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Experimental study of liquid metal flows under volute traveling magnetic fields

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Abstract
Two kinds of volute traveling magnetic fields were simultaneously imposed on free surface of molten gallium. These fields drove an outward radial flow over 30 cm/s with small circumferential velocity component near the free surface of the molten gallium. Diverging radial flow causes upward component of the velocity near the surface. It was induced in wide area $r < 70$ mm in the vessel of 180 mm diameter. The upward component of the velocity was estimated to be 2−3 cm/s. Gallium in the vessel circulates once per 6 seconds. This surface stirrer with soft-magnetic ferrite cores performed continuous operation over 30 minutes that is much longer than the operation time of the coreless surface stirrer. This stirrer is expected to enhance interfacial reactions at slag/metal interface when it is applied to a ladle in steel making.

Key words : Electromagnetic stirrer, Traveling magnetic field, Slag/metal interface

Introduction

Reactions at slag/metal interface in ladles are remarkably influenced by stirring of melt. One of the most effective stirrers is ASEA-SKF ladle furnace [1], [2]. Its disadvantage is expensive cost of the ladle made of stainless steel that enables penetration of the traveling magnetic field to the melt. In order to avoid this difficulty, Suzuki *et al.* [3], [4] proposed an electromagnetic stirrer that drives slag/metal interface in outward direction as shown in Fig. 1. This outward flow produces new-growth interface and induces upward flow that supplies unreacted melt to the interface.

Three-phase coreless co-axial coil in Ref. [3] generates remarkable heat. Operation time of the coil is limited to 2−3 minutes under an oil cooling condition. Another disadvantage of the coreless co-axial coil is short distance between the coil and the surface of molten metal. It depends on the wavelength of the magnetic field, namely difference between the outer radius and the inner radius of the three-phase coil. In the experimental study in Ref. [3], the wavelength of the magnetic field is 28% of the bath diameter and the air gap between the coil and melt surface is 3% of the bath diameter. It is necessary to elongate the air gap when this stirrer is applied to slag/metal interface.

An electromagnetic stirrer driving molten metal surface in outward direction is developed in this study. Soft-magnetic ferrite cores are used in this system. This surface stirrer aims continuous operation by reducing heat production by coil current. This stirrer generates two kinds of volute traveling magnetic fields. The wavelength of the volute magnetic field is longer than that of the radially traveling magnetic field by coaxial coilds. Longer wavelength elongates effective distance of the magnetic field from the coils. One of the volute magnetic fields rotates in clockwise direction and the other rotates in counterclockwise direction. Superimposition of these two fields generates outward flow with small circumferential component of the velocity. This outward flow induces upward flow near the surface. This upward flow is expected to enhances reactions at slag/metal interface when the stirrer is applied to a ladle in steel making.

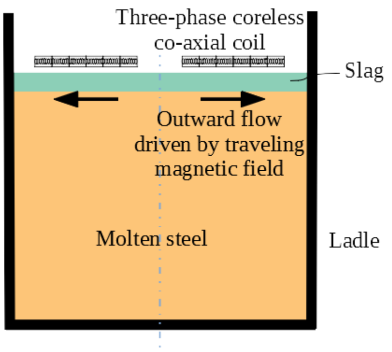

Fig. 1: Electromagnetic stirrer driving slag/metal interface in outward direction.

Experimental apparatus

Figure 2 shows coils, cores and yoke of soft-magnetic ferrite. Coils 1 consist of 6 sets of 4 coils in series connection shown by red lines in Fig. 3, while Coils 2 consist of 6 sets of 4 coils in series connection shown by blue lines in Fig. 3. The coil sets of Coils 1 are connected to a three-phase inverter system by a star connection, and the coil sets of Coils 2 are connected to another three-phase inverter system by a star connection. Magenta arrows in Fig. 3 show the traveling direction of the magnetic field by Coils 1, while cyan arrows show the traveling direction of the magnetic field by Coils 2. Two inverter systems are independent each other. Coils 1 and Coils 2 produce two-pole volute magnetic fields that rotate in opposite direction each other. Both of them are simultaneously outward traveling magnetic fields.

