MHD convection and dynamo in a spherical thin shell

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By means of computer simulation, we have studied thermal convection of a magnetohydrodynamic (MHD) fluid in a thin spherical shell, between two concentric spheres of radii r=0.9 and 1.0. The inner sphere of 0 <= r <= 0.9 is an electrical conductor in a solid state. MHD equations are solved in the outer convection layer and the magnetic diffusion equation is solved in the inner solid core. We have found, in slowly rotating states, that convection motion is organized as (i) a set of multiple ring rolls, or (ii) a single spiral roll, starting from a point and ending at its antipodal point. The diameter of the roll is the width of the shell (0.1). The rolls are dynamo: magnetic fields are generated by fluid flow in them. The simulations were performed on a full-spherical grid system, called Yin-Yang-Zhong grid.

Keywords: MHD dynamo, Spherical shell, Yin-Yang-Zhong grid

MHD Dynamo by Polyhedral Convections

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We performed magnetohydrodynamic (MHD) simulations of dynamo in a rotationg spherical shell under the conditions with low Rayleigh number and low rotation rate Ω. It is known that convections in these cases are organized as polyhedra cells. Computations were done with newly developed spherical grid system called Yin-Yang-Zhong grid [Hayashi & Kageyama, JCP, 2016]. The aspect ratio of radii of the inner sphere and the outer sphere is 0.7. It was found that: (1) In the low Ω limit, basic structures of the convection are (as expected) tetrahedron or hexahedron. (2) These convection structures are robust for larger Ω. (3) Magnetic field grows for $\Omega > 0$ on both the tetrahedron and the hexahedron convections. (4) For $\Omega > 0$, down flows in the vertices of the polyhedra have spiral paths, and dynamo takes place there. (5) The dynamo disappears when Ω is increased more.

Keywords: MHD dynamo, spherical shell, Yin-Yang-Zhong grid

Investigation of Sub-Grid Scale (SGS) terms for dynamo simulations in a rotating spherical shell

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The flow in the Earth's outer core is expected to have vast length scale from the geometry of the outer core to the thickness of the boundary layer. Because of the limitation of the spatial resolution in the numerical simulations, sub-grid scale (SGS) modeling is required to model the effects of the unresolved field on the large scale fields. We model the effects of sub-grid scale flow and magnetic field using a dynamic scale similarity model. Four terms are introduced for the momentum flux, heat flux, Lorentz force and magnetic induction.

In the present study, we adapt the dynamic scale similarity methods to Calypso, which is a numerical dynamo model using spherical harmonics expansion. Spatial filtering operations is required for the scale similarity model. The spatial filtering in the horizontal directions is done by taking the convolution of the Gaussian and spherical harmonics expansion by following Jekeli (1981). The Gaussian filter is applied explicitly in the radial direction. We evaluate the SGS terms in the fluid shell using a snapshot of a fully resolved dynamo simulation using 0.4 and 1/4 coarser resolution in each direction. The evaluated SGS term evaluated has a good correlation with the SGS term directly evaluated on the fine grid to 0.4 times coarser resolution of the reference resolution. The dynamic scale similarity model does not well represent SGS terms near the outer boundary around the equator. The reason is that smaller scale flow motion is excited near the outer boundary than that for the main convective region. Consequently, simulation domain does not have enough spatial resolution to satisfy the scale similarity model near the outer boundary around equator. The scale of the convection around equator near the outer boundary controls the required resolution to work the present SGS model properly.

Keywords: dynamo simulation, sub-grid scale model

Gradual changes of an ordered flow structure in a liquid metal convection with reducing magnetic field

