Electromagnetic flow rate measurement in molten tin circulating in a closed-loop test system

Z. Lyu, Ch. Karcher, Y. Kolesnikov, Th. Boeck
Institute of Thermodynamics and Fluid Mechanics, Technische Universität Ilmenau, P.O. Box 100565, D-98684 Ilmenau, Germany

Corresponding author: christian.karcher@tu-ilmenau.de

Abstract
Flow rate measurement in molten metals at elevated temperatures is still a challenging task in metallurgic application. Due to the opacity and chemical aggressiveness of such melts, non-contact and non-invasive electromagnetic methods are of special interest. In order to develop and to test such methods under controllable laboratory conditions, during the last years at TU Ilmenau we have built up and instrumented the test facility TINTELO (tin test loop). TINTELO is a closed loop facility made of stainless steel in which molten tin at a temperature up to 350°C circulates in the horizontal plane. The flow is driven by an electromagnetic pump based on rotating permanent magnets. The rotation frequency of the pump can be fixed at up to 60 Hz providing a mass flow rate of 17.5 kg/s which corresponds to a Reynolds number of Re = 2 \times 10^5. TINTELO is instrumented with both a Lorentz force flowmeter and a wall potential flowmeter. The Lorentz force flowmeter measures the force which the electrical conducting moving molten tin exerts on a system of permanent magnets arranged outside of the loop. This force is the counter force to the well-known braking Lorentz force that is proportional to the melt flow rate. Moreover, the wall potential flowmeter records the electric potential difference between two electrodes inserted in the conducting wall of the loop. This potential difference, induced by the moving melt when interacting with an externally applied magnetic field, is proportional to melt velocity. In this paper we present the design and the instrumentation of TINTELO, the calibration methods for the used flowmeters and first results of the flow rate test measurements.

Key words: liquid tin, Lorentz force flowmeter, wall potential flowmeter

Introduction
Electromagnetic flow measurement techniques are promising tools to meet the demand of metallurgic industry of controlling and metering liquid metal melt flow under production conditions. However, field tests are expensive, hard to manage and hard to perform under the very harsh ambient conditions including high temperatures, mechanical vibrations, electromagnetic noise, dust, and wind, among others. Hence, before integrating such methods in the production line, it is favorable to develop and to test such techniques under controllable laboratory conditions. In such laboratory test stands usually low-melting metal alloys are used as test melts including GaInSn, NaK, PbLi, and Wood’s metal. However, such substitutes show also some drawbacks like high price, toxicity, or even flammability when handled carelessly. Hence, at TU Ilmenau we have decided to build up a liquid metal test facility operating with tin showing a melting temperature of 232°C. The test facility is named TINTELO (tin test loop). The main goal is to develop and to test the non-contact electromagnetic flow measurement technique called Lorentz force velocimetry (LFV) [1]. This technique has already been applied in several field tests with liquid aluminum and liquid steel [2], [3], [4]. The measurement principle is based on the fact that in electrically conducting fluids eddy currents are induced when the melt flow interacts with an externally applied magnetic field. In turn, these eddy currents interact with the field to generate within the melt Lorentz forces. This force tends to break the flow and is proportional to the flow rate. The scaling relation for the magnitude FL of this force reads as

\[ F_L = \sigma QB^2L, \]  

where \( \sigma \) is the electrical conductivity, \( Q \) the flow rate, \( B \) the magnetic flux density and \( L \) a characteristic length. In LFV the counter force to this force, acting on the externally arranged magnetic field system is measured using a Lorentz force flowmeter (LFF). In this paper we apply this technique to flowrate measurement in liquid tin using the test facility TINTELO. The present study is organized as follows. First, we describe the used test facility TINTELO and its instrumentation. Secondly, we present some details of the calibration of the meters used. Next, we show some first results on flow rate measurement. Finally, we shall give a short summary of the main conclusions.

