally, we discuss the dissipative power $Q \equiv \left\langle (\partial T/\partial t)^2 / \sigma_T^2 \right\rangle_t$ measured in both samples. With the EA, we propose a relation between Q and the local thermal dissipation rate $\varepsilon_T \equiv \kappa \left\langle (\nabla T)^2 \right\rangle_t$.

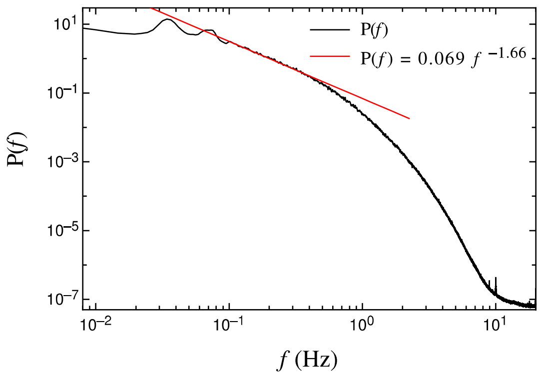

Figure 1: The power spectrum $P(f)$ at the mid-height of the Γ = 1.00 sample for Ra = 1.26×10^{14}. The measuring position is 1.5 cm away from the side wall.

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* Supported by the Max Planck Society, the Volkswagen Stiftung, the DFG SFB963, and NSF grant DMR11-58514.

December 12, 09:00 – 09:40

Stability of Quasi-Keplerian Flow in Taylor-Couette Devices at Large Reynolds Numbers

Hantao Ji

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Stability of rotating shear flows with radially decreasing angular velocity but increasing angular momentum (quasi-Keplerian flow) is investigated experimentally in a modified Taylor-Couette device at Reynolds numbers over a million. Such flows are known to be linearly stable at all Reynolds numbers but their nonlinear or subcritical stability is largely unknown. It is found that such flows are prone to be perturbed by nonoptimal axial boundaries which can generate significant secondary Ekman circulation. When Ekman circulation is minimized by independently rotatable rings at both axial ends, quasi-Keplerian flows are found to be robustly quiescent and strongly resilient against external non-axisymmetric perturbations. More recently, however, conflicting results have been reported from a separate Taylor-Couette experiment where turbulence was detected in the quasi-Keplerian regime. These results challenge our state-of-the-art understanding of nonlinear stability of shear flows and also provide important implications to angular momentum transport in astrophysical accretion disks. This talk will summarize the current status of this particular area and discuss possible future research directions.

December 12, 09:40 – 10:10

Compressible Turbulent Convection in Outer Planets

Kwing Lam Chan

Department of Mathematics and Center of Space Science Research, HKUST

The outer planets of the solar system all emit more energy than what they receive from the sun. They all have large gaseous envelops extending over major fractions of the outer radii. They all have very strong mean zonal winds (up to about 400 m/s), and they all have gigantic long-lived spots. Therefore they have much phenomenology in common. Yet, while the inner most two (Jupiter and Saturn) have prograde equatorial winds, the outmost two (Uranus and Neptune) possess retrograde winds. What makes the similarities and what creates the differences? What are the roles of thermal convection in these phenomena? Based on results of numerical simulation, we are going to discuss these questions.

December 12, 10:10 – 10:30

Statistics in Turbulent Taylor-Couette Flow with Independently Rotating Cylinders

Sander G. Huisman, Chao Sun and Detlef Lohse

Physics of Fluids Group, Faculty of Science and Technology, MESA+ Institutes, and Burgers Center for Fluid Dynamics, University of Twente, 7500AE Enschede, The Netherlands

In this talk we focus on the velocity fluctuations in the highly turbulent Taylor-Couette flow. Turbulent flows are generally characterized by the range of scales of their fluctuations, and a statistical description of the flow is often done by means of correlations of velocity fluctuations. These correlations are found to behave like power-laws over a range of scales, and their exponents characterize a certain geometry of flow. Many systems have been investigated carefully: Pipe-flow, Von Kármán flow, Rayleigh Bénard convection, *et cetera*. There are, however, few reports quantifying the turbulent properties in TC flow.

In the presented work we measure the longitudinal structure functions using LDA, which is a non-intrusive technique and is able to measure the components of the velocity, and thus ideal for obtaining structure functions. We present the statistics of the turbulent velocity fluctuations for counter rotation for varying $a = -\omega_o / \omega_i$.

Our results show the scaling exponents of the ESS structure functions do not depend on the control parameter a in the linearly unstable regime, suggesting a universal scaling behavior for Taylor-Couette turbulence. In addition we provide a comparison of our results with previous measurements in different flow systems including Rayleigh Bénard convection.

December 12, 11:00 – 11:30

Turbulent Rayleigh-Bénard Convection in a Horizontal Cylinder

Penger Tong[1,*], Hao Song[1] and Eric Brown[2]

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[2] *Physics and Chemistry group, University of California at Merced*

We have carried out a systematic study of turbulent thermal convection in a horizontal cylinder of different lengths filled with water. The motivation of the study is to understand the effect of convection cell geometry on the dynamics of large scale circulation (LSC) when compared with that in the upright cylinders. New flow modes are found in the horizontal cylinders. In thin cells with aspect ratio $\Gamma \leq 0.16$, the flow is quasi two-dimensional and a well-defined oscillation is observed in the power spectrum of various fluctuation signals in turbulent convection. In longer cells ($0.16 \leq \Gamma \leq 1.69$), the LSC is found to be aligned along the two longest diagonal planes of the cell with a periodic switching between the two planes. The switching dynamics of the LSC plane is well described by a model for an over-damped harmonic oscillator. For cells with aspect ratios $1.3 \leq \Gamma \leq 1.69$, the bulk fluid sometimes rotates as a whole and the rotation direction changes periodically (periodic reversal). This quasi-two-dimensional flow mode coexists with the LSC switching mode.

* Work supported by the Research Grants Council of Hong Kong SAR.