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Studies of magnetoconvection and rotating convection by liquid metals are both important for understanding the dynamics of flow in planetary cores. On magnetoconvection, we studied the Rayleigh-Benard convection under a horizontal uniform magnetic field by laboratory experiments (Yanagisawa et al. 2013, Tasaka et al. 2016). We have established a regime diagram of convection style on the plane of the Rayleigh number (Ra) and the Chandrasekhar number (Q). Convection regimes are classified well by the value of Ra/Q; when $Ra/Q < 1$ (strong magnetic field), the flow pattern shows steady roll structure whose axes are aligned to the magnetic field. On the other hand, it shows a vessel scale turbulent flow structure with many fluctuations when $Ra/Q > 100$ (weak magnetic field). Among these two extremes, we can identify several flow regimes, such as, oscillation of rolls, repetition of roll number transitions, reversal of the flow direction in rolls. Here we focus on the transitions process from steady laminar flow to turbulent flow by gradual decreases in the Q, at fixed values of the Ra. We performed both laboratory experiments and numerical simulations, and made up a comprehensive view of the process that the convection structure loses the initial ordered roll state. In laboratory experiments, we used an ultrasonic measurement of flow velocity profiles with newly developed transducers to achieve measurements under a strong magnetic field. In numerical simulations, we used sufficient grid points to resolve well the Hartmann layers generated at side walls of the vessel. At very high Q, the pattern shows almost 2-dimensional roll structure, but we observed the existence of small velocities of flow parallel to the imposed magnetic field. Detailed study on the distribution of this flow elucidated that it is a kind of suction generated by the circulation of 2-D rolls. With reducing the Q, this component of flow velocity is getting larger, and secondary vortices emerge at the boundaries of main rolls. Time variations of the roll structure are closely related to the migration of these secondary vortices. At smaller value of the Q, the rolls begin large amplitude of oscillation and 3-D behavior becomes dominant.

Keywords: liquid metal convection, magnetic field, flow pattern

Advection and shape transition of vortices in a rotating Rayleigh-Bénard convection

