Transient Eddy Current Flow Metering:
a calibration-free velocity measurement technique for liquid metals

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Abstract

Most inductive techniques for the velocity measurement of liquid metals have the common problem that the measured signals depend on the electrical conductivity and the temperature of the liquid metal. This is particularly unfavourable for applications with strong temperature fluctuations or for measurements that have to be performed in different liquid metals with the same sensor. Usually these sensors have to be calibrated extensively to ensure accurate measurement results. We present a new measurement technique called Transient Eddy Current Flow Metering (TECFM) which overcomes the need for prior calibration of the sensors. Its principle relies on imprinting transient eddy current systems into the liquid metal and to track their movement as they are advected with the flow. Two kinds of sensors that use this new measurement principle have been developed: An external sensor [1] for the contactless velocity measurement at the boundary of liquid metal flows, and an immersed sensor [2] which allows local velocity measurements in the vicinity of the sensor. Focusing on the latter we present the results of numerical simulations as well as the results of measurements that were performed in the eutectic alloy GaInSn at room temperature and in liquid sodium at 180 °C.

Key words: flow measurement, inductive methods, calibration-free

Introduction

The measurement technique presented in this article traces back to early ideas of Zheigur and Sermons [3]. Although the external [1] and immersed [2] sensor types both track the movement of an eddy current system to determine the flow velocity, the arrangement of their sensor coils as well as the structure of the eddy currents are considerably different. The external sensor (Fig. 1), which is placed outside the boundary of the liquid metal, uses one primary coil to imprint eddy current rings into the liquid metal. This is achieved by suddenly switching a DC current on or off. In this case, the eddy currents are moving with flow velocity and this velocity can be obtained by tracking a distinctive point of the system. This is necessary because the eddy currents are decaying over time and only distinctive points, like the magnetic pole or a zero crossing point, can be identified regardless of the amplitude of the eddy currents. For the external sensor, this point is the pole of the magnetic field, which is generated by the eddy currents and can be tracked by measuring the voltage in both secondary coils [1]. Under the reasonable assumption of steady flow, the flow velocity can be calculated from two or more locations of the magnetic pole at certain points in time with: \( v = \Delta x / \Delta t \).

Since the immersed sensor is the most recent development, this article will focus primarily on that type. In order to allow velocity measurements of the surrounding liquid metal, the coils have to be arranged differently than the ones of the external sensor. There are two primary and two secondary coils (Fig. 2) and the eddy current system is more complex.
Again, the eddy currents are imprinted into the liquid metal by switching a DC current on or off, but the DC currents in the right and left primary coil have to be directed oppositely. As a result, two eddy currents with opposite direction are induced and because they have the same amplitude, the magnetic flux density at the middle of the sensor equals zero. For a symmetric coil arrangement and eddy current distribution, the whole eddy current system and also this zero crossing point $x_0$ will move with the same velocity as the liquid metal. When asymmetries occur, a certain drift of $x_0$ must be taken into account [4]. The two secondary coils are used to track the position of $x_0$, which is calculated from the respective voltages, and the velocity can be obtained with the previously mentioned relation when assuming a linear motion of the eddy currents.

**Numerical simulation**

Numerical simulations for the immersed sensor were performed in COMSOL Multiphysics by creating an axisymmetric model of the sensor and the surrounding liquid metal. One of the most important features of an ideal immersed transient eddy current flow meter (I-TECFM) is the calibration-free character. That means that the sensor yields the same results, regardless of the electrical conductivity (or temperature) of the liquid metal, without any need for calibration. In order to evaluate this property, the parameter $\Delta$ is used. It represents the normalized deviation between the predefined and measured velocity and is displayed in Fig. 3 over a wide range of electrical conductivities for three different cases. Case a) shows the performance of the I-TECFM under almost ideal conditions: All sensor coils are made as small and as close together as possible, in addition there is no stainless steel cladding which separates the sensor coils from the liquid metal. It can be seen that there are nearly no variations in $\Delta$ for case a), the remaining deviations are below 1 % and can be attributed to the finite grid size of the simulation model. Using a smaller grid size will further decrease $\Delta$ but requires a much higher calculation time for a comparably small benefit. When going over to more realistic coil arrangements and sizes in case b), it can be seen that the magnitude of $\Delta$ is increasing with $\sigma$. By adding the stainless steel cladding and using the coil arrangement of the real sensor prototype in case c), the magnitude of $\Delta$ is increasing even further. Larger coil sizes for the actual sensor are necessary to accommodate a reasonable number of wire turns in order to increase the sensitivity of the sensor. For reasons of mechanical stability, the distance between adjacent coils cannot be much smaller than 1 mm.