December 12, 11:30 – 11:50

Geometry-dependence of Large-scale Circulation Dynamics

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I present a simple model for the geometry-dependence of dynamics of the large-scale circulation (LSC) in turbulent Rayleigh-Benard convection. This extends a previous model of stochastic ordinary differential equations (ODEs) that describes LSC dynamics in an aspect ratio 1 upright cylinder. In recent experiments by Song and Tong with a sideways cylinder, the LSC orientation was found to align with the longer diameters, and new oscillation modes around and between these longest diagonals were found. These dynamics can be predicted with the addition of a shape-dependent potential term to the stochastic ODE model that represents the pressure forcing from the sidewall. The potential and dynamics are analogous to a Duffing oscillator. These results suggest the possibility of describing LSC dynamics in arbitrary geometries with a relatively simple stochastic ODE model.

December 13, 09:00 – 09:40

Rotating Rayleigh-Bénard Turbulence

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In Rayleigh-Bénard (RB) flow, the control parameters are the Rayleigh number *Ra* (the dimensionless temperature difference between top and bottom plate), the Prandtl number *Pr* (the ratio of kinematic viscosity and thermal diffusivity), and the aspect ratio Γ. The global response of the system can be expressed in terms of the Nusselt number *Nu* (the dimensionless heat transport) and the Reynolds number *Re* of the emerging large scale wind. The key question is: How do *Nu* and *Re* depend on *Ra* and *Pr*? The scaling of *Nu* and *Ra* as function of *Ra* and *Pr* is well described by the Grossmann-Lohse (GL) theory [1, 2], which has had great success in describing and predicating many measurements [1–3]. Here we use new data obtained in the low *Pr* regime, i.e. $Pr \lesssim 1$, and moderate *Ra* to further improve the quality of the GL in this regime, while all its properties in the high *Pr* and high *Ra* number regime remain unchanged. Subsequently we will discuss the observation of log-layers in high-Ra number experiments and simulations [4].

For geophysical application, another crucial parameter is the inverse Rossby number Ro^{-1}, which quantifies the rotation of the system [3]. Previous experiments and numerical simulations on rotating RB have shown that in an aspect ratio Γ = 1 sample the flow undergoes a sharp transition from being dominated by the global large scale convection roll to being dominated by local Ekman vortices when the rotation rate is increased [5, 6]. In sidewall measurements this transition is observed due to a sharp drop in the relative large scale circulation (LSC) strength, which means that the cosine profile at the sidewall disappears when the heat transport enhancement due to rotation sets in [7]. However, experiments in a Γ = 1/2 sample [8, 9] did not show a strong decrease of the relative LSC strength at the moment that heat transport enhancement sets in. It was suggested by Weiss and Ahlers [9] that this was due to the formation of a two vortex state, but this could not be verified in the experiments. We now present results from direct numerical simulations, for exactly the same control parameters as used in these experiments [8, 9], and have now verified that in a Γ = 1/2 sample [10] indeed a two-vortex state is formed and that this flow structure is consistent with all sidewall measurements that are made.

Acknowledgement
I thank all my coworkers over the years. It has been my privilege and great pleasure to work with them.

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Lagrangian Statistics of Particles in Rotating Turbulent Convection

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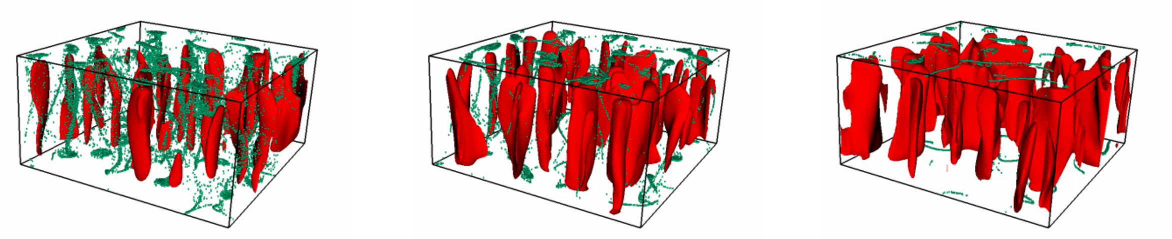
The effect of background rotation on the dynamics of fluid flows is ubiquitous in large-scale geophysical and astrophysical flows, as well as in the context of industrial rotating machinery. In many of these examples also buoyancy may play a crucial role. In this contribution we will discuss and compare Lagrangian data sets measured in (isothermal) forced rotating turbulence experiments and obtained by DNS of turbulent rotating convection.

It is well-known that the Coriolis acceleration term in the Navier-Stokes equations is responsible for altering the flow dynamics including anisotropisation of turbulent flows: 3D turbulent flows subject to fast background rotation evolves towards a quasi-2D state, which is characterised by a strong damping of velocity gradient components along the direction parallel to the rotation axis (and formation of vortex tubes parallel to the rotation axis). Based on Lagrangian measurements by 3D Particle Tracking Velocimetry of the velocity and acceleration of tiny solid particles embedded in the rotating fluid, we have been able to quantify statistically the effect of system rotation on the PDFs and autocorrelations of fluid particle velocity and acceleration in rotating turbulence for a range of dimensionless inverse rotation rates (denoted by the Rossby number which will be as small as 0.05 for the rapid rotation case).[1,2] Some of the typical results will be discussed.

Particle dispersion in buoyancy-driven rotating turbulence has been studied by DNS. We have used here a Lattice Boltzmann Method coupled with Lagrangian particle tracking algorithm[3] to investigate the behaviour of (inertial) particles released in turbulent rotating Rayleigh-Bénard (RB) convection. The flow domain is horizontally periodic and vertically confined. Both gravity and rotation are oriented in the vertical direction. Here we present the results of the acceleration PDFs of particles in both non-rotating and strongly rotating RB convection (for Ro=0.25). It is found that the bulk acceleration PDF in non-rotating RB turbulence is like in homogeneous isotropic turbulence whereas rotation introduces anisotropy similar to the acceleration PDFs obtained from experiments in (isothermal) forced rotating turbulence.[2] We will discuss these PDFs and dispersion results for passive fluid elements and those obtained for inertial particles in rotating convection.



Representative plot of the heavy particle distribution at the initial time and at later times in rotating Rayleigh-Bénard convection (Ro=0.25). The presence of the Coriolis force leads to enhanced ejection of particles from regions of cyclonic vorticity but accumulation in the region of anticyclonic vorticity. These particles are then transported towards the top and bottom walls by the vertical velocity outside the cyclonic vertical vorticity tubes. The pseudo-color plot indicates the presence of vertical vorticity tubes.

