Ultrasonic Visualization of Thermal Convective Motion in Liquid Gallium Layer

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For low Prandtl number fluid, which is liquid metal, optical methods cannot be used and we attempted to visualize a convective motion in a liquid gallium layer by measuring a velocity profile in the fluid layer using UVP. Spatio-temporal behavior of a large-scale convective motion in turbulent convection was observed as a temporal variation of the velocity profile. Furthermore, simultaneous 2-axes measurement of instantaneous velocity showed axial motion of the convection roll similar to the wavy motion predicted by a stability analysis of Rayleigh-Bénard convection for low Prandtl number fluid.

Keywords: Thermal convection, Liquid metal, Low Prandtl number, Visualization

1 INTRODUCTION

Thermal convection induced by a vertical temperature gradient in a shallow fluid layer is one of the fundamental problems in fluid dynamics, thermal engineering and geophysics, but it is not well known for low Prandtl number (*Pr*) fluids. In a phase diagram constructed by Krishnamurti [1], it is expected that the convection of low *Pr* fluid easily changes from two-dimensional steady state to turbulent state via three-dimensional state and time dependent state. A temperature measurement of the convection of mercury supports this expectation. On the other hand, Rossby [2] reported that the convection of mercury has a periodic variation of Nusselt number even in the transition state at the phase diagram. Yamanaka *et al*. [3] showed that the variation is induced by a periodic fluctuation of temperature in a fluid layer in their experimental study using liquid gallium. Such periodic phenomenon might be related to a large-scale convective motion in the fluid layer. These studies, however, cannot clarify what type of the convective motion exists because the studies were made only temperature measurement at a point. Almost all studies of low Pr convection relied on such a temperature measurement because optical visualization cannot be used to observe the convective motion of opaque fluids such as liquid metal. In this study, we attempted to visualize the convective motion of low *Pr* fluid by measuring velocity profile in the fluid layer using ultrasonic velocity profiler (UVP).

We measured instantaneous velocity profiles in a rectangular container filled with liquid gallium, which has around 0.03 of *Pr*, heated from below and cooled from above. Comparison of temporally averaged velocity profiles measured at a higher or a lower position of the container told us that the convective motion is similar to two-dimensional roll as a convective motion at extremely low Rayleigh number but the rotation of the roll is not rigid as the two-dimensional roll. A spatio-temporal velocity map represented two different temporal behaviors of the rolls; one is meandering motion with keeping its size and another one is repetition of expansion and contraction. The period of such a convective motion agrees with the temperature variation in the fluid layer measured by a thermistor. Furthermore, simultaneous two-axes measurement of the instantaneous velocity profile clarified the phase delay of the temporal behavior on the roll axis.

2 EXPERIMENTAL

2.1 Liquid gallium

We used liquid gallium as low *Pr* fluid in this study. An advantage of using liquid gallium as working fluid is its safety. It has a lower vapor pressure than mercury and does not react with water like sodium. Table 1 shows physical properties of liquid gallium given by Brito et al. [4]

UVP measurement requires suspending Ultrasonic reflection particles in a fluid. We use ZrB_2 fine powder , which has 50 μm diameter and 6.17 kg/m^3 density. It was also used in other work of UVP measurement of a liquid gallium flow and gave good results [5].

2.2 Experimental setup

A container for the liquid gallium layer consists of three parts, the lateral wall, the top plate and the bottom plate. Figure 2 shows a schematic diagram of the container. The container has large aspect ratio, i.e. height L is 50 mm, width 200 mm (= $4L$) and depth 50 mm (= L). This shape of the fluid layer may be restrictive for a convective flow pattern appearing in the fluid layer. We expected that roll

Table 1 Physical properties of liquid gallium [4], where almost all value is determined at 30 °C, which is slightly larger then melting temperature, ~ 29.0 °C.

	Symbol	Unit	Value
Density	ρ	kg/m^3	6.095
Bulk modulus	β	K^{-1}	1.26×10^{-4}
Thermal diffusivity	κ	m^2/s	1.18×10^{-5}
Kinematic viscosity	ν	m^2/s	3.22×10^{-7}
Prandtl number	Pr		0.025
Acoustic impedance	Z	kg/(m^{2}s)	17.4×10^6

