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Experimental Investigations and Qualification of Innovative Flow Sensors in the 1000 K SOLTEC-2 Sodium Loop

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Abstract. Liquid metals, such as sodium, have been already successfully used as heat transfer fluids (HTF) in concentrating solar power (CSP) plants up to ~550 °C. Even higher temperatures can be achieved and are envisioned for future CSP plants. The lack of measuring flow rate devices at high temperatures for liquid metals motivated this study. The present paper presents the experimental mock-up and the experimental results obtained with the SOLTEC-2 facility for two test flow sensors, one innovative eddy current flow sensor (ECFM) developed at HZDR, Germany and a built-in permanent magnet fly-wheel sensor for runs up to a sodium temperature of 700 °C. The signals of the sensors are compared also against the power level of the sodium pump.

Keywords: Sodium, Eddy Current Flow Sensor, Magnetic Fly-Wheel Flow Sensor, Experiment

1. Introduction

Several studies underlined the advantages of the liquid metals, such as sodium, as heat transfer fluid (HTF) for concentrating solar power tower plants [1, 2]. Among the main advantages of sodium are its high thermal conductivity, low melting temperature, low density and large temperature range. Furthermore, the operational experience with sodium in the nuclear field and recently in small CSP facilities is extensive. To support the concept of a CSP power plant that uses sodium as HTF, several research topics have been identified that require thorough experimental and numerical investigations [3]. The major topics range between experimental investigations of fundamental thermal-dynamics in CSP relevant geometries, qualification of new materials based on creep-fatigue investigations and studies of corrosion and erosion, and development and tests of components (e.g. receiver) and instrumentation (e.g. flow sensors) for high temperature applications in CSP plants. Several high temperature sodium facilities have been erected at KIT to fulfill these tasks [3, 4]. The lack of appropriate instrumentation for high temperature applications motivated the development at HZDR, Germany [5, 6] and the experimental investigation at KIT, Germany of an innovative eddy current flow sensor. This sensor was installed in the SOLTEC-2 facility at KIT and tested up to a sodium temperature of 700 °C. The measurements are compared against the values reported using the built-in permanent magnet fly-wheel flow sensor, placed in the low temperature side of the SOLTEC-2 loop. The present study describes the experimental mock-up and presents the comparison between the signals obtained with these two flow sensors.

The first eddy current flowmeter (ECFM) was patented in 1948 by Lehde and Lang [7]. Several designs emerged afterwards, which can be classified into ECFMs for typical pipe flows [8, 9] and pool-type flows [10]. Compared to permanent magnet flow meters, the ECFMs can sustain higher temperatures and usually have smaller dimensions. The fly-wheel flowmeter was patented in 1960 by Shercliff [11] and further developed, investigated and modelled by several research groups [12, 13]. It uses permanent magnets distributed equidistantly around the circumference of a disk. The flowmeter is placed close to a pipe in which the liquid metal is flowing. The flow in combination with the magnetic field of the permanent magnets leads to the induction of eddy currents in the liquid metal which, with their own magnetic field, impose a force on the magnets, causing the disk to rotate. The rate of rotation is proportional to the flow velocity of the liquid metal. The main advantages are its simple design and construction, good reliability, linear output signal that is not influenced by the liquid metal temperature and uncomplicated electronic measuring devices.

2. Experimental infrastructure

Each of the three SOLTEC (SOdium Loop to TEst materials and Corrosion) facilities at KIT has its own test section, since the purpose of the facilities is wide and differs for the investigated application and therefore could not be fulfilled solely by one general loop. SOLTEC-1 is used for creep-fatigue investigations, SOLTEC-2 for corrosion/erosion and SOLTEC-SOLAM for tests of thermoelectrical converters and solar receivers. All facilities are used also for investigations and qualification of components and instrumentation. SOLTEC-1 and -2 facilities are designed for a maximal operating temperature of 720 °C at a maximal overpressure of 3.5 bar. The maximal sodium flow rate specified is 300 kg/h, for which sodium velocities up to ~5 m/s can be reached in the test samples. The SOLTEC-1,-2 loops have several innovative characteristics, such as the fact that the sodium storage tank serves also as an expansion tank, reducing the number of components and connections in the high temperature region. Further, an efficient sodium-sodium heat recuperator has been coupled directly to a sodium-air heat exchanger, providing therefore efficient heat recuperation and a compact configuration. Several safety measures have been implemented following the safety by design principle. Therefore, the loop can be easily transported and operated in a research laboratory or to CSP sites at high safety standards. Up to now, more than 15 operating hours at the maximal temperature including the ramp-up and ramp-down transitions have been accumulated.

