THE GEOFLOW-EXPERIMENT ON ISS (PART I): EXPERIMENTAL PREPARATION AND DESIGN OF LABORATORY TESTING HARDWARE

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ABSTRACT

Thermal convection in a spherical shell represents an important model in fluid dynamics and geophysics. Investigations on thermal convective instabilities occurring in the spherical gap flow under terrestrial conditions are of basic importance especially for the understanding of symmetry-breaking bifurcations during the transition to chaos. Microgravity experiments on thermal convection with a simulated central force field are important for the understanding of large scale geophysical motions as the convective transport phenomena in the Earth’s liquid outer core. This report summarizes the concurrent experimental (part I), numerical (part II) and theoretical (part III) studies for the preparation of an International Space Station (ISS) experiment inside the Fluid Science Laboratory (FSL). This special experimental device with respect to geophysical simulations is called GEOFLOW. A central symmetric force field similar to the gravity field acting on planets can be produced using the effect of the dielectrophoretic force field by applying a high voltage potential difference to the inner and outer sphere. Flow visualization, Wollaston Shearing Interferometry and Laser Doppler Velocimetry will be used to determine the expected flow pattern during the space experiments. © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.

INTRODUCTION

Thermal convection in a spherical shell under a central force field represents an important model in fluid dynamics, astro- and geophysics (Busse, 1970 and 1975; Busse and Riahi, 1982; Cardin and Olsen, 1992, 1994, and 1995; Carrigan and Busse, 1983; Cordero and Busse, 1992; Harder and Christensen, 1996; Liu et al., 2000; Roberts, 1968; Zhang, 1992). The large scale motions of atmospheres of planets and in the convection zones of rotating stars are strongly influenced by Coriolis forces (due to rotation) and by buoyancy forces (due to gravity), which drive thermal circulation. The resulting flow structures show a rich variety of different types of instabilities, which depend strongly on different parameters as rotation rate, temperature gradient, gap width, material functions and others. The model of a spherical gap flow experiment should help to understand such phenomena as the zonal bands of Jupiter, the origin of extremely high winds in the tropics and sub tropics of Jupiter, Saturn and Neptune, the persistent differential rotation of the Sun, the complex patterns of convection in the slowly-rotating mantle of the Earth, and the rapidity rotating flows in the Earth’s core. Figure 1 shows a schematic cross section of the Earth. The convective motions of the molten iron alloy in the outer core generate the main geomagnetic field. Microgravity experiments on thermal convection with a simulated central dielectrophoretic force field are important for the understanding of these large scale geophysical motions (Hart et al., 1986; Yavorskaya et al., 1984). An experimental set-up is performed to investigate the problems of thermal convection in the fluid shell between two concentric spheres with and without rotation and also with differentially rotating spheres. A central symmetric force field similar to the gravity field acting on planets can be produced by applying a high voltage between the inner and outer sphere using the effect of the dielectrophoretic force field (Pohl, 1978). To turn off the unidirectional gravitation under terrestrial conditions, these experiments require an environment of microgravity. In preparation of long-term experiments in space, several experiments have been performed under laboratory conditions as well as
under short-term microgravity conditions (Drop Tower, parabolic flights, sounding rockets). Furthermore, in preparation of the experiments, linear stability analysis has been performed to determine the critical Rayleigh and Taylor numbers for the onset of thermal convection under a simulated central force field.

Figure 1. Schematic cross section of the Earth: Thermal convective phenomena occur in the outer (liquid) core.

Nonlinear finite-amplitude convective motions have been studied numerically. Further experiments with different gap widths and supercritical up to turbulent Taylor and Rayleigh numbers of the order of the real geophysical parameters need a microgravity time of days or weeks, i.e. experiments in the Experiment Container of the Fluid Science Lab of the ISS.

In section 2 we describe the scientific programme for the GEOFLOW experiments. Design and layout constrains of the FSL and the EC as well as the Experiment Container (EC) design and the diagnostics prepared for the GEOFLOW experiment are presented in section 3 and 4. Preparatory studies and the experimental methods are described in section 5.