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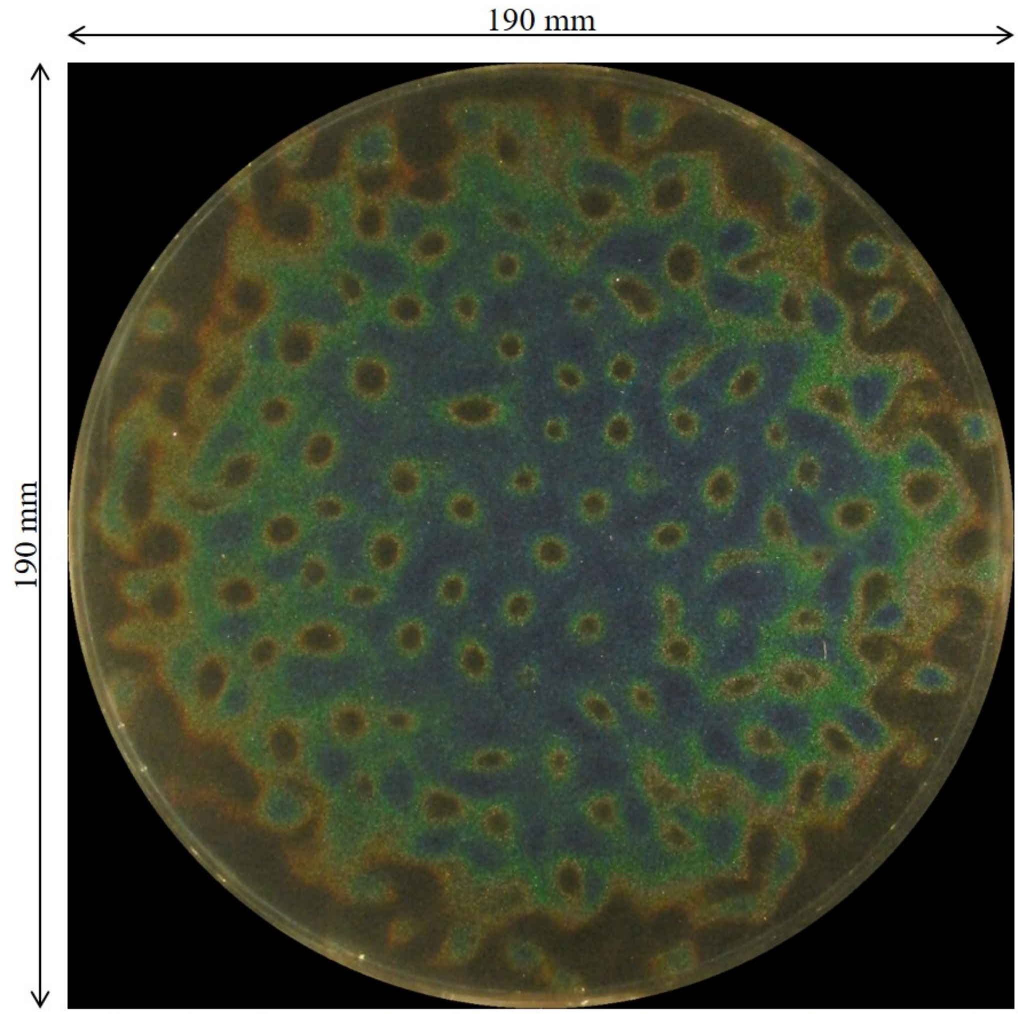
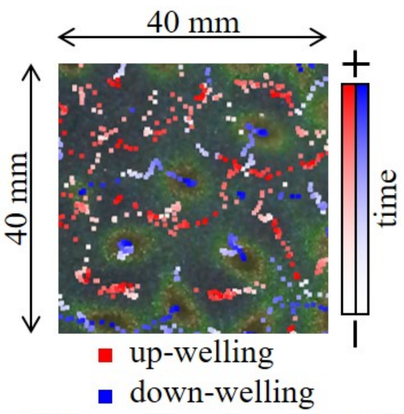
Thermal convection confined between two parallel plates is called Rayleigh-Bénard convection. In considering various fluid dynamics appearing in natural phenomena, this system is the most fundamental one to investigate from perspectives of theoretical, numerical, and experimental approaches. Taking geophysical fluid dynamics, such as atmosphere, ocean, and convection in the outer core, into consideration, the effect of background rotation should be conceived and inevitable. Certainly, the Rayleigh-Bénard convection in a rotating field induces roughly divided two fascinating events. The first one is the appearance of vortical structures because of the influence of the Coriolis force. In non-rotating fields, convection cells or rolls appear, however such structures are transformed by the Coriolis force in a rotating field. Another event is the enhancement of heat transfer because of the Ekman pumping. The phenomena appearing in rotating Rayleigh-Bénard convection are organized by three dimensionless numbers, Rayleigh number Ra, Prandtl number Pr, and Taylor number Ta. Especially, the vortex behavior under the enhancement of heat transfer is paid attention in this study. The objective is to elucidate the vortex dynamics experimentally and quantitatively.
Water suspended with temperature-sensitive liquid crystals is used as a working fluid in order to visualize vortical structures. The fluid layer is composed of an acrylic cylindrical wall with the inner diameter 190 mm and the height 40 mm, which giving aspect ratio 4.75. The fluid layer is heated from the bottom with heater and cooled from above through a glass plate with circulating water from a thermostatic bath. All the parameters are fixed at $Ra = 1 \times 10^7$, $Ta = 1 \times 10^8$, $Pr = 7.01$. Photographing is performed by 3-seconds interval from above the fluid layer by a digital camera.
From visualized images, the horizontal temperature fields are obtained by means of a kind of temperature calibration method. The unevenness in the temperature fields are regarded as the vortices. To detect vortices, the template matching, which is well known as one of the pattern recognition techniques, is performed. Additionally, detected vortices are categorized into several patterns depending on its temperature distribution shapes using the equation of ellipsoid. In this process, radius representing the size of a vortex, height expressing the temperature gap between the center and edge in a single vortex, and curvature showing the temperature gradient, can be modified and categorized. From these procedures, the coordinates and temperature distribution shapes of vortices are determined.
By tracking vortex advections for time course, the vortex dynamics is revealed. In a short time scale, the direction of vortex advection is disorderly. In a longer time scale, the path-lines of up-welling vortices draw hexagonal patterns around a down-welling vortex. In a much longer time scale, the advection is dominated in the radial direction because of the centrifugal force. Such extremely complicated vortex dynamics are observed in entire the fluid layer and thought to be caused by mutual interaction among vortices and the centrifugal force. Accordingly, further experimental studies should be performed.
Moreover, the temperature distribution shapes categorized by the vortex detection method are also tracked for time course. In accordance with the transition of the shapes, as for up-welling vortices, generation occurs near the sidewall and moves toward the center of the fluid layer. The height is getting shorter and the curvature is getting larger along the advection. On the other hand, as for down-welling vortices, generation occurs in the center and moves to the sidewall of the fluid layer. The height becomes shorter and shorter, and the curvature is getting smaller along the advection. Such transition of

temperature distribution shapes along the vortex advection seem to relate the enhancement of heat transfer.

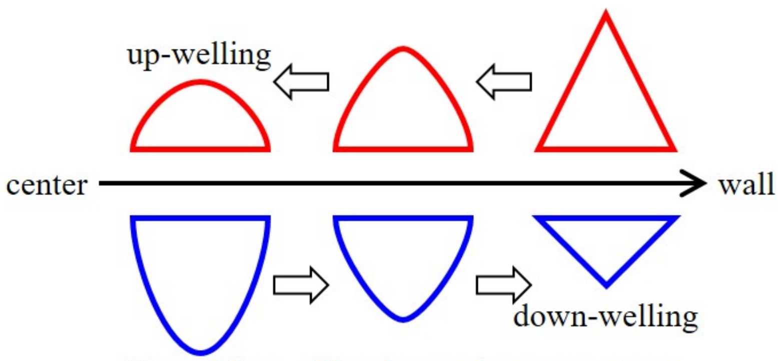
Keywords: Natural convection, Rotating field, Flow pattern, Image processing



