Ultrasonic investigation on coupling of flows between liquid and liquid metal layers

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This study aims to clarify coupling of flows between liquid metal and other usual liquids, e.g. water or oil, in fluid dynamical systems. In past studies for two-layer Rayleigh-Bénard system where the immiscible two liquids are layered, two types of coupling were observed; these are called as “mechanical coupling” and “thermal coupling”. We investigate which type of the coupling is dominant when one of the layers is liquid metal by changing a ratio of the height of the layers and viscosity, and how the oscillation of cells in the liquid metal layer propagates to the upper liquid layer and vise versa. First we attempt to observe ideal mechanical coupling with forced rotating flow, in which the rotating motion and fluctuation in a liquid Gallium layer propagates to the upper layer via the interface by visualization and UVP measurement. And we also investigate how two types of coupling occur in this system by using water and oil for comparison.

Keywords: Ultrasonic measurement, Liquid metal, Coupling of flows, Rayleigh-Bénard convection, Two layers

1 INTRODUCTION

An experiment of thermal convection using liquid metal in a laboratory has grate importance for physical and industrial purposes, e.g. geo-science and manufacturing technology of steel or silicon. Earth’s core consists of molten Iron, and its convective motion generates the earth’s magnetic field. Oscillating convective motion in crystal growth process reduces the quality of products. We have to observe fluid motions in molten metals including molten Iron to understand its properties and mechanism. However, we have never seen fluid motions by ordinary way, e.g. optical visualization, because these are opaque. Ultrasonic Velocity Profiling, UVP, is an useful measuring technique for investigating opaque liquids [1]. UVP gives an instantaneous velocity profile and then it makes possible to observe a spatiotemporal motion of opaque liquids including molten metal [2,3]. We have investigated natural convection, especially Rayleigh-Bénard system, in a liquid Gallium layer by using UVP. The ultrasonic visualization of liquid Gallium flow confirmed that there are convective cells in this layer as a large scale motion of the convection and these cells oscillate in a horizontal direction [4].

Two-layered thermal convection has been studied for fluid dynamical interests and also for industrial applications. Some experimental and theoretical works mentioned that there are two kinds of coupling between the layers, thermal coupling (TC) and mechanical coupling (MC) [5]. Alternation between the couplings depends on the height ratio of the layers, viscosity and thermal diffusivity of fluids. Figure 1 shows a schematic motion in each coupling. In the thermal coupling (TC) the flow of the upper layer is driven by a horizontal temperature gradient at the interface between the layers induced by the convective motion in the lower layer. So the convective cells have the same rotating direction with the lower layer. The flow of the upper layer is driven by viscose effect in the mechanical coupling (MC), namely momentum transportation beyond the interface is the source of the convective motion in the upper layer. So the cells have opposite rotation for the lower layer cells.

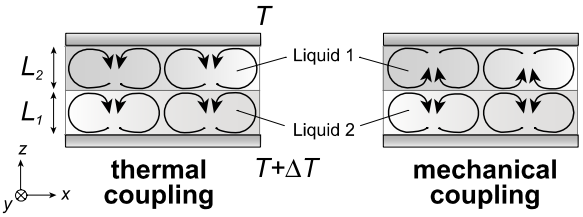

Figure 1: (Left) Thermal coupling: The upper layer fluid is driven by horizontal temperature gradient due to the convective motion in the lower layer fluid. (Right) Mechanical coupling: Motion of the upper layer fluid is induced by momentum transfer from the lower layer motion.

This study provides observations of two-layered convective motion in liquid liquid-metal layers at comparably large Rayleigh number at which the oscillating motion appears in the liquid metal layer. Liquid Gallium and ordinal transparent liquids, glycerol solution and silicone oil, were chosen as the lower layer and the upper layer fluids respectively. We investigate the alternation of the coupling and

how the oscillating motion in the liquid Gallium layer affects the fluid motion in the upper layer. Particle Image Velocimetry, PIV, was utilized to determine the 2D velocity field in the transparent fluids in the upper layer. UVP and PIV measurements at each layer were done simultaneously. Flow pattern in the layers were observed for several settings of the height ratio and viscosity of the upper transparent liquid layer.