Test facility TINTELO
A schematic sketch of TINTELO is shown in Fig. 1, while Fig. 2 provides a photograph of the test sections. 1100 kg of pure tin are molten by induction heating in storage tank 1. The typical operation temperature is 350°C. Then the melt is...
partly transferred into storage tank 2 in order to start the filling process. Here, using a vacuum pump, we first evacuate the piping of the test facility from Argon which is used to avoid oxidation. Upon opening of the valve, the molten tin flows into the loop. The test section is completely filled when the melt reaches the expansion tank arranged at the very top of the facility. The melt flow is driven by an electromagnetic pump based on rotating permanent magnets. The frequency of the pump can be fixed at up to 60 Hz providing a mass flow rate of up to 17.5 kg/s. The pipes are made of non-magnetic stainless steel and have an inner diameter of 72.1 mm (DN65). Thus, within TINTELO we can reach flow Reynolds numbers of up to $\text{Re} = 2 \times 10^5$ which are typical in industrial applications. As it can be seen in Fig. 2, all parts of the facility are thermally well insulated to avoid freezing. Critical parts are even encased by electrical heating jackets.

Depending on the mode of operation, respective valves are set to serve either the horizontal test section or the vertical test section. The horizontal test section is designed as channel with rectangular cross-section and a movable top plate. By that, either closed channel flow or open channel free-surface flow can be established in order to meet flow conditions that are typical in the production of secondary aluminium. The vertical test section is designed as a pipe in order to model flow condition typical in continuous casting of steel, i.e. the flow through the submerged entry nozzle. However, in the present study only the horizontal test section is in operation.

The horizontal test section is equipped with a Lorentz force flowmeter (LFF), see Figs. 2 and 3. A LFF basically consists of two blocks of permanent magnets, connected by a yoke, and an attached force sensor based on digital strain gage. This magnet system provides a magnetic flux density of about 150 mT. The LFF is mounted on the top of the horizontal test section in such a way that a spanwise field is generated that penetrates the entire cross-section of the melt. Thus, as shown in Fig. 3, the measured force acting on the magnet system and pointing in the flow direction is the counterforce to the flow-braking Lorentz force.

As a reference measuring device we use a wall potential flowmeter (WPF) which is positioned between pump and test sections, see Figs. 1 and 4. The WPF consists of a pipe made of stainless steel. In the wall of this pipe two potential probes (electrodes) are inserted. The measurement principle is based on the fact that upon the interaction of the
melt flow and a spanwise magnet field, an electric potential difference $\Delta \phi$ across the pipe is induced. This potential difference is proportional to the mean melt velocity $V$ according to the relation

$$\Delta \phi \sim V D,$$  \hspace{1cm} (2)

where $D$ is the pipe diameter. For proper operation of the WPF it is essential to have very good hydromechanic and electrical wetting conditions between the melt and the inner pipe wall. We solved this problem by soldering the inner pipe wall with a thin layer of tin.

**Calibration procedure**

The calibration of the LFF is performed by a dry procedure. Here, solid metallic bars of known cross-section and electrical conductivity are pulled at controlled speeds through the LFF. As expected from Eq. 1, results show a strict linear relationship between the measured force and the pulling speed. The obtained data can be transformed to construct the calibration curve under wet conditions. Details of this procedure are given elsewhere [5], [6], [7]. The calibration curves of the WPF and the electromagnetic pump are shown in Figs. 5 and 6. The WPF was calibrated using the test melt GaInSn at known flowrate. However, the data can be directly transferred to liquid tin as the conductivity ratio between wall and melt remains nearly the same and effects of temperature do not matter. As shown in Fig. 5, according to Eq. (2) we obtain a strict linear relationship between potential difference and flowrate. Likewise, the calibration curve of the electromagnetic pump is obtained using GaInSn at known flowrate. The data can be transferred to tin by matching the densities. As it can be seen in Fig. 6, both flowrate and pressure increase linearly with frequency.