Visualized image using temperature-sensitive liquid crystals



Path-lines of vortices for 90 s



Transition of horizontal temperature distribution shape of vortices

Experimental study for bubble waves characteristically seen in Guinness

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An analog experiment was performed to investigate the hydrodynamic behavior of a two-dimensional bubbly flow. Bubble waves, spatially periodic distribution of bubbles in bubbly flows, are sometimes observed in various natural situations. In particular, a pint of Guinness beer is a familiar and impressive example of bubble waves. The bubbles are distributed nearly uniformly at the moment when Guinness is poured in a pint glass, and a few seconds later, layers or waves of bubbles develop and propagate downward.Previous works studied the formation and development processes of these waves only theoretically. The present study provides experimental data for characteristics of bubble waves and examines the validity of mathematical models by previous works.
We conducted a series of analog experiments using water and the hollow glass particles (glass bubbles) as analog materials of a beer liquid and bubbles, respectively, presuming that the bubble waves in Guinness are caused by the relative motion between rigid spheres and liquid by buoyancy due to the density difference, but not by the formation and dissolution process of bubbles. We mixed the liquid and the glass bubbles in a rectangular container by gently shaking it. The bubble segregation or relative upward migration of bubbles starts from the homogeneous mixture as an initial state just after stopping shaking. We found that the bubble waves form during the upward segregation of bubbles under some conditions.In order to constrain factors governing the formation of bubble waves, we conducted the series of experiments with varying the volume fractions of the glass bubbles, sizes of them and the inclination of the container. We found that the bubble waves formed only when we incline the container, that is, with non-vertical side wall. If we set the container vertically, the bubble waves didn' t form. On the other hand, if we incline the container, we observed a bubble-free layer along the lower inclined wall where liquid flows downward. The wave like structure of the glass bubbles with the wave length about 7mm developed near the lower wall of the inclined container under certain conditions. We represent the condition for wave formation as a phase diagram which is a function of controlling parameters. It is important that the wave formation requires non-zero positive value of inclination, in such conditions a thin bubble-free layer near the lower wall develops.It is found that the wavy structures reached steady state after a certain period of time of transient state, and eventually the formation of waves stopped. The ratio of duration time of wave formation at steady state to total duration time is nearly constant regardless of controlling parameters. We analyzed the time development of waves and obtained wave velocity and frequency by image analysis for the movies. Waves propagated at constant velocity during a certain period of time after their formation, and slowed down before their disappearance near the bottom. They sometimes coalesced each other, unlike a solitary wave. The wave velocity at early 20s of steady state was constant at any conditions, and the wave frequency was proportional to the volume fraction of the glass bubbles. Our experimental results suggest that the bubble-free layer plays an important role in wave formation rather than the bubble nucleation and growth or diffusion, and that the wave formation can be described by the two-dimensional shallow water theory leading to the roll waves. We propose the formation mechanism of bubble waves by applying the linear stability analysis on the roll waves at the thin fluid film in an inclined channel to the bubble-free layer along the lower side wall.

Keywords: bubble wave, bubbly flow, periodic distribution of bubbles, two-dimensional flow, analog experiment

Sidewall boundary region and instability of an axisymmetric flow in a cylindrical tank with a rotating bottom

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Non-axisymmetric flows are often formed in the terrestrial and planetary atmospheres even under their axisymmetric environments. Such non-axisymmetric flows can be realized in a very simple laboratory experiment using a cylindrical tank filled with water by rapidly rotating a disk at the bottom.
In order to treat theoretically such phenomena, the axisymmetric flow as the basic state has been analyzed. The comparison of the theory with results of laboratory experiments show a slight difference of the water surface height near the side-wall boundary. Considering the angular momentum budget around this region, a corrected theory is shown which predicts the water surface elevation precisely.
Based on the obtained flow field, instability of the axisymmetric flow is investigated. Considering a problem as a shallow water system, the unstable modes are calculated, which shows some differences with the experimental results. The treatment as the shallow water system not only shifts the existence range of the unstable modes, but also may have a significant influence on the existence itself of the unstable modes, through the disappearance of the overlapping of the dispersion curves which should resonate originally.

