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Cryogenic He experiment on natural turbulent convection

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ABSTRACT

Cryogenic helium gas is a suitable fluid for **study of natural turbulent convection at very high Rayleigh numbers**. We present experimental method and new result on Reynolds and Péclet numbers characterizing **large scale circulation (LSC)** of fluid at Rayleigh numbers within the range from 10^{11} to 10^{15}. Observation of LSC is based on measurement of local **temperature fluctuations of convecting helium**. For experiments we used a specially designed cylindrical cell of height L = 0.3 m and diameter D = 0.3 m with minimized parasitic effects on studied convection, previously published on CryoPrague 2006 [1].

Introduction

Natural thermally driven turbulent convection is a ubiquitous phenomenon and its study is of great importance for various fields of science and technology. Basic parameter is the **Rayleigh number (*Ra*)** which characterises intensity of this phenomenon.

Low viscosity and high thermal diffusivity of the He enables to achieve very high values of Rayleigh number in laboratory conditions.

Ra = 10^{17} - Earth atmosphere, *Ra* = 10^{20} - oceanic streams, *Ra* = 10^{21} - effects on the Sun.

The highest value of *Ra* in a laboratory was achieved using cryogenic helium gas (*Ra* = 10^{17}) [2].

This makes the cold He very useful working fluid for experimental studies of turbulent flow

Strong dependence of helium properties on the pressure and temperature in the vicinity of helium critical point (5.195 K, 227.5 kPa and 69.64 kg/m^3) allows to study the convection in a **wide range of *Ra* numbers**.

Table 1. The ratio of the fluids properties in *Ra* number

Fluid	Temperature	$\alpha/\nu\kappa$ ($K^{-1}cm^{-4}s^{-2}$)
Air	20 °C	0.122
Water	20 °C	14.4
Hydrogen (para, liquid)	20.2 K (100 kPa)	5.9×10^3
SF$_6$	50 °C (5 MPa)	7.5×10^5
Helium (gas)	**5.5 K (100 kPa)**	**1.05×10^5**
Helium (gas)	**5.5 K (280 kPa)**	**1.41×10^8**

$$Ra = g\frac{\alpha}{\nu\kappa}\Delta T L^3$$

Model of Rayleigh-Bénard convection (RBC)

A fluid confined between two horizontally infinite plates kept at a constant temperature, is heated with the lower plate and cooled via the upper one.

RBC is realized using a container of height *L,* often of cylindrical shape with diameter *D*. Such a system is possible to study both experimentally, theoretically or by direct numerical simulation.

Conditions of nearly incompressible fluid (Boussinesq conditions): the RBC is fully described by following dimensionless numbers.

Ra – convection intensity, *Pr* – property of the fluid, *Nu* – heat transfer efficiency

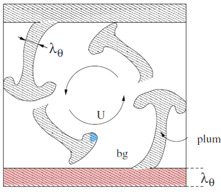
Rayleigh number **Prandtl number** **Aspect ratio (*Γ*)** **Nusselt number**

$$Ra = g\frac{\alpha}{\nu\kappa}\Delta T L^3 \qquad \Pr = \frac{\nu}{\kappa} \qquad \Gamma = \frac{D}{L} \qquad Nu = \frac{H}{H_0}, \quad H_0 = \lambda\frac{\Delta T}{L}$$

g - acceleration due to gravity, *ΔT* - temperature difference between the bottom and top plates separated by vertical distance *L.*

Properties of the He - $\alpha/\nu\kappa$, where α - isobaric thermal expansion, ν - kinematic viscosity, κ -thermal diffusivity.

H - heat flux transferred by convection, H_0 - heat flux transferred by a quiescent fluid, λ – heat conductivity of the fluid.



Main structures in RBC with aspect ratio *Γ* = 1. Thermal boundary layers (thickness λ_θ), LSC with velocity *U* , hot and cold plumes emitted from thermal boundary layers.

Observation of the Large scale circulation (LSC)

At higher Rayleigh numbers LSC starts to coexist with **thermal structures "plumes"** which are emitted from the thermal boundary layers [4]. Together with heat diffusion via boundary layers they **drive LSC** [3].

Characteristic period T_p of detection of plumes was derived from auto-correlation function of the temperature (or from fluctuation spectra)

Velocity of LSC was evaluated from cross-correlation function of two temperature signals.

Reynolds (*Re*) or **Péclet dimensionless numbers** (*Pe*) based on characteristic period T_P[3]:

$$Re \equiv \frac{2L^2}{\nu T_p}, \quad Pe \equiv Pr \cdot Re$$

Summary

- Experimental study of scaling law *Nu*(*Ra*, *Pr*) up to *Ra* = 10^{15}
- Recording of several temperature signals measured by a temperature sensors located in convecting helium gas
- Observation of coherent structures in convective flow in auto-correlation of temperature signals.
- Circulation velocity detection from the cross-correlation of signal from two sensors.
- Detection of the period of coherent structures at very high value *Ra* = 1.6×10^{14}.