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December 13, 10:10 – 10:30

Measured Small-scale Quantities in Turbulent Rayleigh-Bénard Convection with Polymer Additives

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We report an on-going experimental study of local velocity measurement in turbulent Rayleigh-Bénard (RB) convection with polymer additives made in a convection cell with rough top and bottom plates. In a previous study, it was found that the global heat transport is enhanced in this cell when polymer concentration exceeds 120 ppm. This interesting finding is our motivation for the local velocity measurement. We found that the local energy dissipation rate measured at cell center has similar dependence on polymer concentration as that of the global Nu. It is also found that the energy input from the integral scale is strongly affected by the polymer additives. We discuss the relationship between energy dissipation rate and local heat flux and examine the behavior of velocity longitudinal correlation function and that of velocity structure function.

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December 13, 11:00 – 11:30

Theory for Velocity and Temperature Distribution inside a RBC Cell

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[2] *Department of Mechanics, College of Engineering, Sun Yi-san University, Guangzhou, China*
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A quantitative theory [1] is developed for the horizontal and vertical mean profile and the velocity and temperature in turbulent Rayleigh-Benard convection (RBC). Evidence for logarithmic temperature distribution is obtained with no appeal to the assumption of a fully turbulent boundary layer. Quantitative agreement is obtained with numerical observations by ourselves and with experimental and numerical data of Ahlers et al.[2] for Ra over seven decades. The theory is based on a recently developed multi-layer mean-field theory which successfully describes the mean velocity, Reynolds stress, kinetic energy and dissipation profiles in incompressible and compressible pipe and channel, turbulent boundary layer, with smooth and rough surfaces. The application of the theory to RBC reveals the presence of a thermal buffer layer whose thickness follows a 1/7 scaling in Ra like the previously postulated mixing zone [3]. Connection between the internal state (profiles) and the dynamics (plumes) is being investigated, which promises a novel understanding of the Nu-Ra relationship.

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December 13, 11:30 – 11:50

The Prandtl Number Dependence of Heat Transport in Turbulent Rayleigh-Bénard Convection

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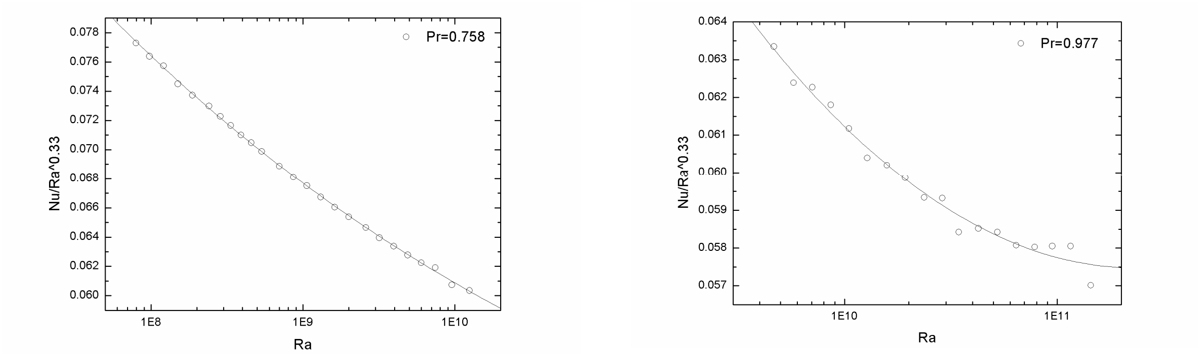
The experimental data for the heat transfer as a function of the Prandtl number in turbulent Rayleigh-Bénard convection are presented. We derived an improved scaling law of Nusselt number and the Rayleigh number based on a phenomenological analysis, i.e. $Nu = ARa^{0.143}\exp(BRa^{\beta})$, derived from a recent multi-layer model of temperature distribution. We found that at small $Pr \leq 1$ and small $Ra \approx 10^8 \sim 10^{10}$, the convection flow has a scaling $Nu = ARa^{0.143}$. However, at the moderate Prandtl number ($1 < Pr < 4$), the exponential part plays a critical role in heat transfer, distinct from that at low Prandtl number – the scaling law becomes $Nu = ARa^{0.143}\exp(BRa^{\beta})$, rather than a power law. Interestingly, when Prandtl number is larger than 4, the convection mechanism seems to recover to the power law. Considering the energy balance and the Prandtl number effects, the present study suggested a more accurate scaling law in predicting the heat transfer in turbulent Rayleigh-Bénard convection, though Prandtl number dependence is still under investigation.



(a) (b)

Figure 1 Nu vs. Ra ($\Gamma = 1.14$). The solid line is the model and the open solid circles are the experimental data [1] with different Prandtl numbers.

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December 13, 11:50 – 12:10

Generalized Autocorrelation Function in Rayleigh-Benard Convection

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We introduce a generalized-autocorrelation function (GACF) analysis to extract scaling exponents $\zeta_A(q)$ from the temperature data sets obtained in the near sidewall region of the Rayleigh-Benard convection cell. Both the Kolmogorov-Obukhov-Corssin (KOC) scaling of the passive scalar for the first-order GACF and Bolgiano-Obukhov (BO59) scaling of the active scalar for the second-order GACF are obtained. These KOC and BO59 scaling laws are also achieved by a probability density function scaling analysis in the probability space on the same scale range. Our results provide an experimental evidence of the mixture of the KOC and BO59 scaling laws on the same range scales. Furthermore, we find that due to the presence of energetic large-scale structures, e.g., large-scale-circulation oscillations, the classical structure-function analysis fails to identify the BO59 scaling. However, due to the nonstationarity and nonlinearity of the large-scale circulation, one cannot separate it clearly from the small scales. It is one reason why the BO59 scaling is so difficult to achieve experimentally.