pattern would appear with a rotating axis parallel to *y* axis. The lateral wall of the container is Pyrex glass, which can be wet with liquid gallium very well. As acoustic impedance of Pyrex glass, $Z = 13.1\times10^6$, is very close to that of liquid gallium, an ultrasonic pulse passes easily through the lateral wall. Furthermore, faces of the both ends at which US transducer is mounted have smaller thickness, 5 mm, than other faces, 10 mm in order to reduce attenuation of ultrasound. The top and the bottom plates are made of copper and the plates are put together with 25 mm thickness acrylic plate. There is a circular channel with 12 mm diameter at the boundary of the plates. Temperatures of flowing waters in these channels were controlled by thermostatic bathes, AS-One model CH-202 and AS-One model LTB400. These water flows kept surface temperatures at the both plates constant. We kept cooling temperature T_1 at 32 °C, which is higher than the melting temperature of gallium, and varied Rayleigh number in a range of R = 200 to 800Rc by changing heating temperature T_2, where Rayleigh number R is defined as

$$R = g\beta(T_2 - T_1)L^3/(\kappa\nu) \tag{1}$$

and R_c is the critical Rayleigh number of R-B convection in a shallow fluid layer, R_c = 1707.7.

An ultrasonic transducer was held at an end and normal to the fluid container and Ultrasonic burst emitted by the transducer propagates in the gallium layer parallel to *x* direction. The burst has 4 MHz basic frequency and 5 mm effective diameter. Received ultrasonic echo was analysed by UVP, UVP monitor model Duo (Met-Flow S. A.).

3 RESULTS AND DISCUSSIONS

3.1 Flow pattern

Since liquid gallium is opaque, it is difficult to make a direct comparison between measured velocity profile and actual convective pattern. We attempt to confirm that UVP can measure convective motion, which has $O(1)$ mm/s of velocity, in transparent glycerol solution.

Figure 2 shows the results of the measurement for 28 wt % glycerol solution. Fluid layer has 200 mm width, 30 mm depth and 20 mm height. The lateral wall is Plexiglas, and the top and the bottom plate are aluminum and copper. Flowing waters, whose temperature is controlled by a thermostatic bath, keep surface temperatures constant at the top and the bottom boundary of the fluid layer. Rayleigh number determined from the temperatures at the both boundary is around 800R_c. Figure 2 (a) is a temporally averaged velocity profile obtained from 1024 instantaneous profiles, where u_x represents velocity component on *x* axis. Figure 2 shows location of the transducer and illustration of observed convection pattern. As shown in the figure, a formed convection pattern is quasi-two dimensional roll, which has the rotating axis on the vertical direction of the larger lateral wall. Convective motion is unsteady and its size temporally changes, however, the width of the roll has never become larger than the height of the fluid container. Measured velocity varies gently on the measurement direction and alternately has positive and negative value. In comparison with the observed convection pattern, such variation between positive and negative value corresponds to

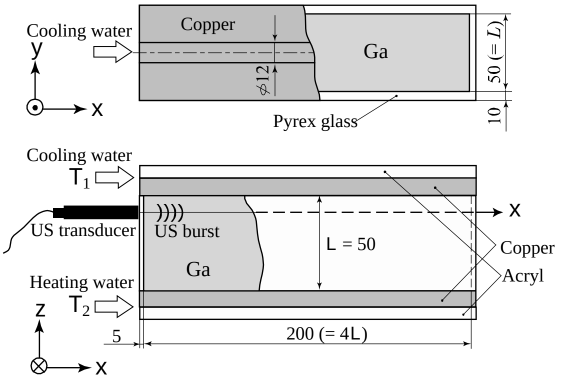
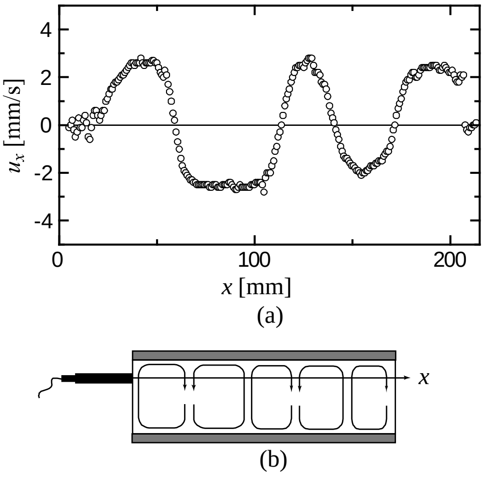


Figure 1: Schematic diagram of the experimental apparatus for the liquid gallium layer, where unit of the scale is mm



(a)

(b)

Figure 2: (a)Temporally averaged velocity profile, and (b)Sketch of observed convective motion in glycerol solution

individual motion of the roll. The obtained velocity profile should show flat distribution without boundary between the rolls if the rotation of the roll is similar to the rigid body motion. The obtained velocity, however, contains both a flat profile and a sinusoidal profile, therefore some rolls take rotation being different from a rigid body motion.

Figure 3 shows temporally averaged velocity profiles measured at higher or lower position of the fluid layer, where the horizontal axis *x* represents distance from the ultrasonic transducer. Sampling period of the profile is 80 msec and the number of profiles for the averaging is 1024. Spatial resolution on the *x* axis is 1.44 mm. Rayleigh number is $770R_c$ at which convective motion is turbulent.