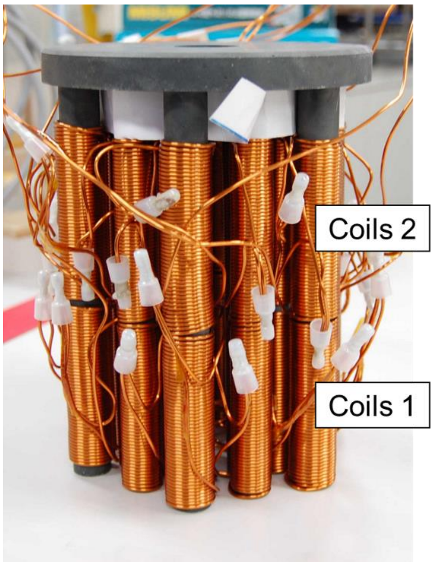

Fig. 2: Side view of the stirrer.

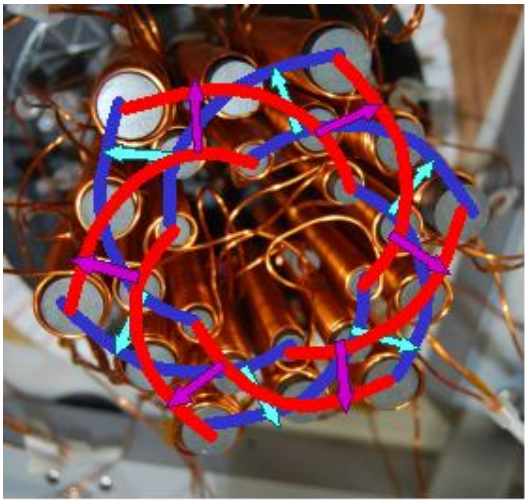

Fig. 3: Bottom view of the stirrer. Red and blue lines show volute connections of Coils 1 and Coils 2, respectively. Magenta and cyan arrows show traveling direction of magnetic fields by Coils 1 and Coils2, respectively.

Root-mean-square value of the vertical component B_z of magnetic flux density is measured as shown in Fig. 4 and 5. Measurable AC magnetic field by our instrument is limited to sinusoidal signal. Hence a three-phase variable transformer connected to 50 Hz power supply was used in this measurement, though two PAM inverter systems are used in stirring experiments of molten gallium as stated below.

Figure 4 shows distribution of root-mean-square value of B_z by Coils 1 below 9 mm distance from the end of core z_{core} when $I = 20$ A. Considerable nonuniformity is caused by cores. Figure 5 shows relation between the distance $z_{\mathrm{core}} - z$ and root-mean-square value of B_z at $r = 60$ mm when $I = 20$ A. The magnetic flux density is inversely proportional to the distance in this range. Decreasing rate with z is moderate compared with the coreless co-axial coil in Ref. [3]. Value of B_z by Coils 2 is about a half of that by Coils 1, because flux leakage of Cols 2 is remarkable.

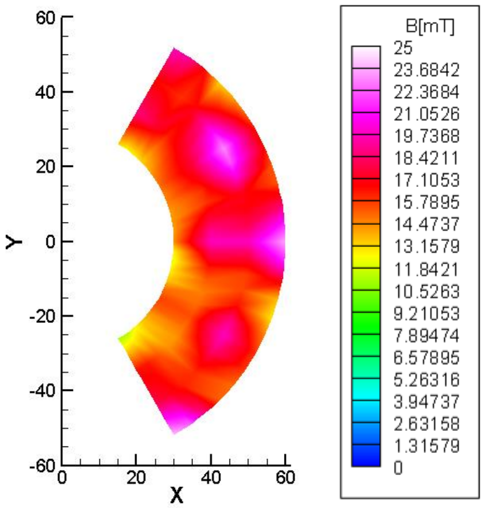

Fig. 4: Distribution of root-mean-square value of the vertical component B_z of magnetic flux density by Coil 1 below 9mm distance from the core end when $I = 20$ A.