December 13, 12:10 – 12:30

Large Scale Structures in the Velocity Field of Boundary Layer in Rayleigh-Bènard Convection Measured with PIV

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We report about the measurement of the velocity field in the boundary layer in a Rayleigh-Bénard cell filled with air. The rectangular convection cell made of Perspex has a size of 2.5m x 2.5m x 0.625m resulting in aspect ratios of Γ=1 and 4. The Rayleigh number is in the range of 10^{10}. This convection cell is inserted in a larger Rayleigh-Bènard facility called "Barrel of Ilmenau". With particle image velocimetry (PIV) the time dependent 2D velocity field is measured through a window below the cooling plate. With two different orientated laser light sheets with a size of 100mm x 100mm we study the horizontal and vertical velocity field. Two different PIV regimes are used: (i) short term time series with high repetition rate (200 images with 10 Hz) and (ii) long term time series with low repetition rate (3000 images with 1 Hz). From the PIV data we calculate with ViDPIV software 2D time averaged velocity field, vorticity, velocity fluctuation and Reynolds stress from the boundary layer of the center of the convection cell in horizontal (Fig. 1) and vertical direction (Fig. 2). The horizontal velocity field was recorded in 10 layers until a distance of 210mm from the cooling plate by moving the light sheet and the PIV camera. The data show coherent flow structures with different length and time scales. Velocity profiles extracted from the horizontal and vertical time averaged fields show a good agreement with high-resolution laser Doppler anemometry (LDA) data. With these data we are able to investigate the temporal variation of the boundary layer thickness.

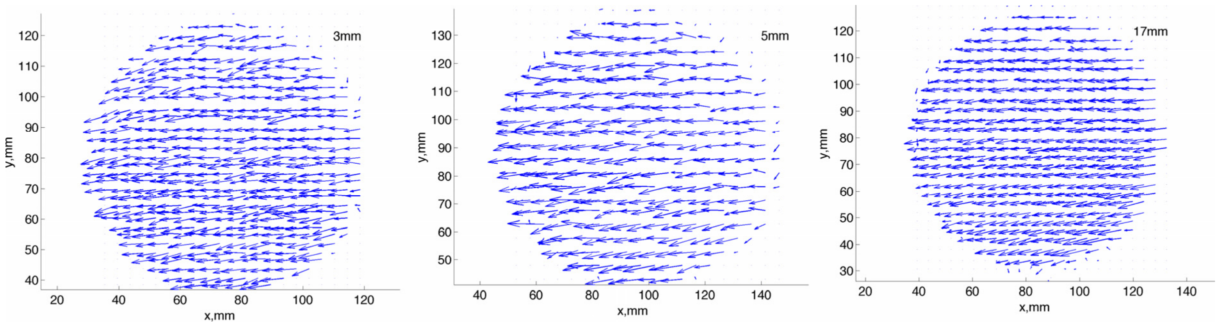

Fig. 1: Time averaged horizontal velocity fields at different distances from the cooling plate show the large scale circulation (wind).

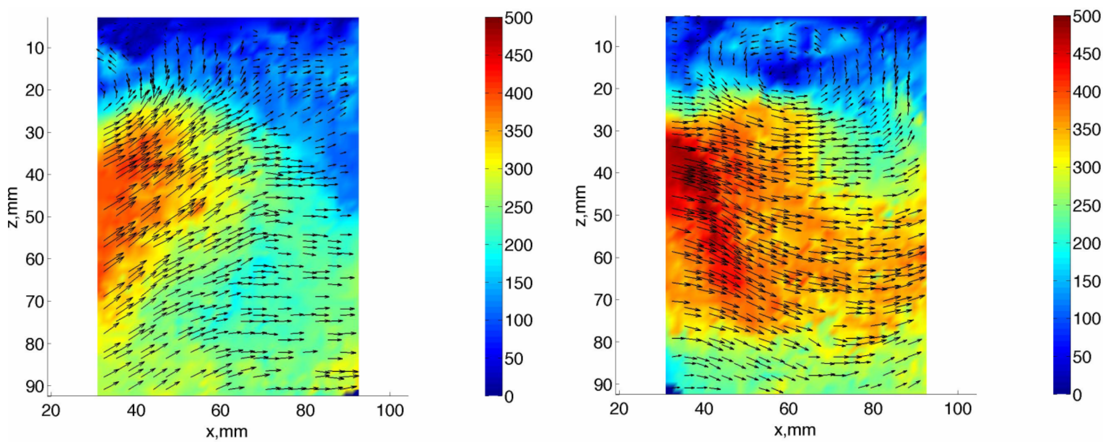

Fig. 2: Snapshots of vertical velocity fields showing coherent flow structures in the boundary layer (thermal plumes). The colors represent the velocity magnitude in mm/s.

December 13, 14:00 – 14:40

The Influence of Confined Geometry and Interior Walls on Heat Transport and Boundary Layer Structures in Turbulent Thermal Convection

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The present study is devoted mainly to the investigation of the effects of outer and interior walls on the structures of the kinetic and thermal boundary layers in turbulent thermal convection.

With this respect we first analyse the influence of the confined geometry on main boundary layers' characteristics like their thicknesses and the vertical profiles of the velocity and temperature in the case of classical Rayleigh-Bénard convection.

Further, introducing relatively high regular roughness of the heated/cooled horizontal plates in a Rayleigh-Bénard cell, we investigate how the presence of the roughness elements affects the heat transport and approximate the deviation of the mean vertical heat flux enhanced by the wall roughness from that in the classical case. The obtained results can be further generalized to the case of turbulent natural convection in domains with interior walls (obstacles), the linear size of which is significantly larger than the mean thermal boundary layer thickness.

Analytical estimations of the boundary layer characteristics influenced by the confinement of the convection cell are compared to the results obtained in Direct Numerical Simulations (DNS). The model to estimate the deviation of the mean vertical heat flux enhanced by the wall roughness is checked in two-dimensional numerical simulations.

If time allows, we further discuss the problem of complexity and mesh resolution requirements in DNS of turbulent thermal convection in bounded domains with and without interior walls or obstacles. Estimating the scaling of the dimensionless velocity of Large-Scale Circulation (LSC) and turnover time in turbulent natural convection with respect to the Rayleigh number (Ra), Nusselt number and Prandtl number (Pr), we evaluate the number of dimensionless time units, required for the statistical averaging of the DNS data and estimate the total DNS complexity, measured in arithmetical operations needed to conduct DNS, dependently on the Rayleigh number.

