Towards local resolution measurements in turbulent liquid metal duct flows

Christiane Heinicke & André Thess & Ilko Rahneberg
Faculty of Mechanical Engineering, Ilmenau University of Technology, Ilmenau, 98693, Germany
E-mail: christiane.heinicke@tu-ilmenau.de

Abstract. This document provides most important guidelines for the preparation of the ETC13 Proceedings papers. Please follow the formatting rules within this document.

Lorentz Force Velocimetry (LFV) is a novel technique for measuring flow properties of liquid metals that has successfully been applied to the experimental determination of global flux rates. A flowmeter based on this technique consists of a small number of palm-sized magnets that interact with the conductive working fluid, a eutectic alloy liquid at room temperature in our laboratory test case. We examine the turbulent flow inside a 1 m long square duct with a 5 cm by 5 cm cross-section. Unlike the Lorentz Force Flowmeters (LFF) employed so far, the focus of this work is accessing local quantities of the metal flow by a small magnet cube (1 cm edge length). The aim is to resolve the flow profile and three-dimensional structures inside the flow by a completely contactless method. In this work we present the general eligibility of the small magnet. Application of the locally resolved LFV is intended for where there is a lack of understanding of a liquid metal flow because of its inaccessibility to established flow measurement techniques due to its hotness and aggressiveness.

1. Introduction

The measurement of volume fluxes remains a challenge for hot, aggressive fluids like metal melts. Common flowmeters either need to be immersed or at least have contact with the fluid or require it to be translucent. Liquid metals preclude both these types of flowmeters. Lorentz force velocimetry (LFV), on the other hand, is a contactless measurement technique making use of interaction forces between the flow of conductive fluids and a magnet system.

The magnets induce a Lorentz force inside the fluid, generating eddy currents that in turn generate a secondary magnetic field backreacting on the permanent magnet [1]. By this, the magnet indirectly exhibits a braking force on the flow and simultaneously experiences a force in flow direction. As the magnet needs not be in touch with the metal melt under investigation, LFV allows to determine flow structures inaccessible to both the eye and other flow measurement devices.

Different from the Lorentz Force Flowmeter used in global flow measurements as in [2] this work aims to reach local resolution inside liquid metal flows by use of small magnets (∼ 1 cm³). The flow we investigate here is inside a rectangular duct, a schematic diagram can be seen in fig. 1, where the flow points in positive x-direction. The magnet is placed below the duct. The
experimental challenge is the detection of the Lorentz force which is ten thousand times smaller than the weight of the magnet. Application of the locally resolved LFV is intended for where there is a lack of understanding of a liquid metal flow because of its inaccessibility to established flow measurement techniques due to its hotness and aggressiveness.

2. Setup

2.1. Duct
The liquid metal duct is a closed metal loop with an 80 cm long test section made of plexiglass. The cross section inside this test section is 5050 mm² (width × height). The plexiglass walls are 5 mm thick. Fig. 2 shows a sketch of the setup. The liquid metal duct is filled with a eutectic alloy liquid at room temperature, Ga₆₈In₂₀Sn₁₂, whose density $\rho$, electrical conductivity $\sigma$, and kinematic viscosity $\nu$ are $6.36 \times 10^3$ kg/m³, $3.46 \times 10^6$ 1/Ωm, and $3.40 \times 10^{-7}$ m²/s, respectively. The (average) flow velocity of the liquid metal can be regulated by the rotation speed of the pump driving the flow. An electromagnetic fluxmeter measures the total flux rate, from which the velocity is determined by division with the cross section of the plexiglass duct. The maximum velocity achievable with this setup is approximately 13 cm/s. An Ultrasonic Doppler Velocimeter can be installed in the duct to provide spatially resolved reference velocity measurements.

2.2. Measurement System
The heart of the measurement system is a magnet mounted on a deflection body. When a force acts on the magnet, the deformation of the deflection body is registered by an interferometer. Strain can only be measured in one direction. However, the system can be turned such that streamwise and spanwise velocity, though not simultaneously, can be measured. The aluminum deflection element reaches a resolution of less than 1 $\mu$N.

The measurement system is placed beside the duct; its distance from the duct can be adjusted by a step motor in the range of approximately 5 cm. In fig. 2 the measurement system is shown as a box beside the duct; the magnet is on the side facing away from the viewer.

Before each measurement, the duct system is allowed to become steady, which takes no more than one minute. Thus, a typical measurement lasts several hundreds of seconds. For this work, only mean values have been considered.
Figure 2. Experimental setup. The liquid metal loop consists partly of steel pipes and a plexiglass section of 5 cm × 5 cm cross section. Magnet system is placed beside the 5 mm thick plexiglass wall and records the main force component which points in flow direction (from left to right inside the plexiglass). Control measurements are performed using a volumetric flux sensor and an Ultrasonic Doppler Velocimeter (UDV).

