GeoFlow: On the status of experimental preparation of spherical gap flow experiments with central force field on International Space Station (ISS)

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Abstract. The GeoFlow experiment focus on convective flows in rotating spherical shells influenced by a central force field. To eliminate the unidirectional acceleration due to gravity on earth, these long-time experiments require microgravity environment on the International Space Station. While recent results of accompanying numerics are presented in [1, 2], here we present the actual status of experiment preparation.

1. Introduction

Research on thermal convection in spherical gap flows is a suitable model in geophysical fluid dynamics. Instabilities provide details for understanding large scale geophysical flows as e.g. convective phenomena in Earth’s outer core. The objective of the GeoFlow experiment is to investigate flow stability and pattern formation as well as transition to turbulence in a rotating layer of viscous incompressible fluids in a spherical gap forced by radial thermal gradient as well as a radial high voltage field.

These physical mechanisms are important for a large number of astrophysical and geophysical problems, e.g. mantle convection of the Earth, zonal atmospheric jets on the giant planets, or flows in a planet’s interior.

The experiment is going to take place in the Fluid Science Laboratory (FSL) of Columbus Orbital Facility (COF) and is therefore to be designed to adapt to an Experiment Container (EC) of dimensions \(40 \times 27 \times 28\, cm^3\) which allows its insertion in the optical bench. Figure 1 illustrates the implementation of the FSL inside COF as the configuration of FSL.

The experiment hardware, i.e. Engineering Model (EM) and Flight Model (FM) is built and verified by industry. Preparative experiments are performed using the Science Reference Model in the laboratory at Cottbus as well as the Engineering Model. Numerical investigations and bifurcation analysis are performed by European research groups from France, United Kingdom and Germany which are members of the GeoFlow Topical Team. These studies focus on preparation of the experiment design and on the observable parameter space by flow states simulations and on linear stability analysis and bifurcation analysis.
In space station experiments, parameter variation focuses on set-up of temperature gradient and rotation rate of spherical system, while high voltage will be kept fix at maximum value of 10 kV. Work schedule is splitted into two parts. During first loop, rotation rate will be set to zero and temperature difference will be increased stepwise. During second loop, the temperature difference will be set to preferred values while rotation rate will be stepwise increased to maximum.

2. Experiment set-up and status of hardware preparation

The experiment cell, as core of the experiment set-up (cf. fig. 2), consists of a solid inner sphere made of tungsten-carbide and two outer spherical shells made of glass. Silicone oil is used as working fluid. In the research cavity a temperature gradient is realised by heating the interior sphere and cooling the fluid in the outer gap using temperature-controlled fluid circuits filled also with the silicone oil. The experiment cell is mounted on a rotating tray which allows for solid body rotation. Central force field is produced by applying an alternating high voltage field between inner sphere and outer side-wall of the spherical gap. While Coulomb force does not affect the fluid due to high frequency alternation, the dielectrophoretic effect results in central force field. Geometry and dynamic parameters of the set-up as well as physical properties of working fluid are shown in Table 1, and figure 3 shows photographs of the experiment hardware.

3. Measurement techniques and data analysis

Since high voltage safety requirements does not allow for tracer particles in the working fluid, application of measurement techniques like flow visualisations or quantitative methods as e.g., Laser-Doppler-Velocimetry, is not possible. Therefore, indirect optical measurement techniques as Wollaston-Shearing-Interferometry (WSI) and in addition Schlieren technique and Shadowgraphy which are also provided by FSL are going to be applied.

WSI principally detects refractive index gradients and is therefore sensitive for density gradients, i.e. temperature differences in GeoFlow experiments. This results in variation of optical path length which causes interference phenomena. As an example, figure 4 shows a typical interferogram recorded during preparatory studies using the EM.

Numerical simulations of thermal convection phenomena typically focus on calculation of velocity field as well as temperature field of the flow state and its time-dependence. Moreover, by applying nonlinear methods of time series analysis allows for complex flow analysis. Considering
Figure 2. Sketch of experiment cell (left) and photograph of the breadboard cell (right).

Figure 3. Hardware of the space station experiment. left: photograph of FSL, by courtesy of MARS, Napoli, Italy. right: photograph of closed EC with implemented experiment cell and technical supplies, by courtesy of Astrium GmbH, Friedrichshafen, Germany.
Table 1. Experiment parameters and physical properties of working fluid.

| Parameter                          | Value  |
|------------------------------------|--------|
| Inner radius \(a\) [mm]            | 13.5   |
| Outer radius \(b\) [mm]            | 27.0   |
| Gap width \(b - a\) [mm]           | 13.5   |
| Radius ratio \(\eta = a/b\)        | 0.5    |
| Aspect ratio \(\Gamma = (b-a)/a\)  | 1      |
| Rotation rate \(\Omega\) [Hz]      | 0 - 2  |
| High voltage \(HV\) [kV]           | 0 - 10 |
| Temperature difference \(\Delta T\) [K] | 0 - 10 |
| Density [g/cm³]                    | 0.92   |
| Kinematic viscosity [m²/s]         | \(5 \times 10^{-6}\) |
| Thermal conductivity [W/K m]       | 0.116  |
| Cubic exp. coefficient [1/K]       | \(108 \times 10^{-5}\) |

Figure 4. Exemplary interferogram acquired during test campaign at Astrium GmbH, Friedrichshafen, using GeoFlow EM. Parameters: \(HV \approx 10\, kV\), \(\Delta T \approx 8\, K\), \(n = 0\, Hz\). The interferogram shows convective flow structures at the pole. Considering the whole experiment run, the flow pattern was identified as thermal blob convection.

GeoFlow experiments, in addition, artificial interferograms are processed from the calculated temperature field (cf. fig. 5) which can then be compared with the experimental interferograms.

Figure 6 shows the way for processing and analysing space station experiments and accompanied numerical simulations. By comparing calculated temperature fields and artificial interferograms with fringe pattern in experimental interferograms and temperature fields derived from acquired interferograms, it is possible to analyse the observed flow states in detail.

Figure 7 shows organisation of the data transfer and of experiment operation. The data will be downlinked by NASA and will then be distributed to the scientists at BTU Cottbus as well as to the parties involved, i.e. \(a\) Columbus Control Center, Oberpfaffenhofen, Germany, \(b\) USOC, MARS, Napoli, Italy, \(c\) E-USOC, Madrid, Spain. The scientists are allowed to operate
Figure 5. Left: Example of numerical simulation of temperature distribution in the spherical gap with cooled inner sphere (white). In the lower hemisphere, a downward channel of cold fluid directed to the south pole occur. Right: cut of associated calculated interferogram looking from the south pole.

Figure 6. Flow chart of numerical (left) and experimental (right) data analysis.

4. Summary
The GeoFlow experiment focus on convective flows in rotating spherical shells influenced by a central force field. The overall research program comprises work packages as development of hard- and software as well as preparative experiments on earth and accompanying numerical investigations regarding both, space station experiments and earth lab experiments. With the numerical simulations we focus on prediction of experiment scenario as described in [3, 4, 5].
Experiments with rotation rate $0\,Hz$ and increasing temperature difference focus on the investigation of different stable states and their dependence on initial conditions. By setting a fixed temperature difference between inner and outer shell and varying the rotation rate, time dependent convective flows with different dynamical behaviour are expected to be observed.

While the launch of the GeoFlow Experiment Container was in February 2008, the experiments were started successfully in July 2008, and the data processing is currently in progress.

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