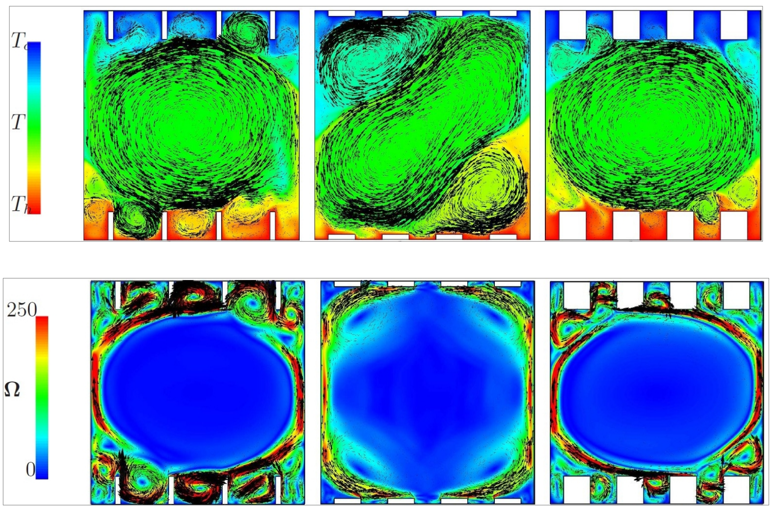

Figure 1. Instantaneous temperature distributions with superimposed velocity vectors (top) and distributions of the norm of the time-averaged heat flux with superimposed mean heat flux vectors (bottom), for different types of regular wall roughness and Ra=1.0e8, Pr=1. Adopted from O. Shishkina and C. Wagner, Modelling the influence of wall roughness on heat transfer, J. Fluid Mech., (2011), vol. 686, pp. 568-582.

December 13, 14:40 – 15:10

Convection under Stress-free Boundaries- Reversals without Corner-effects

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Convection at high Rayleigh number plays a central role for the dynamics of planetary interiors. Phenomena like plate tectonics, as well as the generation and maintenance of planetary magnetic fields are intimately coupled to convectively driven flows within the planetary mantles and cores. Neglecting typical complications (e.g. temperature dependence of viscosity by several orders of magnitude, strong rotation in the Core), convection at infinite Prandtl number (mantle) and low Prandtl number (Pr around 0.01) within stress- free boundaries resemble these scenarios. Stress-free boundaries are experimentally difficult to realize. It seems however important to address similarities and differences between stress-free and, as accessible to laboratory experiments, rigid boundaries. For the infinite Prandtl number limit, we demonstrated that 2D calculations are a sensible approach. We investigated the Nusselt-Rayleigh (Nu – Ra) scaling, and observed the internal dynamics of the LSC. The results are very much dependent on the aspect ratio of the computational domain. In square boxes, we find virtually the Malkus scaling ($Nu \sim Ra^{\frac{1}{3}}$) for Rayleigh numbers up to 10^{13}. In larger domains we can clearly identify different time scales, one associated with the internal plume dynamics, the other with variations of the LSC. We also see a dependence of the exponent in the Nu-Ra scaling on the aspect ratio. Spontaneous reversals of the flow take place at appropriate values of aspect ratio and Rayleigh number. Since corner flows don't exist due to the stress-free conditions, the mechanism behind the reversals lies in the interaction of the plumes with the LSC. At aspect ratios, smaller than unity, we observe typically 'excursions', rather than reversals at $Ra > 10^{11}$. The flow reaches an virtually stationary state, interrupted by intermittent phases of turbulent convection. Similar to experiments within rigid boundaries, we observe a clear dependence of Nu on Pr. For Prandtl numbers Pr < 1, Nu strongly increases with increasing Pr, for Pr > 1 there is hardly an increase of Nu with Pr. Due to the stress-free boundaries, classical velocity boundary layers do not exist. We address the behavior to the relative importance of toroidal to poloidal field strength of the flow.

December 13, 15:10 – 15:30

Optimal Taylor-Couette Turbulence

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Strongly turbulent Taylor-Couette flow with independently rotating inner and outer cylinders with a radius ratio of $\eta = 0.716$ is experimentally studied. From global torque measurements, we analyse the dimensionless angular velocity flux $Nu_\omega(Ta, a)$ as a function of the Taylor number Ta and the angular velocity ratio $a = -\omega_o/\omega_i$ in the large-Taylor-number regime $10^{11} \lesssim Ta \lesssim 10^{13}$ and well off the inviscid stability borders (Rayleigh lines) $a = -\eta^2$ for co-rotation and $a = \infty$ for counter-rotation. We analyse the data with the common power-law ansatz for the dimensionless angular velocity transport flux $Nu_\omega(Ta, a) = f(a)Ta^\gamma$, with an amplitude $f(a)$ and an exponent γ. The data are consistent with one effective exponent $\gamma = 0.39 \pm 0.03$ for all a, but we discuss a possible a dependence in the co- and weakly counter-rotating regimes. The amplitude of the angular velocity flux $f(a) \equiv Nu_\omega(Ta, a)/Ta^{0.39}$ is measured to be maximal at slight counter-rotation, namely at an angular velocity ratio of $a_{opt} = 0.33 \pm 0.04$, i.e. along the line $\omega_o = -0.33\omega_i$. This value is theoretically interpreted as the result of a competition between the destabilizing inner cylinder rotation and the stabilizing but shear-enhancing outer cylinder counter-rotation. With the help of laser Doppler anemometry, we provide angular velocity profiles and in particular identify the radial position r_n of the neutral line, defined by $\langle\omega(r_n)\rangle_t = 0$ for fixed height z. For these large Ta values the ratio $a \approx 0.40$, which is close to $a_{opt} = 0.33$, is distinguished by a zero angular velocity gradient $\partial\omega/\partial r = 0$ in the bulk. While for moderate counter-rotation $-0.40\omega_i \lesssim \omega_o < 0$, the neutral line still remains close to the outer cylinder and the probability distribution function of the bulk angular velocity is observed to be monomodal. For stronger counter-rotation the neutral line is pushed inwards towards the inner cylinder; in this regime the probability distribution function of the bulk angular velocity becomes bimodal, reflecting intermittent bursts of turbulent structures beyond the neutral line into the outer flow domain, which otherwise is stabilized by the counter-rotating outer cylinder. Finally, a hypothesis is offered allowing a unifying view and consistent interpretation for all these various results.