Figure 1. View of the SOLTEC-2 facility (lateral safety walls removed for visualization).

3. Description of the flow sensors

3.1 Eddy current flow sensor

The eddy current flow meter is an inductive sensor capable of measuring the flow rate or flow velocity of an electric conductive fluid near the sensor. The relative movement between the fluid and the sensor induces velocity-dependent eddy currents and their amplitude or phase shift can be is determined in order to estimate the fluid flow rate, since they are correlated by a linear relationship. The high temperature ECFM sensor [5, 6] consists of three magnetic coils positioned vertically one above the other. The middle coil is used to generate a magnetic field, which induces eddy currents in the surrounding fluid. These currents affect in turn the excitation field of a primary coil and these changes are quantified using the output voltage of the other two coils. The sensor is placed in a stainless steel casing to prevent the direct contact with the surrounding fluid. Thereby the sensitivity of the sensor is reduced, however it can be employed in challenging applications, such as high temperatures and chemically aggressive materials. The primary coil has a height of 10 mm, while each secondary coil has a height of 16 mm. They are mounted on a ceramic holder, which can sustain high temperatures and provides structural support (Fig. 2). The coils consist of ceramic insulated nickel plated copper wires. A balance is established between the outer nickel layer, which on one side reduces the risk of corrosion at high temperatures, while the wire resistance and its diameter are increased still at reasonable values.

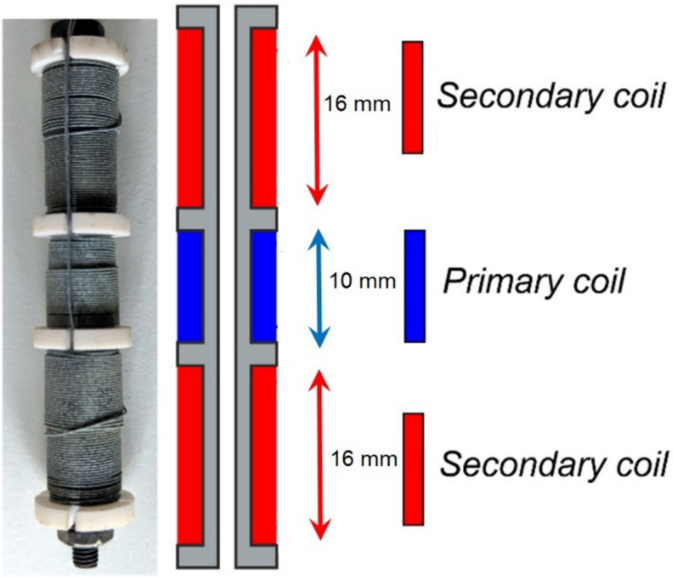


Figure 2. Eddy current flow sensor.

3.2 Magnetic fly-wheel flow sensor

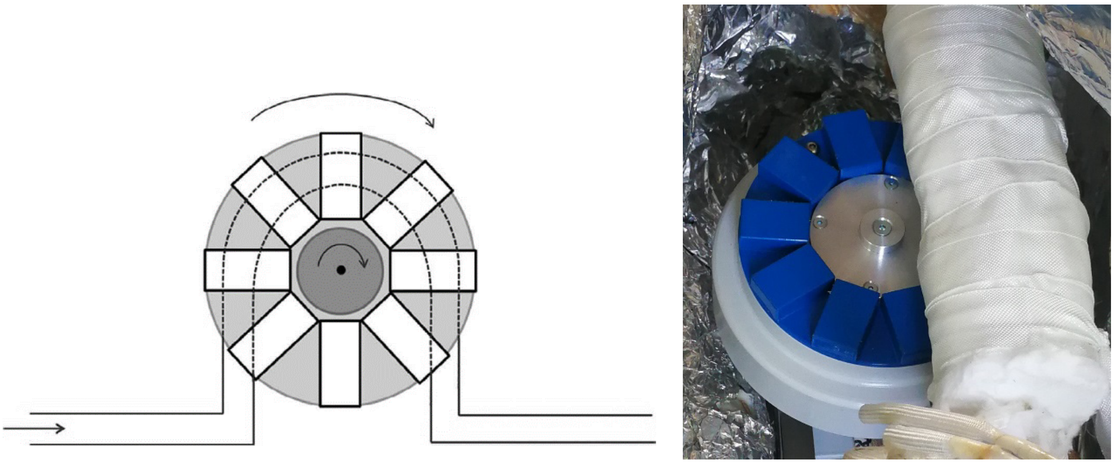
A magnetic fly-wheel flow sensor (Fig. 3) is installed by default in the low temperature side of the SOLTEC-2 facility. The moving sodium through a pipeline is rotating a disc equipped with permanent magnets and the rotational speed of the disc *u* is quantified as follows:

$$u = (f \cdot \dot{m}) / (A \cdot s) \qquad (1)$$

$$f = N \cdot (N^2 - 4) / [(N + 1) \cdot (N^2 - 1)] \qquad (2)$$

where *A* is the flow channel cross-section, *s* is a sensitivity coefficient, *N* is the number of magnetic pole pairs. The magnetic fly-wheel sensor has been calibrated using a GaInSn test bench according to the formula for the volume flowrate:

$$\dot{V} = \dot{V}_0 \cdot \sigma_{GaInSn}(T_{cal}) / \sigma_{Na}(T) + 2 \cdot \pi \cdot r \cdot u \cdot A \cdot [1 + k \cdot \sigma_{Wall}(T) / \sigma_{Na}(T)] \tag{3}$$

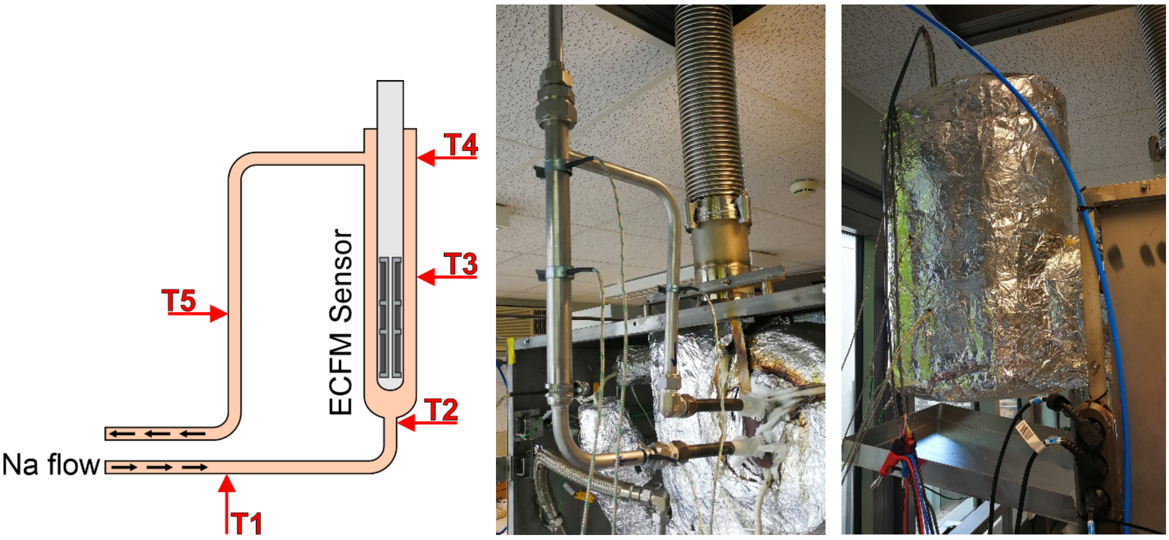


a) b)

Figure 3. Magnetic fly-wheel sensor: a) schematic construction and b) sensor installed in the SOLTEC-2 facility.

4. Experimental setup

The eddy current flow sensor was integrated in a dedicated designed test section in the SOLTEC-2 facility, as presented in Fig. 4. Five thermocouples (see Fig. 4a) were integrated on this test section to monitor the temperature before, after and in the region of the ECFM sensor. The thermocouple closest to the sensor (T3) was used as a reference temperature for the sensor, which was inserted in a high temperature austenitic steel casing to avoid the direct contact with the hot sodium. A sufficient gap between the inner diameter of the housing pipe and the outer diameter of the sensor was considered, to avoid possible sodium flow blockages.



a) b) c)

Figure 4. a) Sketch of the test section and the position of the thermocouples, b) integration of the eddy current flow sensor in the SOLTEC-2 facility and c) final assembly after mounting of the thermal insulation.