At a lower position of the fluid layer, velocity varies with two periods on the measurement direction. Magnitude of measured velocity is in the range from 0 to ± 10 mm/s. At a higher position, velocity also varies oscillatory and a measured velocity profile is approximately symmetrical to that measured at the lower position. Furthermore, range of magnitude of velocity is similar.

We can easily draw a flow pattern from these velocity profiles; there are two pairs of roll arranged parallel to *y* direction. This flow pattern agrees with what is expected. At the Rayleigh number, $R = 770R_c$, state of convection is turbulence according to the flow régime diagram drawn by Krishnamurti [1]. However, such large-scale convective motion exists stably. The velocity fluctuation should contain small-scale motion but it does not appear on the measured velocity. It is difficult to detect such a motion because convective motion is too slow.

3.2 Spatio-temporal behavior

UVP can measure an instantaneous velocity profile, and we can investigate spatio-temporal variation of large-scale convective motion. Figure 4 shows spatio-temporal velocity distributions measured at $R = 428R_c$ and $770R_c$, where the horizontal and the vertical axes are time and position respectively, color code represents velocity value. Black points appearing in the figures "zero" data caused by lack of reflection particle of ultrasonic burst. A vertical cross section of these figures represents an instantaneous velocity profile and thus we can see two pairs of rolls in these figures. These velocity distributions were measured at a lower position of the fluid layer.

At $R = 428R_c$, there are four convection rolls in the fluid layer (Figure 4 (a)), where counter clockwise rotation of a roll is represented by yellow and clockwise rotation by green. The rolls sway slowly as expressed by moving boundary between yellow and green. Small-scale velocity fluctuation, which is expressed as slight color variation in the figures, is superimposed on the large-scale fluctuation. But it is difficult to discuss such small-scale phenomenon because a degree of the small-scale fluctuation is only few times of a velocity resolution of the measurement, *O*(1 mm/s), and is indistinguishable with noise. A band enclosed by broken line repeats expansion and contraction of the roll with keeping its position on *x* axis. This movement is very slow and its period is approximately 60 sec (it corresponds 0.017 Hz on frequency). At higher Rayleigh number, $R = 770R_c$, we can see a different type motion of a convection roll (Figure 4 (b)). There are also four rolls, which has the same size with that measured at lower Rayleigh numbers. But enclosed roll moves on the *x* axis periodically without changing its size in contrast to the convective motion shown in Figure 4 (a). Furthermore, a motion of neighbouring rolls of the focused roll corresponds to that at lower *R*. Convective motion becomes faster than in lower *R* and its frequency determined by Fourier analysis is 0.059 Hz. Simultaneous measurement of temperature fluctuation by using a thermistor shows the corresponding frequency on the fluctuation.

Convective motions shown in Figure 4 appear not always at each Rayleigh number, the number of roll and fluctuation pattern of roll are strongly depending

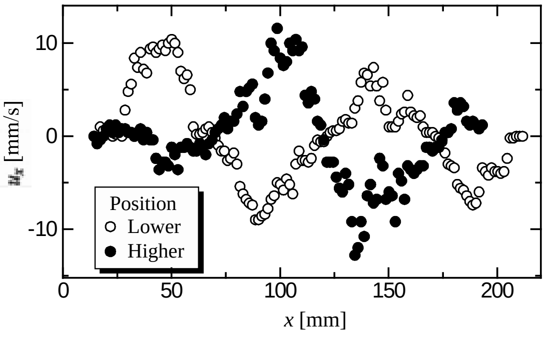


Figure 3: Temporally averaged velocity profile at a lower position or at a higher position, where *u*x represents *x*-axial velocity component of the convective motion

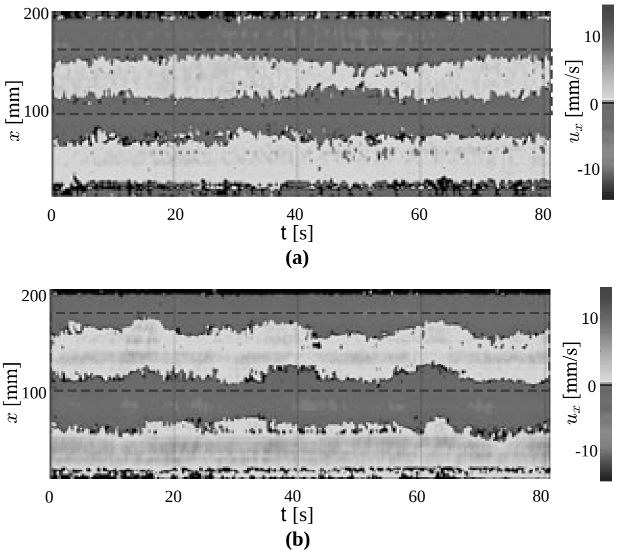


Figure 4: Spatio-temporal velocity profile; (a) $R = 428R_c$ and (b) $R = 770R_c$

on initial condition and boundary condition. We confirmed, however, that there are three states of the number of roll, which are 2, 3 and 4. Currently, it is difficult to control the number of rolls.

