Experimental study of liquid metal flows under volute traveling magnetic fields

K. Ueno1, T. Kamada2

1 Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
2 Tohoku University, 6-6-01 Aobayama Aoba-ku, Sendai 980-8579, Japan

Corresponding author: uenok@iwate-u.ac.jp

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 interface generation 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 coils. 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.

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.
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 $z_{core} - z$ 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 Coils 2 is remarkable.

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.

![Fig. 2: Side view of the stirrer.](image1)

![Fig. 3: Bottom view of the stirrer.](image2)

![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.](image3)

![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,](image4)
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.

Radial component $v_r$ and circumferential component $v_\theta$ 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.

### Experimental results

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 maximum value of $v_r$ was greater than 30 cm/s.

The averaged value of circumferential component $v_\theta$ was $-0.1$ cm/s and the standard deviation of $v_\theta$ 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.

### Table 1: Conditions of inverter-coil system.

| Coils          | Frequency | Voltage | Current  | Rotation   |
|----------------|-----------|---------|----------|------------|
| Coils 1        | 540 Hz    | 43 V    | 10.0 A   | counterclockwise |
| Coils 2        | 460 Hz    | 130 V   | 11.8 A   | clockwise  |
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:

\[
\frac{1}{r} \frac{\partial r v_r}{\partial r} + \frac{\partial v_z}{\partial z} = 0.
\]

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

\[
v_z(r, z) = v_z(r, z_{\text{face}}) + \int_{z}^{z_{\text{face}}} \frac{1}{r} \frac{\partial r v_r}{\partial r} \approx (z_{\text{face}} - z) \left( \frac{1}{r} \frac{\partial r v_r}{\partial r} \right)_{z_{\text{face}}}
\]

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.

**Acknowledgment**

The authors are grateful to Takeshi Suzuki, Tsutomu Ando, Jinya Sato, Shogo Arai, Masahide Watabe and Hiromune Morikawa for collaboration on the early stages of this work. This work was supported by JSPS KAKENHI Grant Number JP14702053.

**References**

1. J. Szekely and K. Nakanishi, Metallurgical Transactions B, 6 (1975), 245-256
2. S. Chung, Y. Shin and J. Yoon, ISIJ International, 32 (1992), 1287-1296
3. T. Suzuki, K. Ueno and S. Taniguchi, Proc. Int. Symp. EPM2006, (2006), 200-205
4. K. Ueno, T. Suzuki and S. Taniguchi, Proc. Int. Symp. EPM2006, (2006), 311-315