December 13, 16:00 – 16:30

Anatomy of Thermal Plumes in Strongly Temperature-dependent Viscosity Fluids at High Prandtl and Rayleigh Numbers: Local Heating Versus Uniform Rayleigh-Bénard Configuration

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Thermal plumes constitute the building blocks of high Rayleigh number convection. They are developing from the thermal boundary layers (TBLs) and are responsible for the vertical heat and mass transport across the fluid layer. They are a common occurence both in industry and Nature. For exemple, since planets cool by convection within their mantles, hot plumes should develop there and they probably are responsible for hot spot volcanism such as Hawaii on Earth, or Coronae on Venus. Geological fluids encountered in lava flows or solid planetary mantles have a high Prandtl number and a viscosity which depends strongly on temperature.

We present an experimental study of the characteristics of such plumes generated in two different convective settings: a) a small heat source and b) the classical Rayleigh-Bénard configuration. Rayleigh numbers were up to 10^8, Prandtl numbers up to 10^6, and viscosity ratios across the tank up to 4000. The velocity field was determined with particle image velocimetry (a and b), while the temperature field was measured using differential interferometry (a) and thermochromic liquid crystals (a and b). The combination of these different techniques run simultaneously allows us to identify the different stages of plume development.

In a), we compared the positions of key-features of the velocity field (centers of rotation, maximum vorticity locations, stagnation points) respective to the plume thermal anomaly. Two important measurements are then the velocity of the stagnation point located on the top of the plume head VA, and the velocity of the particles at this point Vz(A). The former will give the same information as following dye (which underlines the maximum deformation) or following shadowgraph (which underlines the maximum temperature gradient), while Vz(A) gives the same value as the uplift of the maximum vorticity centers. The latter constitutes the ‘‘true’’ plume head velocity. The difference VA - Vz(A) represents plume head growth by thermal diffusion. We further show that the stem velocity structure is quite sensitive to the temperature dependence of the viscosity and to confinement.

In b), the temperature-dependence of viscosity introduces a strong asymmetry in the TBLs. Hot instabilities develop as mushroom-shaped plumes while cold instabilities develop as thin fingers. Howard’s phenomenological model (1964) describes well the instabilities formation: the TBL first grows by conduction until the local Rayleigh number calculated across it reaches a critical value Ra_c. Then a plume develops and drain the TBL. We compare the plumes'anatomy with a). Each plume can be considered as "confined" in a virtual box defined by its closest neighbours. However, this confinement is only temporary and plumes lateral motions and merging occur along networks of ridges localized at the edges of the TBLs.

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December 13, 16:30 – 16:50

Transition to the Ultimate Regime in Turbulent Taylor-Couette Flow: Numerical Simulations

R. Ostilla Mónico, E. van der Poel, S. Grossmann, R. Verzicco and D. Lohse

Physics of Fluids Group, University of Twente, The Netherlands

Experiments in the Twente Taylor-Couette facility at high Taylor numbers have revealed a local scaling exponent of $Nu \sim Ta^{0.38}$, in direct correspondence to the local scaling exponents seen in the ultimate regime of Rayleigh-Bénard ($Nu \sim Ra^{0.38}$) in the Goettingen experiments by Ahlers, Bodenschatz, and coworkers. We numerically simulate Taylor-Couette flow for pure inner cylinder rotation, reaching Reynolds numbers of up to $Re_i = 2.5 \cdot 10^4$, corresponding to Taylor numbers of up to $Ta=10^9$. Effective scaling laws for the torque and other system responses are found. For large enough Ta, we see a transition from an effective scaling law exponent of 0.33 to the ultimate effective exponent 0.38. The appearance of this scaling can be linked to changes in the angular velocity profiles and the breakdown of large scale vortices. In this large Ta regime, the angular velocity develops a logarithmic profile in regions of the flow in which plume-like structures are ejected. The relative size of these regions in which the log-profiles develop grows with increasing Ta. For the largest Ta which we can achieve the whole domain is filled up with such plume-like structures and the corresponding logarithmic angular velocity profiles, which characterize the ultimate regime.

December 13, 16:50 – 17:10

Confinement Induced Enhancement of Flow Reversals and Heat Transport in Turbulent Rayleigh-Bénard Convection

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We report an experimental study of the confinement effects on flow reversals and heat transport in turbulent Rayleigh-Bénard convection. The experiments were conducted in three rectangular cells with the heights and lengths being equal and fixed at 12.6 cm, while the widths being 3.84 cm, 2.56 cm and 1.92 cm, giving rise to lateral aspect ratios 0.3, 0.2 and 0.15, respectively. It is found that, as the lateral aspect ratios decreases, i.e. the confinement increases, both the flow reversal frequency and heat transport efficiency enhance significantly; In contrast, the Reynolds number Re remains unchanged. The increased temperature fluctuations in the bulk and a transition of its probability density function from exponential to Gaussian forms indicate that highly confined geometries lead to stronger and better flow mixings, which is believed to be responsible for the observed enhancement of flow reversals and heat transport.

December 13, 17:10 – 17:30

Rayleigh-Bénard Convection in Thin Liquid Films – An Experimental Study

Michael Winkler

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A newly developed setup to drive thermal convection in a freestanding liquid film will be presented. The focus of this experiment is the study of reversals for a large range of aspect ratios in a truly two-dimensional setup. The liquid film has a thickness to area ratio of approximately 10^8 and is placed in a fixed frame which can be adjusted in height and length to vary the aspect ratio. Temperature at the bottom and top and the environment of the film are carefully controlled to achieve reproducible results and allow a comparison to experimental data from other 2D or 3D Rayleigh-Bénard convection experiments. Differences and similarities will be discussed with emphasis on the boundary conditions.

Another aspect that is studied with this setup is the convection in ultrathin liquid films with a thickness below 50 nm (black film). At these thicknesses the film is dominated by surface forces as almost no free water exists between the two surfactant sheets.

December 14, 09:00 – 09:40

Coherent Structures of Large Scale Natural Convection

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Thermal convection is the most common fluid flow in nature. Despite small scale randomness high Rayleigh number convection systems are characterized by persistent coherent structures which resemble patterns of convection observed on the laboratory scale. This surprising similarity can be investigated through the analysis of sequences of bifurcations at moderate supercritical Rayleigh numbers. An example is the transition from sheet-like convection to plume-like convection. Convection rolls in the presence of shear and bimodal convection seen in experiments also exist in the atmosphere as demonstrated by cloud patterns.