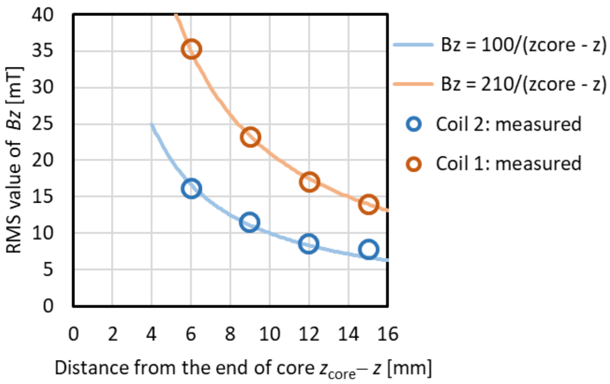

Fig. 5: Distribution of root-mean-square value of the vertical component B_z of magnetic flux density at $r = 60$ mm when $I = 20$ A,

Fig. 6: Experimental apparatus for stirring of molten gallium.

Table 1: Conditions of inverter-coil system.

Coils 1	540 Hz	43 V	10.0 A	counterclockwise
Coils 2	460 Hz	130 V	11.8 A	clockwise

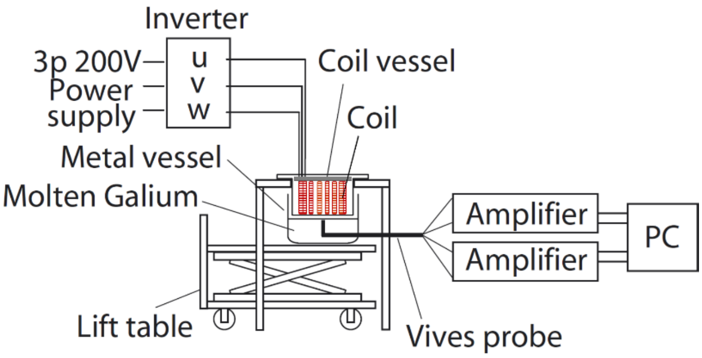

Fig. 7: Schematic of experimental system.

Figure 6 shows the experimental apparatus for stirring of molten gallium. Inner diameter of the cylindrical vessel is 180 mm and molten gallium depth is 75 mm. Distance between the end of cores and gallium surface is 6 mm. The velocity of molten gallium was measured at 5 mm below the surface. Conditions of inverter-coil system are shown in Table 1. The frequency and the voltage values in Table 1 are set points, while the currents are typical values measured in experiments. Figure 7 shows schematic of experimental system.

Radial component v_r and circumferential component v_θ of the velocity were simultaneously measured by Vives probe shown in Fig.8. This probe consists of one permanent magnet and four small electrodes as shown in Fig.9. Low pass filters in amplifiers for Vives probe were used. The cut off frequency of them is 10 Hz. Furthermore, measurement data of velocity were obtained in intervals in the following operation sequence: (35 s stirring) $-$(3 s interval) $-$(27 s stirring) $-$(3 s interval) $-$(27 s stirring) $-$(3 s interval). During stirring periods, velocity measurement is impossible because of noise from three-phase inverter systems.

Fig. 8: Vives probe.

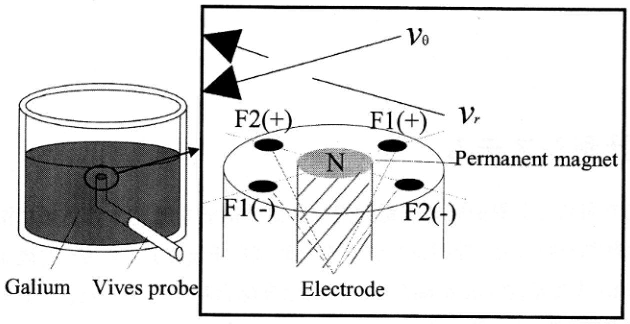

Fig. 9: Velocity components measured by Vives probe.

Experimental resutls

Figure 10 shows measurement results of the horizontal component v_x of the velocity along x axis. The radial component v_r is equal to v_x where $x > 0$, and v_r is equal to $-v_x$ where $x < 0$. The maxmum value of v_r was greater than 30 cm/s.

The averaged value of circumferential component v_θ was -0.1 cm/s and the standard deviation of v_θ was 1.5 cm/s. Rotational forces by Coils 1 and Coils 2 are almost canceled out each other in the conditions of Table 1. Consequently, hollow of free surface did not observed. This property is necessary for actual stirring of molten metal with slag layer in a ladle.