Conclusions

Péclet number follows approximately dependence $Pe\sim Ra^{1/2}$ previously observed by other laboratory for $Ra \leq 10^{13}$ [5]. To our knowledge, it is the first observation of large scale circulation at Rayleigh numbers above *Ra* = 10^{13} in RBC in laboratory conditions.

Acknowledgement

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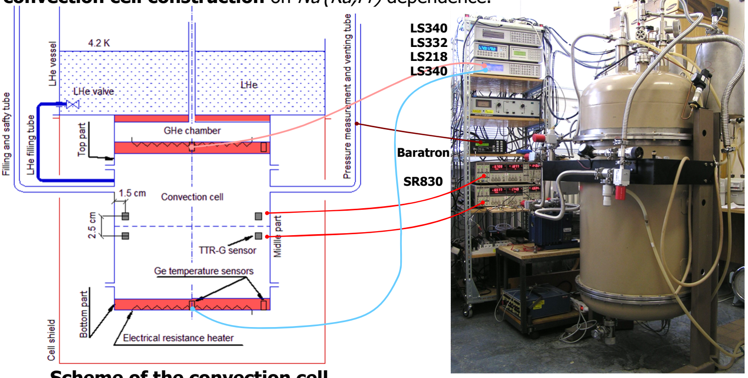
Apparatus ConEV

The helium cryostat with cylindrical experimental cell has been developed at the **ISI Brno** in cooperation with Department of low temperature physics of **Charles University, Prague**. Parameters of this unique apparatus enable to study thermally driven convection within wide span of *Ra* numbers, from 10^6 up to 10^{15}, with **minimum influence of the convection cell construction** on *Nu (Ra,Pr)* dependence.



Scheme of the convection cell

ConEV in the laboratory

Cell diameter and height 0.3 m. Sidewalls with very low thermal conductivity.

The top and bottom plates - **28 mm thick annealed OFHC copper** (Outokumpu) of high thermal conductivity, at least 2 kWm^{-1}K^{-1} (at 5 K).

Total **parasitic heat leak** to the cell is **suppressed to < 1%** of the lowest convective heat flux used in the experiment.

Better than **1 mK temperature homogeneity** of plates.

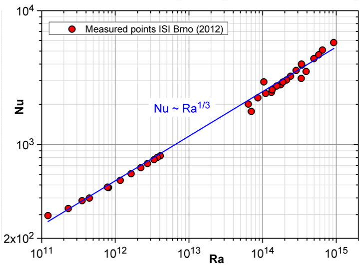
Four calibrated Lake Shore GR-200A-1500-1.4B Ge **temperature sensors** imbedded in the plates (5 mK absolute accuracy and 2 mK accuracy of ΔT)

Four miniature sensors TTR-G (Institute of Semiconductor Physics, Kiev, Ukraine) - 0.2 mm cubes of doped Ge, 6 kΩ and 10^3 Ω/K at 5 K. Temperature fluctuations detection by **Lock-in amplifier SR830**.

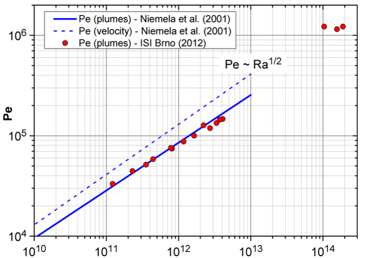
MKS Baratron 690 A: pressure in the cell with 0.08 % accuracy (calibration traceable to NIST) .

Helium properties: NIST database [7], based on the measured pressure in the cell and the mean temperature T_m assessed as arithmetic average of the plate temperatures

Nu(*Ra*) and *Pe*(*Ra*) scaling laws



Measured *Nu*(*Ra*) together with power law $Nu \sim 0.051\ Ra^{1/3}$ [8].

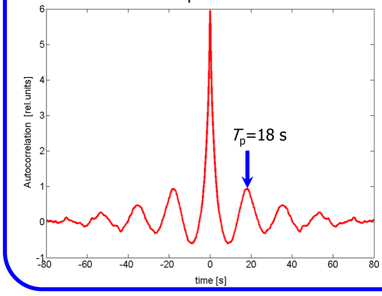


Péclet number($Pe \sim 0.13\ Ra^{1/2}$) evaluated from the plumes detection (auto-correlation)

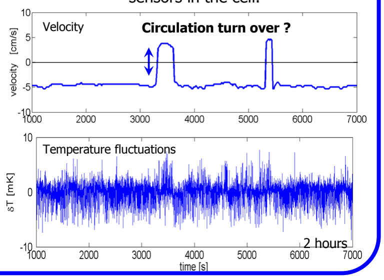
Observation of the Large scale circulation

Ra = 4.82×10^{11}, *Nu* = 415.5, *Pr* = 0.87

Auto-correlation function of the time signals of one miniature temperature sensor in the cell.



Velocity from the cross-correlation of the time signals from two miniature temperature sensors in the cell.



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