We also provided a simple experiment to clarify effects of an oxidized film on the mechanical coupling.

2 PRERIMINALY EXPERIMENT – ROTATING TOW-LAYERED FLOW –

Liquid Gallium we use is easier to treat on experiment in a laboratory than other liquid metals, e.g. Sodium or Mercury. But it quickly oxides in ordinal atmosphere and then oxidized film at the interface between the Gallium and other fluid may affect momentum transfer. We attempt here to clarify the effect of the oxidized film by a simple experiment of a rotating two-layer flow. Table 1 shows a specification of physical properties of liquid Gallium and water. The sound speed in liquid Gallium which is required for UVP measurement is around 2860 m/s at working temperature. There is small temperature dependence and it does not affect accuracy of the measurement [4].

Table 1: Physical properties of water and liquid Gallium, each symbol indicated as density, kinematic viscosity and thermal diffusivity

	Water	Gallium
ρ [kg/m^3]	0.9982×10^{3}	6.095×10^{3}
ν [m^2/s]	1.004×10^{-6}	1.96×10^{-3}
κ [m^2/s]	1.44×10^{-7}	1.18×10^{-5}

2.1 Experimental setup and method

Figure 2 shows an experimental setup. It consists of a glass beaker put on a magnetic stirrer (0.2 T magnet). The glass has similar acoustic impedance with liquid Gallium and makes easy to propagate ultrasonic wave. The diameter of the beaker is around 90 mm. The working fluids, water and liquid Gallium, are poured into the beaker. The height of liquid Gallium layer is about 50 mm, and that of water is about 20 mm. A 4 MHz ultrasonic transducer was mounted at the side wall of the beaker with almost half height of the Gallium layer. The measurement line corresponding to the propagation line of ultrasonic wave was parallel to the horizontal center line of the beaker with small distance. UVP monitor model Duo (Met-Flow S.A.) was used for the signal processing. Fine powder of ZrB_2 was used as tracer particles; these are 50 μm in diameter and have a density of 6.17 kg/m^3. This kind of powder has also been used in other work of UVP measurements in liquid Gallium and provided good results [2]. A white light sheet created by a metal halide lamp with a cylindrical lens illuminated the upper layer close to the interface for visualization. A digital video camera was fixed above the beaker to record a movie of the illuminated layer. Drops of hydrochloric acid were poured into the rotating fluids to remove an oxidized film. Influence of removing the film on the mechanical coupling was observed by UVP and the video camera.

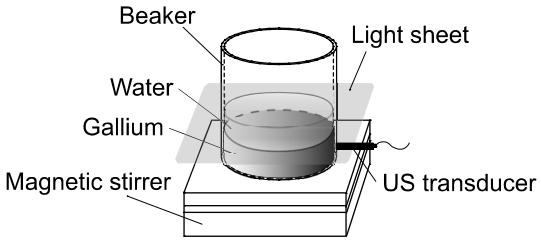

Figure 2: Schematic diagram of experimental apparatus for two-layer rotating flow

2.2 Summary of the results

Figure 3 shows a spatiotemporal velocity distribution of the liquid Gallium layer measured by UVP; at 5 seconds past the start of the measurement, drops of the acid were added into the fluid. The horizontal axis is time and the vertical axis is distance from the transducer in the measurement line. The gray scale shows the instantaneous velocity and the positive value are indicated the velocity of a direction getting away from the transducer.