SCIENTIFIC PROGRAMME FOR MICROGRAVITY EXPERIMENTS

The purpose of these experiments under microgravity with central force field is to investigate the stability, pattern formation and transition to turbulence in thermally driven rotating fluids, based on complementary experimental, theoretical and numerical studies of the flow of a viscous incompressible fluid between concentric coaxially rotating spheres. We plan to focus on wide and medium gaps. In thick layers, in which the radius of the outer sphere is considerably larger than that of the inner sphere, the geophysical application is the flow in planet’s interior. The atmospheric motion of the giant planets takes place in medium gaps.

The main objectives are:

- to study experimentally the stability of the basic state and its transition and to determine the characteristics of the flow. In the project the supercritical Rayleigh number of the experiment should be detected. The stability diagram for the different states should be measured. Also states of hysteresis could be inquired. The energy transport from inner sphere to outer sphere should be measured. The characteristic wave numbers and frequencies should be determined. The influence of boundary layers or inertial layers should be detected.

- to compare theoretical predictions for the flow pattern bifurcating from trivial state, with the experiments. In the nonrotating spherical shell we expect polygon pattern of the flow field, i.e. tetrahedral symmetry for radius ratio \( \eta = 0.4 \) or cubic symmetry for radius ratio \( \eta = 0.45 \) (Chossat, 1999).
The Geoflow-Experiment on ISS – Experiment

- to compare experimental and numerical results to elucidate the physical mechanisms of instability and to understand the physical mechanisms of flow instability for different Taylor numbers (Liu et al., 2000).
- to draw comparisons between the experimental results of the flow in wide spherical shells with theoretical work on the flow in the Earth’s interior.
- to describe the transition to turbulence in distributed systems (in spherical systems: plane convection at the pole, cylindrical convection at the equator), to study the dependence on meridional coordinate.
- to study the changes of the transition scenarios to chaos and of the attractor characteristics when the parameters are changing (aspect ratio, Taylor number, Prandtl number) (Wulf et al., 1999).
- to investigate the occurrence of complex time-dependent behaviour (e.g. intermittent-like) near onset of convection, for radius ratios close to critical values.
- to set-up experiments where a forced symmetry-breaking imperfection is introduced in the system, and compare its effect with theoretical predictions (Chossat, 1975 and 1999; Chossat and Guyard, 1994 and 1996; Chossat et al., 1990 and 1999).
- to compare the theoretically predicted bifurcation scenarios with experimentally (LDV-) measured ones (Wulf et al., 1999).

THE FLUID SCIENCE LABORATORY (FSL)

The Fluid Science Laboratory (FSL) is a part in the European Columbus Orbital Facility (COF) of the International Space Station (ISS) as illustrated in figure 2. The FSL supports scientific microgravity research in the field of fluid physics by means of specific triggering and observation of phenomena inside of transparent and at the surface of opaque media. It is characterised by a high level of modularity on all experiment and facility (sub-)system levels. Specific control and data processing modes allow for quasi real time experiment operation.

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Figure 2. Principle sketch of the European Columbus Orbital Facility (COF) on ISS, left; Fluid Science Laboratory (FSL), right
The FSL enables the scientific fluid physics research in microgravity and provides in principle the following measurement tools as described in detail in (Egbers, 1999):

- Direct viewing of the experimental volume (fluid cell) with different Cameras
- Velocimetry with monochromatic and white light sheets (extension to PIV is possible)
- Electronic Speckle Pattern Interferometry (ESPI), sensitive to refractive index changes (in transmission as in reflection)
- Wollaston Shearing Interferometry (WSI)
- Holographic Interferometry (HI), sensitive to refractive index changes (in transmission)
- Shadowgraph/Schlieren method