Convection in spherical shells offers another example for patterns in the presence of horizontal isotropy. At intermediate shell thicknesses convection exhibits the symmetries of Platonic bodies at onset. Convection in the Earth's mantle, for example, is responsible for plate tectonics. The dominant l=2 component of mantle convection influences the moment of inertia of the Earth and thus determines the axis of rotation of the Earth.

Convection in stars, gaseous planets and in the Earth's core is strongly influenced by rotation with the resulting loss of horizontal isotropy. The inhibiting influence of rotation is typically counteracted by the magnetic forces generated by a dynamo process.

December 14, 09:40 – 10:10

Self-aggregation of Moist Convection in a Conditionally Unstable Environment

Thomas Weidauer[1], Olivier Pauluis[2], and **Joerg Schumacher**[1]

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Conditionally unstable convection occurs when the stratification is stable for unsaturated air parcels but unstable for saturated air parcels. This leads to the development of isolated convective plumes or clouds which are separated by an extended unsaturated dry environment. Here the statistical behavior of conditionally unstable convection is studied in a model of moist turbulent convection with a simplified thermodynamics of cloudy air. It is closely related to the classical Rayleigh-Bénard dry convection problem, but includes phase transitions between the gaseous and liquid phase and the effect of latent heat release on the buoyancy of air parcels. We demonstrate that this simplified model is not only capable to simulate cloud formation processes, but also indicates that the complex dynamics of moist convection results in the emergence of new convective regimes that do not exist in the absence of phase transition. The transition to self-aggregated convection is however highly sensitive to the diffusivity and viscosity used in the model, with the aspect ratio necessary for the transition increasing as the viscosity and diffusivity are decreased. In addition, it is also found that conditionally unstable moist convection is inefficient at transporting energy. We argue that this weak energy transport is tied to the presence of a diffusive layer near the lower boundary, which remains present even when the diffusivity is small. Furthermore, we investigate the impacts of radiative cooling on the self-sustained convective regimes. Therefore a simple steady bulk cooling scheme is added to the advection-diffusion equations for the scalar fields.

December 14, 10:10 – 10:30

Development of Supersaturation in Rayleigh-Bénard Convection

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Through a multitude of physical processes spanning over many spatial and temporal scales, clouds are responsible for the radiative, thermodynamic, and hydrodynamic balance on Earth. In the atmosphere where clouds reside, varying dynamical and chemical conditions make precise and repeated testing of hypotheses difficult. Laboratory cloud chambers provide an environment in which boundary conditions are well characterized and statistically stationary conditions can be imposed, but existing cloud chambers only operate in the laminar hydrodynamic state. A ~3 m^3 cloud chamber capable of supporting turbulent Rayleigh-Bénard convection over a range of atmospherically relevant pressures, temperatures, and humidities is currently being developed at Michigan Technological University. One aim of the chamber is to investigate the interactions between temperature and vapor concentration fields to form varying supersaturation and resulting cloud particle growth. Here, we describe a numerical study to simulate the condition in this type of chamber, albeit of a much smaller dimension. The fluid is a binary gas mixture, consisting of nitrogen (N_2) with water vapor (H_2O) as a trace species. The mixture is confined in a cylindrical cell of aspect ratio (diameter/height) 2 with adiabatic side walls and heated from below. The Prandtl numbers is 0.7 and the Rayleigh number is varied from onset of convection (approximately 2500) and over a range in which steady, laminar convection results. In addition to thermal boundary conditions, the bottom and top surfaces have specified water vapor concentrations, and we investigate the combined influence of temperature and water vapor concentration on the buoyancy, as well as the formation of supersaturation. We discuss how this work sets the stage for simulations

at higher Rayleigh numbers with turbulent convection, and for the design of experiments in cloud chambers that better mimic the actual environment in the atmosphere.

December 14, 11:00 – 11:30

Validity of the Bolgiano-Obukhov Phenomenology in Turbulent Thermal Convection*

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According to the Bolgiano-Obukhov phenomenology, velocity and temperature fluctuations in turbulent thermal convection exhibit Bolgiano-Obukhov (BO) scaling plus possible intermittency corrections for scales larger than the Bolgiano scale. The BO scaling has been observed in numerical simulations of two-dimensional homogeneous turbulent thermal convection and also in experiments using soap films but has not been clearly found in three-dimensional turbulent thermal convection. The validity of the BO phenomenology in turbulent thermal convection has thus been called into question. Direct numerical simulations show that the local Bolgiano scale in three-dimensional turbulent Rayleigh-Benard convection is generally comparable to the largest scale of the system --- the height H of the convection cell, and is considerably smaller than H only near the top and bottom plates. By studying the conditional temperature structure functions evaluated at given values of the locally averaged thermal dissipation rate using experimental measurements, we reveal the BO scaling at the bottom plate of the convection cell. On the other hand in a numerical study of two-dimensional homogeneous turbulent thermal convection, we show that the Bolgiano scale can be increased by polymer additives and the BO scaling indeed holds only for scales larger than the Bolgiano scale. Our work thus confirms the validity of the BO phenomenology in turbulent thermal convection.

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December 14, 11:30 – 11:50

Characterizations of Double Diffusive Convection Steps and Heat Budget in the Deep Arctic Ocean

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Recently, it has been shown that the geothermal heating has significant influence to the interior ocean based on the numerical experiments with the oceanic general circulation models. In the present work, the hydrographic structures and heat budget in deep Arctic Ocean were explored. From bottom to top, four double diffusive convection (DDC) steps were identified at mooring A (75^{o}N, 150^{o}W). Two methods were used to evaluate the vertical heat flux of the DDC layers, but the results are of big difference. But, both results indicate that the vertical heat flux is much smaller than the geothermal heating, which means that DDC layers act as thermal barriers in deep basin. Moreover, the vertical heat fluxes vary in log-normal distributions within one year, which demonstrate turbulent features. Between 2003 and 2011, the hydrographic data suggest that deep water is warmed at a rate of ~ 4×10^{-4} ^{o}C/year. After the examination of the salinity trend of deep water and the temperature increments of middle and deep waters, it is concluded that geothermal heating is the dominant process for the warming of deep water. The presences of DDC layers prevent the escape of geothermal heating, and its influence is mainly limited in the deep ocean.