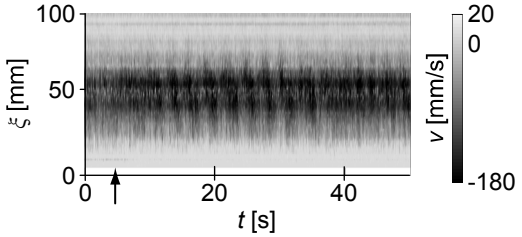

Figure 3: Spatiotemporal velocity distribution of the liquid Gallium layer; adding drops of the acid into the fluid after a lapse of 5 seconds indicated by arrow

Before adding the acid the surface of the liquid Gallium layer is covered with the oxidized film. The film is stationary and there is no momentum transmission from the liquid Gallium layer to the upper water layer. Strong shear waves are observed on the film and it may dissipate the kinematic energy. Therefore the velocity in the liquid Gallium layer is generally smaller than that after adding the acid. When we pour the acid into water the oxidized film is dissolved by deoxidization and the water layer starts to rotate by propagation of the momentum from the liquid Gallium layer. We omit here to show this behavior of the upper layer because of the lack of space, but it will be shown as movie in the presentation. Periodic oscillation with 3 sec in the

period appears after adding the acid around 20 seconds. The rotating liquid Gallium originally has such the oscillating motion due to the eccentricity of the rotating magnetic field [4]. The oxidized film, however, prevents the oscillation. Dissolving the film therefore allows a deformation and a stagger of the interface between the layers. Because of small amount of the adding the acid, the oxidized film forms again. It also prevents the periodic oscillation and the amplitude of the oscillation decreases (cf. around 40 sec in Fig. 3).

We confirmed that an oxidized film at the surface of the liquid Gallium layer fully prevents the diffusion of momentum from the lower layer to the upper layer. This condition is not suitable to investigate the mechanical coupling, but is useful to realize the perfect thermal coupling.

3 TWO-LAYER THERMAL CONVECTION

3.1 Experimental setup

A 200×50×60 mm rectangular vessel was used for the experiment of the two-layer Rayleigh-Bénard convection. Top and bottom plates are made of copper and the thickness of these plates is 5 mm. The plate was cooled or heated by flowing water through the surface provided by a constant temperature bath. All of the side plates are made of Pyrex glass and the thickness of the shorter sides at which the ultrasonic transducer is mounted is 5 mm for the penetration of the ultrasonic wave, other 10 mm.

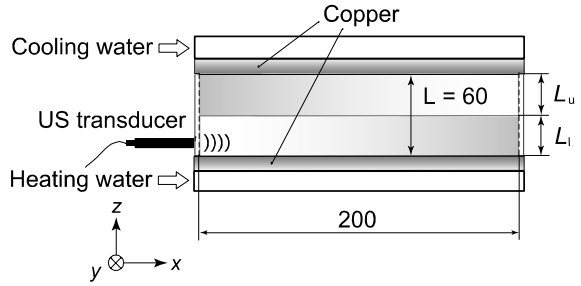

Figure 4: Schematic diagram of experimental apparatus for Rayleigh-Bénard convection

First water-oil two-layer experiment was made for understanding both of the flow pattern and the coupling phenomenon in usual fluids. 100 cSt Silicone oil and 80 % glycerol solution were used as working fluids. The physical properties of these fluids are shown in Table 2. Different tracer particles were mixed into each fluid for visualization. Particles are porous resin (1020 kg/m^3 in density and 50 μm in diameter) for water and spherical powdered resin (981 kg/m^3 in density and 180 μm in diameter) for Silicone oil. Temperature difference between the plates, defined as ΔT, was changed as 0.5, 1, 2, 4, 8, 16 degrees Celsius. A green laser light sheet created by a 50 mW Nd YAG Laser with a cylindrical lens illuminated the vertical cross section of the layers. Several pictures of the visualized motion were taken by a digital camera and PIV analysis was made on the pictures.

Subsequent measurement of liquid Gallium-liquid two-layer flow used 50 % glycerol solution. UVP and PIV measurements were done simultaneously. The transducer was put at the side wall near the bottom of the vessel, and the picture of the upper transparent layer was taken as the same way of water-oil experiments. A height ratio of the layers, Γ = L_u/L_l (here L_u and L_l are height of the upper and the lower layer.), was varied for several values but results in the case of Γ = 2/3 are shown here.