3.3 Axial motion of convection roll

We investigated spatio-temporal behavior of the convection roll on the rotating axis by simultaneous two-axes measurement of the instantaneous velocity profile. The measurement was realized by setting two transducers parallel at the same height of the fluid container. Figure 5 shows the results at $R = 770R_c$, where distance between the transducers is 32 mm and the location of each transducer on the y axis is 16 mm from the center. There are three rolls at the both measurement positions during measurement time and thus three rolls stably exist in the fluid layer. Motion of two rolls near the transducer is similar to the motion in Figure 4 (a), namely, the rolls repeat expansion and contraction with keeping its position on x axis. In comparison of the motion of the rolls between the figure 5 (a) and the figure 5 (b), there is a phase delay on the temporal variation of the boundary between the rolls and thus the motion of expansion and contraction has phase delay with around half period. Figure 6 shows the model of the motion of convection roll with phase delay.

Axial motion of convection roll in low *Pr* fluid was predicted by a stability analysis and figure 7 shows the sketch of the motion in which the bending of the rolls propagates along the roll axis in time. The motion expressed in figure 5 is not such a wavy motion but the propagation of the oscillation on the axial direction is similar to the motion predicted by stability analysis. The motion in this experiment may be strongly restricted by the fluid container that has small aspect ratio. Investigation about how the convective motion changes in the container with a large aspect ration is a future work.

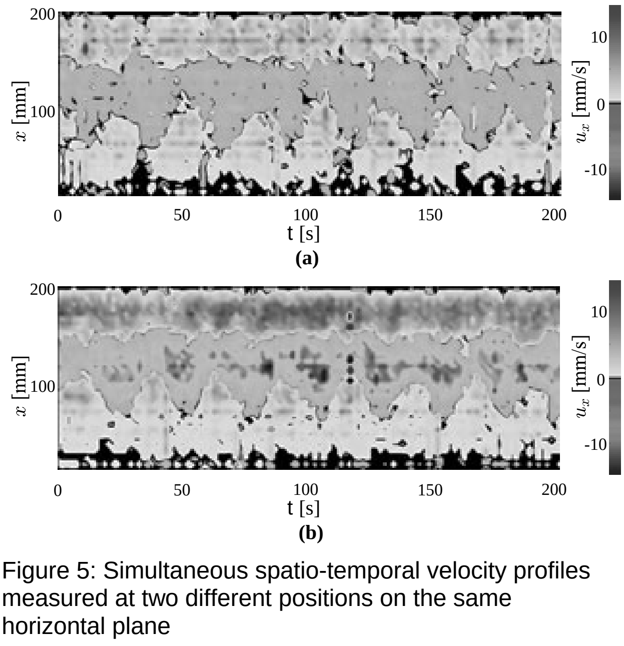


Figure 5: Simultaneous spatio-temporal velocity profiles measured at two different positions on the same horizontal plane

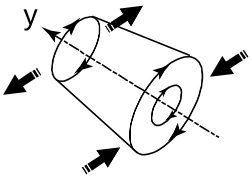


Figure 6: Schematic illustration of motion of a convection roll

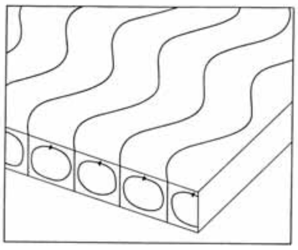


Figure 7: A qualitative sketch of oscillating convection rolls predicted by a stability analysis [6]. The bending of the rolls propagates along the roll axis in time.

4 SUMMARY

UVP was used for investigation of large-scale convective motion of low Prandtl number fluid. Liquid gallium container was designed and was constructed to solve wetting problem. Velocity profile measured at lower and higher position of the fluid layer showed convection rolls in the liquid gallium layer. Spatio-temporal velocity field measured by UVP expressed different motions of convection roll, which are repetition of expansion and contraction or periodically meandering motion. Such large-scale motion has been discussed on temperature variation at a point in the fluid layer [3], however, its spatio-temporal behavior has never been discussed on flow pattern until now and were first shown in this study. Simultaneous two-axes measurement of the instantaneous velocity profile clarified the phase delay of the temporal behavior on the roll axis.

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