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# From isoviscous convective experiment 'GeoFlow I' to temperature-dependent viscosity in 'GeoFlow II'—Fluid physics experiments on-board ISS for the capture of convection phenomena in Earth's outer core and mantle ☆

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ABSTRACT

With the hydrodynamic experiment 'GeoFlow' (Geophysical Flow Simulation) instability and transition of convection between two spherical shells are traced. The flow is driven by a central-symmetry buoyancy force field in microgravity conditions. We performed experiments for a wide range of rotation regimes, within the limits between non- and rapid-rotation. Here we focus on the non-rotational convection in an isoviscous experimental fluid as in 'GeoFlow I' and the preparation of 'GeoFlow II', that uses a temperature-dependent viscous fluid. Theoretical predictions on thermal, dielectric and optical performance of the fluid suggest the use of an alkanole, i.e. 1-Nonanol as working fluid for 'GeoFlow II'. Initial ground based experiments demonstrate the influence of the viscosity contrast on fluid flow patterns. Specific results from the 'GeoFlow I' experiment, i.e. steady-state convection above a threshold and transition to chaos, are used as a reference.



## 1. Introduction

The overall driving mechanism of fluid flow in the inner Earth is convection in the gravitational buoyancy field of our planet (Fig. 1). In particular there has been involved a lot of effort in theoretical prediction and numerical simulation of both the geodynamo [1], which is maintained by convection, and mantle convection, which is the main cause for plate tectonics [2]. These two different manifestations of convection inside Earth are extensively described on the one hand in [3] for the Earth core, and on the other hand for the Earth mantle in [4]. Both books highlight the complementary aspects of theoretical, numerical and experimental research for a rich variety of physical conditions. While the theory determines the basic concepts, the numerical simulation is able to check approximations and modeling concepts for a rich variety of parameters. Finally there are the experiments, that allow to capture all non-linear effects and associated instabilities without analytical and numerical simplifications. Up to now, the comparison between all the three approaches is done only at selected points and is destined to benchmark each other.

To sharpen this discussion, especially laboratory experiments on mantle dynamics are considered as 'crucial for exploring new physics and testing theories' [4, chap. 3, p. 90]. For core dynamics, the experiments are 'designed to

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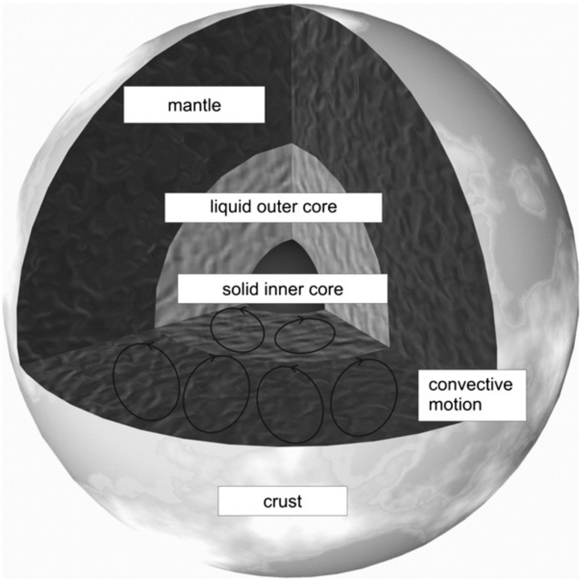


**Fig. 1.** Convection inside the Earth's outer core and the mantle.

understand the basic fluid (···) mechanical processes' [3, chap. 11, p. 319]. In summary, one can state that different approaches have been followed in order to study specific phenomena experimentally, against the background of magneto-hydrodynamic (if especially the outer core is regarded) but also on the pure hydrodynamic physics of fluids. Depending on the research focus, rectangular, cylindrical, as well as spherical geometries are in use, even if the geometry of the Earth suggests the use of the spherical coordinate system. With the experiment 'GeoFlow' (Geophysical Flow Simulation) instability and transition of hydrodynamic convection in spherical shells are traced. In the specific focus here is the realization of a so-called self-gravitating spherical shell setup [1]. More precisely, the fluid motion in a gap between two concentric spheres is observed, with the inner spherical shell heated and the outer spherical shell cooled. A high voltage potential between the inner and outer spheres together with the use of a dielectric working fluid induces an electro-hydrodynamic force, which is in analogy to the gravitational buoyancy force inside the Earth. To reduce unwished directed gravity this experiment requires microgravity conditions. We refer to [5–8] for scientific background and application of this technique in spherical shell experiments.

The 'GeoFlow I' experiment was accomplished on the International Space Station's module COLUMBUS inside the Fluid Science Laboratory FSL. Special goal of that experiment was to capture the large-scale convection without as well as with rotation. For the rotational situation, the stabilizing effects due to centrifugally driven convection are discussed against the gravitational-buoyancy driven convection. For this spherical Rayleigh–Bénard convection in different rotating regimes the working fluid was a silicone oil, for which kinematic viscosity $\nu$ is approximately constant. In contrast, for the second experiment, named 'GeoFlow II', we propose to use a working fluid with temperature-dependent viscosity.

This topic is of high interest in mantle convection studies. Here temperature-dependent viscosity is believed to play a fundamental role [9]. The extremely high temperature difference across the mantle generates a variation of viscosity up to a factor $10^5$ that deeply influences the properties of the flow in the entire domain. In particular, it affects the properties of the upper boundary layer that, being very viscous, takes the form of a so-called stagnant lid, where convection is heavily depressed and conduction becomes an important heat transport mechanism. Viscosity contrast generated stagnant lids are an essential feature of mantle convection and are at the basis of the still not fully explained formation of plate tectonics [10].

Focusing now on this temperature-dependency of a basic fluid flow in spherical geometries, we find that, again, different approaches are in use, which still need more interference for complementary benchmarks. Hence, so far temperature-dependent viscosity convection has been subjected to numerous numerical studies [2]. But these were mainly carried out in Cartesian box geometries, which elucidate the transition to different convective regimes as viscosity contrast is increased. Furthermore there are only few results obtained in the spherical geometry. A current limitation of these studies is the lack of experimental evidence, as the computational codes often also assume an infinite Prandtl number and therewith a Stokes flow with dropping the inertial part of the equations. Thus the purpose of 'GeoFlow II' is to observe the basic properties of the flow in the small viscosity contrast regime, by achieving the maximal viscosity variation allowed with the hardware limitation of the 'GeoFlow' inside the Fluid Science Laboratory. Even if the flow parameters are far from representing the realistic ones found inside the mantle (a condition that poses an insurmountable experimental challenge), they are to be considered still useful for a first verification of present spherical numerical models. This will extend the state of the art simulations to more realistic three-dimensional spherical geometry, a clear trend of present research activities in the study of Earth mantle evolution [2]. To summarize, the main objective will be the experimental modeling of mantle convection within temperature-dependent viscous fluid flow in a spherical shell setup.

In order to introduce the 'GeoFlow II' experiment we will discuss the basic equations and motivate the use of the alkanole as working fluid. To give an initial impression of viscosity influences with the chosen 1-Nonanol, results from laboratory tests will be shown in the third section. There we will also discuss the experimental procedure as well as overall principles of the measurement technique, to be specific the Wollaston shearing interferometry. Furthermore we will also present the possibilities to compare experimental and numerical approaches. Then in the final section specific results from the 'GeoFlow I' experiment, i.e. the non-rotating isoviscous thermal convection in spherical shells, will be presented as a reference for 'GeoFlow II'.

## 2. Physical basics

The equations of continuity, motion and heat conduction describe the hydrodynamic convection in fluids, which is generated by density, temperature and concentration