Coil current increased with temperature increasing of the coil system when voltage of inverter was fixed. Experimental data shows that there was no correlation between the coil current and the velocity of molten gallium. These facts suggest that the volute traveling magnetic field of this study is proportional not to the coil current but to the voltage of the coil. The coil current increasing is presumed to be an automatic compensation for decreasing of magnetic permeability of the ferrite cores with temperature increasing.

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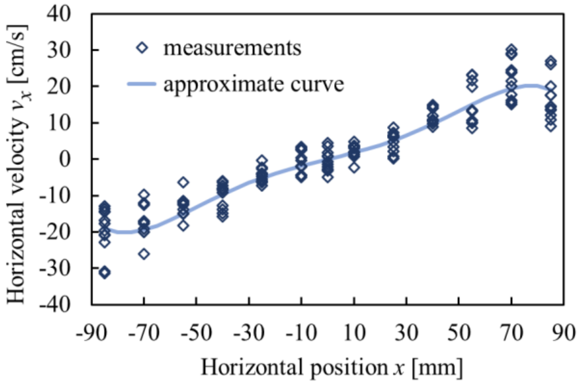

Fig. 10: Horizontal component v_x of the velocity along x axis . The radial component v_r is equal to v_x where $x > 0$, and v_r is equal to $-v_x$ where $x < 0$.

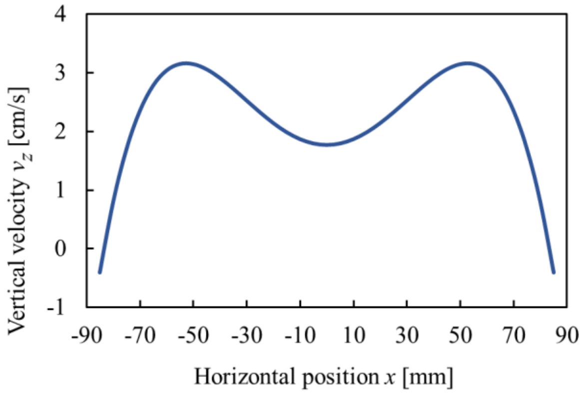

Fig. 11: Distribution of v_z that is derived from Eq.(2) and the approximated curve of v_r in Fig. 10.

The surface stirrer developed in this study performed continuous operation over 30 minutes that is much longer than the operating time of the coreless surface stirrer[3].

Let us estimate vertical component v_z. Continuity equation for axisymmetric flow is given as follows:

$$\frac{1}{r}\frac{\partial r v_r}{\partial r} + \frac{\partial v_z}{\partial z} = 0. \tag{1}$$

Integrating this equation from the position z of the Vives probe to the free surface z_{face}, we obtain

$$v_z(r,z) = v_z(r, z_{\text{face}}) + \int_z^{z_{\text{face}}} \frac{1}{r}\frac{\partial r v_r}{\partial r} \approx (z_{\text{face}} - z) \times \left(\frac{1}{r}\frac{\partial r v_r}{\partial r}\right)_{z_{\text{face}}} \tag{2}$$

where we assume that v_r does not depend on z in this range. Figure 11 shows distribution of v_z that is derived from Eq.(2) and the approximated curve of v_r in Fig. 10. The maximum value of the estimation of v_z is more than 3 m/s. The ratio of the vessel volume to the upward flowrate through the area of $r < 70$ mm gives the characteristic period of circulation. It is estimated to be 6 s.

Conclusion
An electromagnetic stirrer driving molten metal surface in outward direction is developed. Soft-magnetic ferrite cores are used in this system. This stirrer generates two kinds of volute traveling magnetic fields. One rotates in clockwise direction at 460 Hz and the other rotates in counterclockwise direction at 540 Hz. Superimposition of these two fields generated outward flow over 30 cm/s with small circumferential velocity component near the surface in molten gallium. Upward component of the velocity near the surface was induced in wide area $r < 70$ mm in the vessel of 180 mm diameter. The upward component of the velocity was estimated to be 2–3 cm/s. Gallium in the vessel circulates once per 6 seconds. This surface stirrer performed continuous operation over 30 minutes that is much longer than the operation time of the coreless surface stirrer. The electromagnetic stirrer in the present study is expected to enhance interfacial reactions at slag/metal interface when it is applied to a ladle in steel making.

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