These diagnostic methods can be operated from different observation directions (top -, bottom - and front viewing) and partly in combination/ simultaneously. The FSL consists of two main parts (figure 3): the Central Element Module (CEM) and the Optical Diagnostics Module (ODM). The CEM includes a manually accessible operational area which is designed to integrate the modular experiments in different Experiment-Containers (EC) as
The Geoflow-Experiment on ISS – Experiment 175 illustrated in figure 3(a). The Experiment-Container is a multi-user facility and contains the specific fluid dynamic experiments. The EC's are individually exchangeable. The design of the EC's considers a volume of 270x280x400mm³. The fluid experiment is housed inside the Experiment Cell which is arranged in the center of the EC housing in the crossing of the perpendicular optical axis. The windows are designed to allow a Field Of View of 80x80mm². The two optical paths cross the EC center parallel to the y-axis (front-back view) and to the z-axis (top-down view). To realise the operation of the two optical paths two moveable and four fixed mirrors are mounted in the periphery of the CEM (figure 3(b)).

THE GEOFLOW EXPERIMENT CONTAINER

On the basis of the geometrical data of the Experiment Container a special double containment Experiment Container has been designed for experiments on electrohydrodynamic effects as foreseen in the spherical gap flow experiment with central force field generation by applying a high voltage and with integrated adaption optics for interferometry or shadowgraph diagnostics (figure 4). The Facility Performance Data and the Resource Requirements of this special GEOFLOW Experiment Container are listed in table 1:

Figure 4. GEOFLOW Experiment Container: Adaption optics (up) and spherical shell system mounted on a rotary tray (down) for the integration into the FSL

The experimental cell is formed by an outer glass sphere, which can be cooled, and an inner sphere, which can be uniformly heated from within. Both spheres can be rotated as a rigid body on a rotating tray inside the container. Thermal convective pattern occur due to the interaction of rotational and density effects. The central force field is generated by applying a high voltage of 10 kV between inner and outer sphere to generate the central symmetric body force field analogous to the earth's gravity field. Due to the action of the high voltage potential on the fluid in the gap it would be desirable to use an optical observation technique for flow visualization and temperature...
measurements without tracer particles, i.e. the Schlieren-/Shadowgraph or Interferometry method. For that purpose, an adaption optics is integrated into the container as illustrated in figure 4.

At the time, three different inner radii (R₁) are possible to vary the radius ratio. As working fluid silicone oils with different viscosities are used to investigate the influence of the Prandtl number. For further experiments it is possible to rotate both spheres in the same or different direction. Thus, four parameters can be adjusted by the experimental set-up:

- Rayleigh-number: \( Ra = \frac{\alpha g d^3 \Delta T}{\nu} \), \( 10^3 < Ra < 10^7 \)
- Prandtl-number: \( Pr = \frac{\nu}{\chi} \)
  \( Pr = 8.44, Pr = 37.5 \) and \( Pr = 100 \) have been realized (depending on the test fluid)
- Radius ratio: \( \eta = \frac{R_1}{R_2} \), \( 0.34 \leq \eta \leq 0.6 \)
- Reynolds-number: \( Re = \frac{(R_1^2 \Omega_1)}{\nu} \), \( 0 < Re < 10^5 \)

For experiments with a central force field based on the dielectrophoretic effect, the outer sphere has to be coated inside with a thin layer of a semiconductor material.