PIV analysis was utilized to determine the motion in the transparent liquids. Fundamental PIV algorithm, cross correlation between two particle images, was used. It generally has a disadvantage on the spatial resolution in contrast with its easy handling. But it does not affect this study because the phenomenon observed here is still laminar. The velocity is calculated from particle moving distance and time interval of these pictures, 1 sec in this study.

Table 2: Physical properties of glycerol solution (GS) and Silicone oil

	80% GS	50% GS	Silicone oil
ρ [kg/m^3]	1.208×10^3	1.125×10^3	0.965×10^3
ν [m^2/s]	49.57×10^{-6}	5.364×10^{-6}	100.0×10^{-6}
κ [m^2/s]	7.82×10^{-8}	10.4×10^{-8}	10.94×10^{-8}

3.2 Results and discussions

The experiment with transparent liquids shows a typical flow pattern of the coupling. Figure 5 shows an instantaneous velocity vector field calculated by PIV. Temperature difference is 4 degrees Celsius and height ratio is 0.5. In velocity vector field gray scale shows the amplitude of velocity; a darker arrow shows a larger velocity. In each layer certain convective cells exist. The direction of the horizontal flows is opposite in both sides of the interface, and the vertical flow has the same position and direction. This therefore shows the thermal coupling (cf. Fig.1). The horizontal length of the cells in such a system usually becomes smaller than the height of the fluid layer. The cells in the upper layer, however, have larger horizontal length than the height.

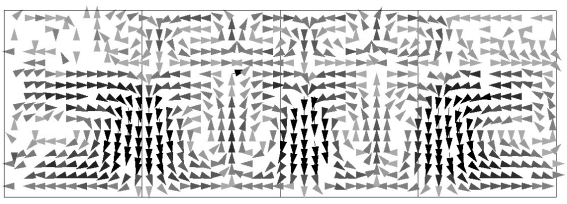

Figure 5: Instantaneous velocity vector field calculated by PIV analysis; temperature difference ΔT = 4 K and height ratio of the layers Γ = 0.5

The upper layer cells near the side walls are unclear than the other cells because there is no clear

horizontal temperature difference due to the influence of the side boundary. These indicate that the fluid motion in the upper layer is dominated by the convective motion in the lower layer.

Figure 6 shows (a) instantaneous velocity vector field of the upper glycerol solution layer and (b) spatiotemporal velocity distribution of the liquid Gallium layer. This state is before adding the acid into the upper fluid, i.e. the momentum transfer from the lower to the upper layer is prevented by the oxidized film. The horizontal scales of the figures roughly correspond. In the liquid Gallium layer, the velocity changes from negative to positive or vice versa at the positions around 50, 120 and 160 mm. These positions roughly correspond to the positions at which the boundary of the cells exists in the upper layer. The flow direction of the liquid Gallium layer at the boundary estimated from the velocity distribution is the same to that of the upper layer (see Fig.6 and Fig.7). This therefore mentions that the thermal coupling is there as our expectation (see Fig. 7). Furthermore the spatiotemporal velocity distribution in the liquid Gallium layer shows periodic oscillation of the cells, and this layer behaves as the liquid Gallium single layer [4].

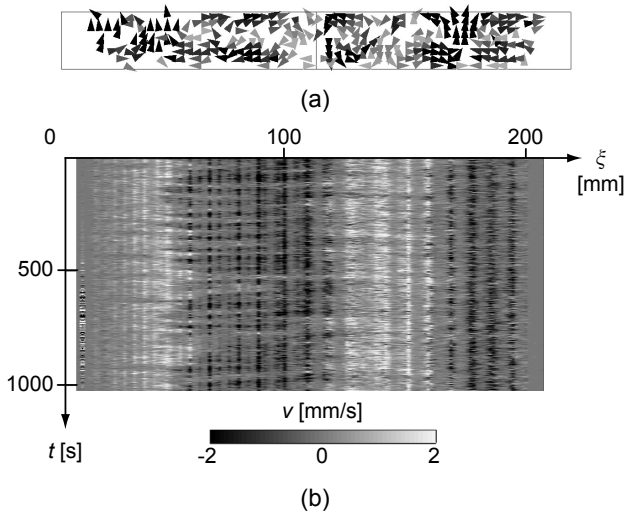

Figure 6: (a) Instantaneous velocity vector field in the glycerol solution layer; (b) spatiotemporal velocity distribution in the liquid Gallium layer before adding the acid, where the temperature difference is ΔT = 10 K