Keywords: rotating flow, instability, shallow water waves, laboratory experiment

Concrete Buildings + Fractal Sunshade = Cool Island

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Urban concrete is considered to be a cause in the city's heat island. In fact, concrete exposed to direct sunlight in the summer is higher by 30 °C than the surrounding temperature. However, for daytime, concrete with large thermal inertia should rather play a role of suppressing the temperature rise in the city. Nevertheless, the cause of extremely high temperature is not the characteristic as a material but the shape. Artificial objects such as buildings and roads have a surface of a size in meters. In contrast, the leaves of natural trees are about several centimeters in size. Since the heat transfer rate from an object with a large surface area is small, if heat from the sun is taken in to the concrete, it must be very high temperature to release it. On the other hand, a fractal sunshade is one which is an artificial object but has a shape close to the leaves of trees and keeps the heat transfer rate to the air low. By shading the sunshine with this sunshade and utilizing the high thermal inertia inherent in concrete, the city during the day should be a cool island.

In order to demonstrate this, we set up a fractal sunshade in the scale model for urban climate (COSMO) at Nippon Institute of Technology. The experimental site COSMO has a concrete slab of 100 m ×50 m on which 512 dice-shaped concrete blocks of 1.5 m square model buildings are arranged at intervals of 3 m. Since the area of the concrete surface including the wall surface is twice the ground surface area, the bulk thermal inertia is twice that of the concrete surface. Here we set up a 20 m ×20 m fractal sunshade and compared it with a section without a shade. The fractal shade has a three-layer structure with a layer that blocks solar radiation in the morning and afternoon, in addition to the layer that has the maximum light shading ratio in the south middle time, and it maintains the light shielding ratio of about 90% almost throughout the day . For comparison, observation at the grassland adjacent to COSMO was also conducted.

Temperature observation in the grassland adjacent to the COSMO, the concrete section under the fractal shade, the concrete section under the direct sunlight were made. The temperature during the day was the lowest under the fractal shade. Looking at the vertical distribution of the temperature during the day, in the grassland and the concrete section, the temperature is higher as the closer to the ground surface and the unstable stratification is made, whereas the air is stably stratified under the fractal sunshade. It was confirmed that the concrete was working as a heat sink.

Keywords: Fractal Sunshade, Heat Island, Thermal Inertia

Singular-Value Analyses of Perturbations on a Cylindrical Vortex Sheet

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A cylindrical vortex sheet is an idealized vortex consisting of a cylinder of infinite vorticity, whose thickness is zero, and zero vorticity regions elsewhere. It is often adopted as a model for the explanation of a multiple vortex structure seen in tornado-like vortices. There, the cylindrical vortex sheet and the perturbations developing on it are regarded as a parent vortex and the secondary vortices formed within it, respectively, and linear stability of cylindrical vortex sheet against such symmetric and/or asymmetric perturbations is investigated. Since the analyzing field is zero vorticity except for the cylindrical vortex sheet of infinitesimal thickness, Bernoulli's equation is used as the governing equation.
Here, it is necessary to carry out a singular-value analysis, not an eigenvalue analysis, to detect a possible perturbation which grows most rapidly during a given finite target time. This is because such an optimally-excited perturbation is, even if the equation is linear, not necessarily the most unstable eigen mode due to a non-normality of the governing equation. In this study, therefore, a singular-value analysis is carried out instead of an eigenvalue analysis. Three norms (i.e. L2 norm, energy norm, and Sobolev norm) are adopted as indices to measure the growth of perturbations, and then analytical forms of singular-values are derived for each norm. As a result of the analyses, it is revealed that non-normal growth of the perturbations is seen in all parameter space, where the amplitude of perturbations under L2 norm is generally largest and that under energy norm is the minimum.

Keywords: singular-value analysis, cylindrical vortex sheet, multiple vortex

Numerical Experiments on Cumulus Convection in Hot and Humid Environment

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See Japanse Abstract.

Keywords: planetary atmospheres, cumulus convection, runaway greenhouse state, numerical modeling, compositional convection

Different viewpoint of researchers in science and engineering for making a wind-wave tank

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Laboratory experiments using wind-wave tank is important for investigating wave laws such as the fetch law and Toba’ s 3/2 law, and for investigating production process of sea salt aerosol and whitecap and mass/heat transfer mechanism. Recently, one of the purposes of studies using wind-wave tank is to investigate the momentum/heat transfer at extreme high wind speed under hurricane. Therefore, I will introduce the different viewpoint of researchers in science and engineering for making a wind-wave tank, and then introduce recent studies using wind-wave tank.

Keywords: laboratory experiment, wind-wave tank