<table>
<thead>
<tr>
<th>Table 1. Resource requirements for the GEOFLOW Experiment Container</th>
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</thead>
<tbody>
<tr>
<td>- accessible temperature range: ( 15°C ) to ( 35°C ) (Experiment-Container)</td>
</tr>
<tr>
<td>- temperature stability: ( 0.1°C ) (sample)</td>
</tr>
<tr>
<td>- temperature gradient: ( 1°C-25°C ) (sample)</td>
</tr>
<tr>
<td>- pulling rate: %</td>
</tr>
<tr>
<td>- sample number: 6 samples (= 6 different gap widths)</td>
</tr>
<tr>
<td>- sample dimension: ( 100mm \times 100mm \times 100mm ) (sample) ( 400mm \times 280mm \times 270mm ), FSL-TC</td>
</tr>
<tr>
<td>- diagnostics: (high speed) video-camera</td>
</tr>
<tr>
<td>- temperature measurements</td>
</tr>
<tr>
<td>- flow visualisation / PIV / LDA</td>
</tr>
<tr>
<td>- interferometry/Shadowgraph-Optics</td>
</tr>
<tr>
<td>- process environment: normal pressure</td>
</tr>
<tr>
<td>- telemetry and telecommand capability: telemetry: see FSL documentation</td>
</tr>
<tr>
<td>telecommand: see FSL documentation</td>
</tr>
<tr>
<td>- mass:</td>
</tr>
<tr>
<td>- Test-Container: 15 kg</td>
</tr>
<tr>
<td>- sample: 2 kg</td>
</tr>
<tr>
<td>- dimension: ( 100mm \times 100mm \times 100mm ) (sample)</td>
</tr>
<tr>
<td>- power (test-Container): 100 W</td>
</tr>
<tr>
<td>- high voltage (external): 100 W (10 kV, 50 to 500 Hz)</td>
</tr>
<tr>
<td>- data (telemetry, video, voice,..): telemetry, telecommand, video</td>
</tr>
<tr>
<td>- typical experiment duration: 3 hours / parameter</td>
</tr>
<tr>
<td>- 100 parameter variations / sample</td>
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<tr>
<td>- total time: 1800 hours / 6 samples</td>
</tr>
<tr>
<td>- ambient conditions (g-level, temp.,..): (high speed-) video film, photographic film</td>
</tr>
<tr>
<td>- crew time: 20 min / sample exchange</td>
</tr>
<tr>
<td>- consumables (gas, tapes, film-stripes,..) (high speed-) video film, photographic film</td>
</tr>
<tr>
<td>- stowage: 1 stowage rack for 6 samples</td>
</tr>
</tbody>
</table>
EXPERIMENTAL METHODS AND DIAGNOSTICS

Interferometry And Schlieren /Shadowgraph Techniques

The Schlieren method and the Interferometry are well known methods for flow visualization and temperature measurements, although these methods have been rarely used for flow visualization in spherical geometry. Figure 5 shows a sketch of the principle set-up of a Wollaston Shearing Interferometer in backscatter arrangement which is used for the running investigations on a plane cavity. If the Wollaston Prism is replaced by a pinhole, a slit or another aperture, the shown assembly can be used to execute Schlieren visualization (Egbers, 1999).

The Schlieren method depends on the deflection of a ray of light from its undisturbed path, when it passes through a medium with a density gradient which implements a refractive gradient, that leads to a curvature of the ray. The curvature of the ray is proportional to the gradient. Though if parallel rays of light are sent through a transmissive medium with variable density, the rays will be deflected differently in areas of different density.

The rays can also experience a phase shift. The Interferometry uses the phase shift by interfering two coherent rays from which one has passed the test cell. The displacement of the two rays is proportional to the density variation. Therefore both visualization methods show different information about the observed flow. The Schlieren method reproduces a pattern which is proportional to the observed flow. In principle, it shows mainly the first derivative of the temperature gradient, whereas the Wollaston Shearing Interferometry gives an image of the gradient. Another
important difference between both methods of visualization is that the Interferometry is much more sensible than
the Schlieren method, which in the end leads to demand a much higher quality of all optical components than
would be necessary for the Schlieren optic. First investigations have been made on a plane cavity in a laboratory
based experiment. These investigations have been done to verify if schlieren or interferometric diagnostic methods
can generally be used to visualize weak convective flows. The experiments have proved that temperature gradients
of 2 Kelvin and more can easily be visualized, which signifies that the temperature gradients of 10 Kelvin planned
for the GEOFLOW experiment can be visualized (Egbers, 1999).