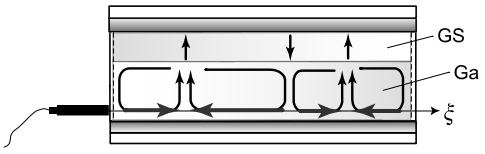

Figure 7: Schematic illustration of the flow pattern in the liquid Gallium layer

Figure 8 shows the fluid motions in the layers after adding the acid. In both layers, the velocity becomes small in comparison with that before adding the acid. It is confirmed that the several convective cells exist in the upper layer but the flow near the interface weakens independently from the convective motion. Dissolution of the oxidized film allows the momentum propagation: It reduces rotating velocity of the cells in the liquid Gallium layer and the horizontal temperature gradient. Finally the motion due to the thermal coupling is prevented. The cells in the upper layer may not be driven by the couplings, because the motion of the cells seems independent from the motion in the lower layer.

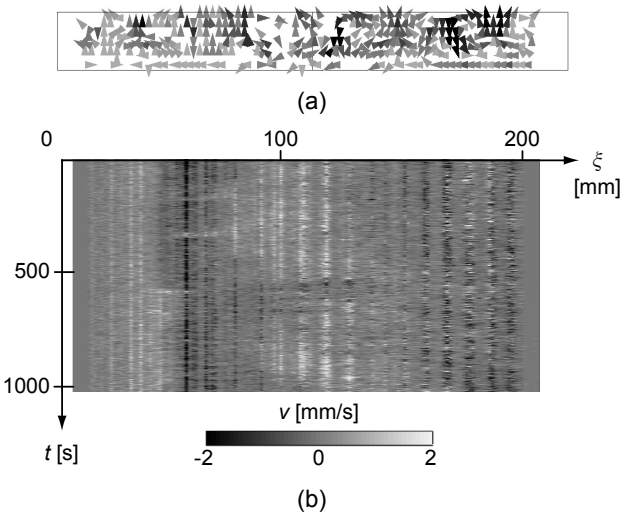

Figure 8: (a) Instantaneous velocity vector field in the glycerol solution layer; (b) spatiotemporal velocity distribution in the liquid Gallium layer after adding the acid

CONCLUDING REMARKS

We investigated the coupling of flows between liquid and liquid metal layers. It was confirmed in the two-layer rotating flow that the oxidized film formed on the liquid Gallium layer fully prevents the momentum transmission between the layers. We realized and observed the perfect thermal coupling utilizing the oxidized film. Effects of the momentum transmission in the thermal coupling were observed by dissolving the film using the acid. The transmission weakens the motion in the lower layer and allows the independent motion in the upper layer from the lower layer.

REFERENCES

[1] Takeda Y: Measurement of velocity profile of mercury flow by ultrasound Doppler shift method, Nuclear Tech. 79 (1987) 120-124.

[2] Brito D, *et al*.: Ultrasonic Doppler velocimetry in liquid gallium, Exp. in Fluids 31 (2001) 653-663.

[3] Mashiko T, *et al*.: Instantaneous measurement of velocity fields in developed thermal turbulence in mercury, Phys. Rev. E 69 (2004) 036306.

[4] TASAKA Y, *et al*.: Ultrasonic visualization of thermal convective motion in a liquid gallium layer, Flow Meas. Inst. 19 (2008) pp.131-137.

[5] Michael M. Degen, *et al*.: Time-dependent patterns in the two-layer Rayleigh-Bénard system, Phys. Rev. E 57 (1998) 6647- 6659