![Fig. 3: Influence of the electrical conductivity of the liquid metal on the measurement error $\nu_3$ of the velocity for different coil arrangements: a) idealized arrangement, b) very small coil distance, c) real coil arrangement of the prototype with stainless steel cladding of 2 mm thickness.](image)

The primary reason for an increased $\nu_3$ is the penetration depth $\delta$ (skin depth) of the magnetic fields into the liquid metal in combination with the distance between the sensor coils. For high conductivities $\delta$ is decreasing and therefore the position of the zero crossing point appears to blur when the sensor coils are too far apart because the signal strength is rapidly decreasing with the distance. This is also the reason for the differences between case b) and c) since there is a significant difference in coil size and distance for both cases. Another reason are parasitic eddy currents that are induced within the stainless steel cladding that protects the sensor from direct contact with the liquid metal. Their magnetic field is superimposed with the magnetic field of the eddy currents that are located within the liquid metal and therefore the whole eddy current system appears to move slower than it actually does. This effect is especially significant for low $\sigma$ since the parasitic eddy currents have the same order of magnitude as the eddy currents within the liquid metal. This effect becomes worse with increasing wall thickness of the sensor cladding.

In order to obtain accurate measurements it is important to assure that the excitation current in the primary coils has reached its stationary value. Usually this takes between 10 $\mu$s to 100 $\mu$s after initiating the switching operation, depending on the excitation current source. Otherwise, the primary magnetic fields would interact with the eddy current system, resulting in a significant increase in $\nu_3$. 
Measurement results

Measurements with the I-TECFM prototype have been conducted at different experimental facilities using the liquid metal alloy GaInSn at room temperature or sodium at 180 °C. The charts in Fig. 4 and Fig. 5 show the location of the calculated zero crossing $x_0$ in dependence on time for different pre-adjusted velocities $v$, and the corresponding (non-normalized) deviation $v_A$ from the measured velocity, which is equivalent to the slope (obtained by linear regression) of the measurement series. Each point displayed in Fig. 4 and Fig. 5 represents the mean value of 2500 successive measurements. During production of the sensor, asymmetries resulting from manufacturing tolerances occur, and therefore the previously mentioned drift of $x_0$ [4] was observed during measurements. Even for very slight asymmetries, this drift cannot be ignored. Since the drift velocity is constant for each sensor, it can be determined simply by conducting measurements in a resting liquid metal. Once the drift velocity is known, it can be subtracted from each measurement series to obtain the real, compensated velocity or $v_0$, respectively. The following charts already contain the compensated measurement results.

The measurements that were performed in the liquid metal alloy GaInSn with an electrical conductivity of 3.3 MS/m [5] at room temperature yield promising results (Fig. 4). They were conducted at the GaInSn-Loop at HZDR. The test section has an inner diameter of 27 mm and the sensor has an outer diameter of 11.6 mm. $v_A$ reaches a maximum value of 0.05 m/s. Only for the lowest velocity a comparably high relative error of around 15 % is observed; this is a general problem of the I-TECFM since the drift velocity lies within the same order of magnitude which results in higher relative measurement errors, especially at low velocities.

Fig. 4: Measurement results for the immersed sensor in GaInSn at room temperature for different velocities $v$.

The measurements in liquid Na with an electrical conductivity of 8.1 MS/m [6] at 180 °C yield similar results (Fig. 5), although $v_A$ is considerably higher. There are various reasons for the higher deviation from the pre-adjusted velocity: The measurements were performed in a completely different experimental facility with different instruments, pump, flow structure inside the test section and, most importantly, a different sensor cladding with increased wall thickness to comply with security requirements. As shown in Fig. 3 a higher wall thickness of the cladding results in a loss of signal strength and quality. Since $v_A$ lies around 0.1 m/s for nearly all measurements, it is also possible that some part of $v_A$ does not come from measurement errors but from an unknown offset whose origin has yet to be determined.

Fig. 5: Measurement results for the immersed sensor in liquid Na at 180 °C for different velocities $v$.

In both Fig. 4 and Fig. 5 distinct oscillations that are superimposed with the actual measurement values can be observed. They result from voltage changes within the sensor coils due to resonance oscillation of the coils which is
caused by the suddenly switching off the excitation current. This effect can be mitigated by increasing the resistance of the coil wires, especially the ones of the secondary coils.

Conclusions
We have demonstrated via numerical simulations and first measurements which were conducted with sensor prototypes of the external and immersed implementations that TECFM is a viable method to determine the flow velocity of an electrically conductive fluid such as liquid metal. The distinguishing features of TECFM are the possibility for the direct measurement of the fluid velocity and the calibration-free character of this measurement technique. Although there is an additional measurement error in the range of a few percent when comparing the idealised and prototype sensor design, the flow velocity can still be determined with adequate accuracy. There are certainly more measurements needed at different electrical conductivities and temperatures to identify the reasons for increased deviations from the pre-adjusted velocity that could be observed for the measurements. However, the current implementations of the sensors already deliver promising results. Other inductive measurement techniques like the ECFM [7] can provide more accurate measurements (for the moment), as long as they have been properly calibrated for different temperatures and electrical conductivities of the liquid metal. This is the reason why TECFM is most suitable for applications where there are large fluctuations of the electrical conductivity and/ or a prior calibration of the sensor is not possible or wanted.

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