2.3. Magnetic fields
For the measurements presented here, the implemented cube magnet has an edge length of 10 mm. It is a NdFeB-magnet with Ni-coating. The grade of the magnet corresponds to N42, with a remanence of 1.09 T. The magnet is attached to the deflection body such that its magnetization points in spanwise (z-) direction of the flow, “poking” into the flow from the side. The stray field in the laboratory was determined to be up to 1.9 mT. Variation of the magnetic flux density due to temperature fluctuations are determined to be within the order of the stray field.

3. Results
3.1. The Experiments
The measured quantity is the Lorentz force acting on the magnet. This force in streamwise direction can be influenced by the following experimental parameters:

(i) The distance of the magnet to the duct. This changes the magnetic field acting on the liquid metal inside the duct.
(ii) The flow velocity. By changing the pump speed, the liquid metal can be made to flow faster or slower.
(iii) The vertical position of the magnet. This yields the main force component in dependence of the flow profile.

3.2. Parameters
The parameters were nondimensionalized the following way:

\[ L \quad \text{halfheight of the duct, 2.5 cm} \]
\[ \bar{u} \quad \text{typical flow velocity of 13 cm/s}. \]
Figure 3. The dependence of the drag coefficient $C_L$ on the distance of the magnet to the liquid metal inside the duct. The exponent of the power law is approximately $-3.8$.

$\bar{u}$ is determined by the ratio of the fluxrate (measured by an electromagnetic fluxmeter) to the cross-sectional area of the duct ($A_{\text{duct}} = 25 \text{ cm}^2$). The length of the duct is 80 cm.

With these, the characteristic drag coefficient for each magnet and the duct can be defined as

$$C_L := \frac{F_{\text{measured}}}{1/2 \rho \bar{u}^2 A_{\text{duct}}},$$

and the Reynolds number as

$$Re := \frac{\bar{u}L}{\nu}$$

where $\sigma$, $\rho$, and $\nu$ are the electrical conductivity, density and kinematic viscosity of Galinstan as mentioned in section 2.1 and $F_{\text{measured}}$ is the measured signal.

3.3. Measurement results

Three major experiments were carried out which will be explained in the following:

The first experiment determined the dependence of the Lorentz force (here correspondent to the drag coefficient $C_L$) on the distance of the magnet from the duct. As can be seen from fig. 3, the drag coefficient is decreasing as the magnet is placed increasingly far away from the duct.

Secondly, the velocity of the flow was varied between 0 and 7 cm/s corresponding to a Reynolds number of 5000. The force increases roughly linearly with increasing velocity ($\sim Re$), as can be seen in fig. 4. This is expected and the main reason for the existence of Lorentz Force Velocimetry: By virtue of measuring the Lorentz force, the flow velocity of the fluid can be determined.

And finally, the position of the magnet has been changed along the vertical side of the duct. That is, the main force component in $x$-direction has been measured in dependence of the vertical
Figure 4. The dependence of the drag coefficient $C_L$ on the velocity of the liquid metal inside the duct. As the exponent is roughly $-1$, the dimensional force depends roughly linearly on the mean flow velocity.

$y$-coordinate. The force clearly decays towards the edges of the duct, and the force profile is symmetric to the mid-height of the duct.

4. Conclusion and Outlook

Lorentz force measurements have been conducted with a small magnet cube on a horizontal liquid metal duct. The streamwise Lorentz force decreases with increasing distance of the magnet to the duct and decreasing flow velocity. It also decreases towards the edges of the duct. These results will be compared with numerical simulations. The magnet system will be adjusted such that the spanwise forces, i.e., the vertical component of the Lorentz force, can be measured. Local reference measurements using an Ultrasonic Doppler Velocimeter will be performed.

5. Acknowledgements

The authors wish to sincerely thank G Pulugundla and S. Tympel for all the useful discussions. Also, the authors gratefully acknowledge the financial support from the Deutsche Forschungsgemeinschaft in the framework of the RTG Lorentz Force Velocimetry and Eddy Current Testing (grant GRK 1567/1).

References

[1] Thess, A., Votyakov, E., Knaepen, B., Zikanov, O.: Theory of the Lorentz force flowmeter. *New Journal of Physics*. 9:299–325, 2007.

[2] Kolesnikov, Y., Karcher, C., Thess, A.: Lorentz Force Flowmeter for Liquid Aluminum: Laboratory Experiments and Plant Tests. *Metallurgical and Materials Transactions B*. 42:441–450, 2011.