December 14, 11:50 – 12:10

Compositional Buoyancy Driven Convection during Sea-ice Solidification

Jin-Qiang Zhong and Zuo-Chao Yin

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In winter growth seasons, brine within the interstices of sea ice drains into the ocean as a result of natural convection in the lower parts of the sea ice, a mushy-layer in which dendritic solid ice and concentrated liquid coexist. Convection within a mushy-layer is determined principally by the porous-medium Rayleigh number Rm. Recent theoretical models indicate that the brine flux through such a salt-rejection process is proportional to Rm.

We report studies on the compositional transports during sea-ice growth through laboratory experiment in solidifying aqueous ammonium chloride. Driven by compositional buoyancy force, cold, compositional plumes from the mushy-layer are carried continuously into the warm, salt-stratified liquid region. We observe the formation of downwelling double-diffusive layers that form initially adjacent to each vertical compositional plume. Using shadowgraphy and dyed fluids we demonstrate the vigorous flow circulations and turbulent compositional mixing within each layer. The advancing velocity of the layers decreases as the layers approach to the mush-liquid interface, which is interpreted by a filling-box model representing the momentum and compositional transports of turbulent continuous plumes in a confined region. The present studies provide insight to evaluate the brine fluxes through growing sea-ice.

December 14, 12:10 – 12:30

The Boundary Layer Structure in Turbulent Rayleigh-Bénard Convection for Different Prandtl Numbers

Nan Shi, Mohammad S. Emran and Joerg Schumacher

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We report results on the boundary layer structure in turbulent Rayleigh-Bénard convection in a cylindrical cell of aspect ratio one. They are based on three-dimensional direct numerical simulations (DNS) of the Boussinesq equations at Rayleigh number $Ra = 3 \times 10^9$ and Prandtl numbers Pr between 0.007 and 7. We investigate how the mean profiles of the temperature and velocity fields as well as their fluctuations vary with respct to the Prandtl numbers. Furthermore it is studied how the boundary layer dynamics is coupled to the large-scale circulation. We thank the Deutsche Forschungsgemeinschaft for support with the Research Focus Group 1182.

December 14, 13:30 – 14:10

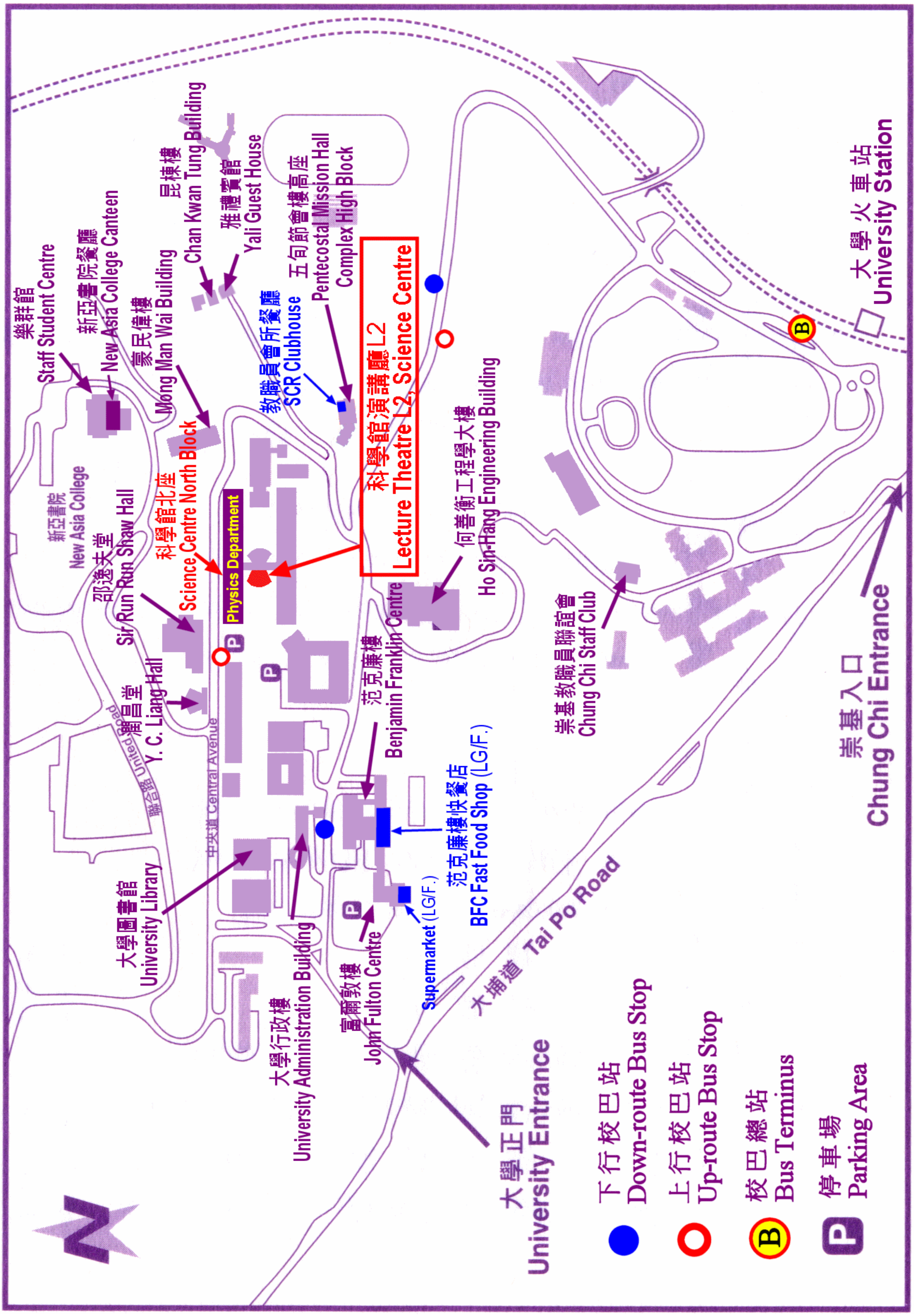
Rigorous Results for Heat Transport in High Rayleigh Number Convection

Charles R. Doering

Department of Mathematics, Department of Physics, and Center for the Study of Complex Systems, University of Michigan

We review both long established and more recent mathematical results regarding heat transport in Rayleigh-Bénard convection with an eye toward rigorously determining predictions of the Boussinesq model and related systems.

CUHK Campus Map



MTR System Map