Flow Visualization Technique And PIV-Technique

Because the expected flow structures occuring in the spherical Couette flow during the laminar-turbulent
transition are non-axisymmetric and in some cases non-equatorially symmetric, both for thermal and isothermal
flow, it is necessary to use an observation-technique, which provides simultaneously flow visualization of both the
azimuthal and the meridional flow. Therefore, a combination of the following two visualization methods is used:
To investigate the flow structures occuring in the meridional cross-section of the spherical annulus, a light sheet
illumination technique is employed as illustrated in figure 6. In addition, a system with a fiber-optic is applied to
visualize the polar region with the azimuthal waves. In this way, the cellular structure of the occuring vortices in the
meridional plane as well as the azimuthal and polar behavior of the arising flow pattern can be obtained (Egbers,
and Rath, 1995). Photographs or prints from video-records were taken. The pictures were taken with a CCD-camera
digitized by a frame grabber facility. The difference of the gray values between a picture of an instability and a
reference picture of the basic flow is calculated, amplified and pseudo colored for each pixel to maintain only the
structures of the instability (Wulf et al., 1999). This kind of flow visualization technique gives a global, but
qualitative view of the flow structures.

Integrated Miniaturized LDV Measuring Technique

Laser Doppler Velocimetry (LDV) is a well known non-invasive diagnostic technique in fluid research on
ground for highly precise velocity measurements. As common LDV-systems use gas lasers and have extensive
devices they are not suitable for the use in a microgravity environment. However, new developments in laser diode
based optics allow the application of miniaturized LDV-devices, so that they become practical for the integration on
Experiment-Container level of the Fluid Science Lab (FSL) as illustrated in figure 7 for the GEOFLOW
experiment.

Local velocity measurements will be carried out using an autonomous miniaturized LDV-system based on EC-
level. The following flow characteristics can be obtained as described in (Wulf et al., 1999), i.e. velocity time series
and bifurcation scenarios, autocorrelation function, power spectra, Lyapunov exponents and reconstructed

Figure 7. The application of miniaturized LDV-technique on the GEOFLOW experiment
attractors. Since LDV-systems are well established in investigations of a lot of different ground based flow
problems, it is expected that in the future of microgravity experiments in fluid dynamics a lot of experiments will as
well require this precision tool. Especially the application on unsteady phenomena will be of more and more
interest. The wide spread application of this technique is, beside its high precision and non-invasion based on the
possibility to run the system fully automatically, the very easy adjustment compared to other measurement methods
and the reliable operation in different environments. This is especially useful in a space laboratory, where
calibrations are difficult during a mission.

CONCLUSIONS

The thermal convection between spherical shells under a simulated a central force field with and without
rotation under microgravity conditions will be investigated, in addition to terrestrial experiments and numerical
simulations.

To achieve the objectives of chapter 3, different diagnostic tools will be needed. The laboratory hardware of
the GEOFLOW experiment built for earth-bound testing and optimization will prove if the proposed optical
methods can work on spherical geometries, especially in the environment of the FSL experiment container. Apart
form the scientific results, the experience with the laboratory hardware will help to construct a universal spherical
gap in the Fluid Science Laboratory, which could profit of all the different optical methods supplied by the Optical
Diagnostics Module. In addition, a miniaturized LDV-system would give more insight into the dynamics of time
dependant flows. Together with the global optical visualization methods, the LDV technique could help to answer
some of the open questions of transition phenomena of thermal convection in rotating spherical gaps.

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REFERENCES

Cardin, P., and P. Olsen, An experimental approach to thermochemical convection in the Earth’s core, Geophys.
Cardin, P., and P. Olsen, Chaotic thermal convection in a rapidly rotating spherical shell: consequences for flow in
Cardin, P., and Olsen, P., The influence of toroidal magnetic field on thermal convection in the core. Earth Planet.
Carrigan, C. R., and F. H. Busse, An experimental and theoretical investigation of the onset of convection in
Chossat, P., Bifurcation and stability of convective flows in a rotating or not rotating spherical shell, SIAM J. Appl.
Chossat, P., and F. Guyard, F., A classification of 2-modes interactions with O(3) symmetry and applications; In
Chossat, P., and F. Guyard, Heteroclinic cycles in bifurcation problems with O(3) symmetry, J. of Nonlinear
Science, 6, 201-238, 1996.
Chossat, P., Private communication, 1999.
Chossat, P., F. Guyard, and R. Lauterbach, Generalized heteroclinic cycles in sphericaly invariant systems and their


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