![Fig. 5: Calibration curve of wall potential flowmeter.](image1)

![Fig. 6: Calibration curve of electromagnetic pump.](image2)

**Results and discussion**

Some first results of test measurements are shown in Fig. 7. The upper graph (blue curve) shows raw data of a time series of about 25 min of the measured Lorentz force given in mN. The lower graph (black curve) shows the respective raw data of the same time series of wall potential difference given in mV. The sampling rate was 2 Hz. During this run the frequency of the pump was successively changed within the range of 0 – 25 Hz and remained constant for about 30 s. From the graphs it is clearly seen that both electromagnetic flow measurement techniques work well in liquid tin at 350°C. Moreover, it can be seen that the signals obtained by the WPF is more robust than those recorded by the LFF. This reflects the fact that the force sensor is very sensitive to mechanical vibrations caused by the rotating pump and/or the melt flow. It should also be mentioned that we do not observe any hysteresis effects, as upon increasing and decreasing the frequency of the pump, nearly identical measurement values are obtained both LFF and WPF.

![Fig. 7: Time series data of LFV and WPF.](image3)
At the end of the run, i.e. at about $t = 19$ min and $t = 21$ min, the Argon pressure was increased two times in order to compensate back flow of tin into the storage tank due to a slightly leaky ball valve. As it can be seen from Fig. 7, again the LFF is much more sensitive to such sudden changes of pressure and the resulting vibrations. However, in application the somewhat noisy signals of the LFF can be effectively filtered in order to give reliable measurement values.

Fig. 8 shows the results of the time-averaged raw data within the frequency range of the pump of $2 – 25$ Hz. Here, the upper graph shows the results of the flow measurement using the wall potential flowmeter, while the lower graph refers to the Lorentz force flowmeter. For the averaging, only the raw data of the first 8 min of the time series were used, corresponding to the increase of pump frequency. Again, we can observe the nearly linear dependence of both signals on pumping frequency. We can thus conclude that even at the highest frequency we are still in the regime of low magnetic Reynolds numbers $Re_M$. A rough estimate shows that $Re_M$ is of order $10^{-1}$. Finally, Fig. 9 shows the correlation of the time-averaged signals obtained by LFF and WPF. From this graph we can conclude that there is likewise a linear relationship between the signals. This gives the potential for using both non-contact electromagnetic flow measurement techniques for mutual calibration.

Summary and conclusions

In this study we have investigated experimentally liquid tin flow at a temperature of $350^\circ$C. Both a Lorentz force flowmeter and a wall potential flowmeter have been tested in order to demonstrate their feasibility for non-contact electromagnetic flow measurement at such elevated temperatures. Our first test runs clearly show that both techniques operate well. Both methods show an almost linear dependence of their signal amplitudes on the frequency of the flow-driving electromagnetic pump which is related to the flowrate via its calibration curve. Moreover, we observe likewise a linear dependence between both signals.

Acknowledgment

The authors acknowledge financial support by Deutsche Forschungsgemeinschaft (DFG) within the Research Training Group on Lorentz force velocimetry and Lorentz force eddy current testing under grant GRK1567 and within the Research for Proposals of Major Instrumentation on Liquid Tin Channel Ilmenau under grant INST 273/37-1-FUGG. We acknowledge fruitful discussions with Dr. Th. Wondrak from Helmholtz Center Dresden-Rossendorf. Furthermore, we acknowledge scientific support by Dr. I. Bucenieks from University of Latvia in Riga for manufacturing the electromagnetic pump and the wall potential flowmeter and providing the respective calibration data. We also acknowledge the technical support by V. Mitschunas, A. Thieme, S. Buchelt and N. Lukin.

References

1. A. Thess, E. Votjakov, B. Knaepen, O. Zikanov, New journal of Physics, 9 (2007), 299 – 326.
2. Y. Kolesnikov, Ch. Karcher, A. Thess, Metallurgical and materials transactions B, 42 (2012), 441-450.
3. D. Jian, Ch. Karcher, X. Xu, A. Deng, E. Wang, A. Thess, J. Iron Steel Research, 9 (2012), 509 – 513.
4. Ch. Weidermann, PhD dissertation, TU Ilmenau (2013).
5. V. Minchenya, Ch. Karcher, Y. Kolesnikov, A. Thess, Magnetohydrodynamics, 45-4 (2009), 569-578.
6. X. Wang, Y. Kolesnikov, A. Thess, Measuremet Science and Technology, 23 (2012), 0450051-045060.
7. M. Gramfl, PhD dissertation, TU Ilmenau (2013).