5. Experimental results and tests of flow sensors

In the present experimental campaign several tasks were followed in order to investigate the ECFM sensor, namely during the first experimental day a stepwise temperature increase up to 600 °C was made, while during the second day tests up to 700 °C were performed. The temperature distribution in the experiments for the T3 thermocouple near the ECFM sensor and the temperature at the inlet of the fly-wheel sensor are presented in Fig. 5. A comparison between the signals of the two flow sensors is shown in Fig. 6, for different sodium flow rates at ECFM temperature levels 200 °C, 300 °C and 400 °C. For the ECFM sensor the voltage gradient is considered, since the absolute voltage is changing due to the increasing wire resistance and decreasing sodium electrical conductivity with increasing sodium temperature. A good agreement between the signal detected by the ECFM sensor, the power of the sodium pump and the sodium flow rates determined with the fly-wheel sensor is obtained. All flow changes induced by varying the sodium pumping power are followed by both sensors, however differences between their behaviors can be observed. The signal of the fly-wheel sensor has a clear inertial effect and requires a few minutes to reach a constant level. In contrast, the ECFM sensor reacts practically instantaneously and exhibits a sharp sensitivity to the changes occurring in the local sodium flow.

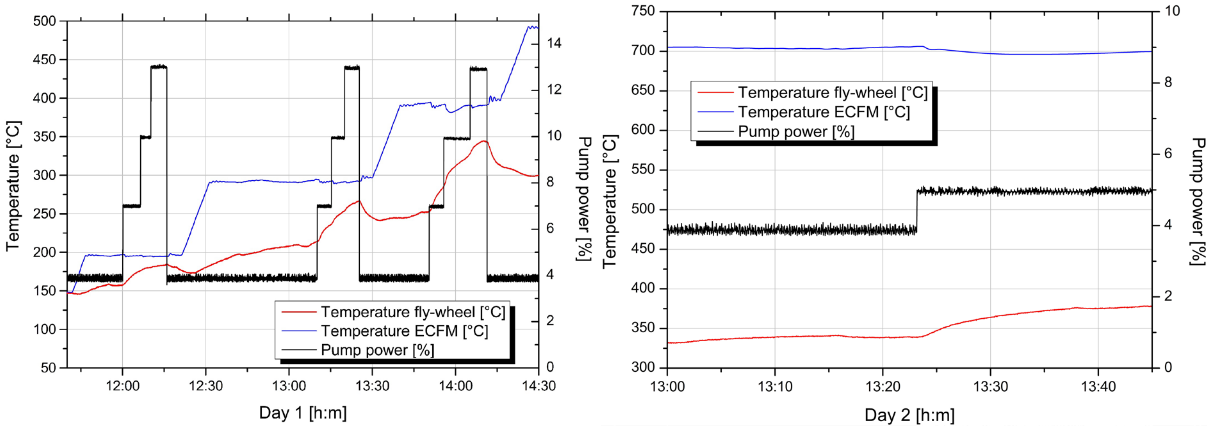


Figure 5. Temperature of the magnetic fly-wheel and ECFM sensors and the sodium pump power level during the tests.

The sodium electrical conductivity varies significantly in the temperature range 150-700 °C by a factor of 3.4. This aspect influences the signal of the ECFM sensor, since the amplitude of the eddy currents induced in the liquid metal depend on the electrical conductivity of the fluid. Therefore, a calibration of the ECFM sensor is required in order to provide reliable measurements.

The coils of the ECFM sensor [5, 6] are manufactured from nickel-plated copper wires that have a 27% nickel content to prevent the oxidation of the copper at high temperatures, while still ensuring a low wire resistance. At temperatures above 315 °C nickel penetrates the copper core, an effect called nickel migration, which results in increasing the wire resistance. However, this effect can be reduced if the diameter of the wires is increased above 0.15 mm [6].

Since nickel is a ferromagnetic material, it is characterized by a specific Curie temperature, which is the specific temperature at which the material is losing its ferromagnetic properties. Pure nickel has a Curie temperature of 358 °C [14] and this temperature is lower for copper-nickel alloys. Above the Curie temperature, the inductivity of the ECFM sensor is significantly reduced and the amplitude of the sensor output voltage decreases also, as can be observed in Fig. 6c. Due to this effect, no reliable measurements around the Curie temperature in the range 345°C ±15 °C can be made, since the coils of the sensor exhibit a loss of inductivity.

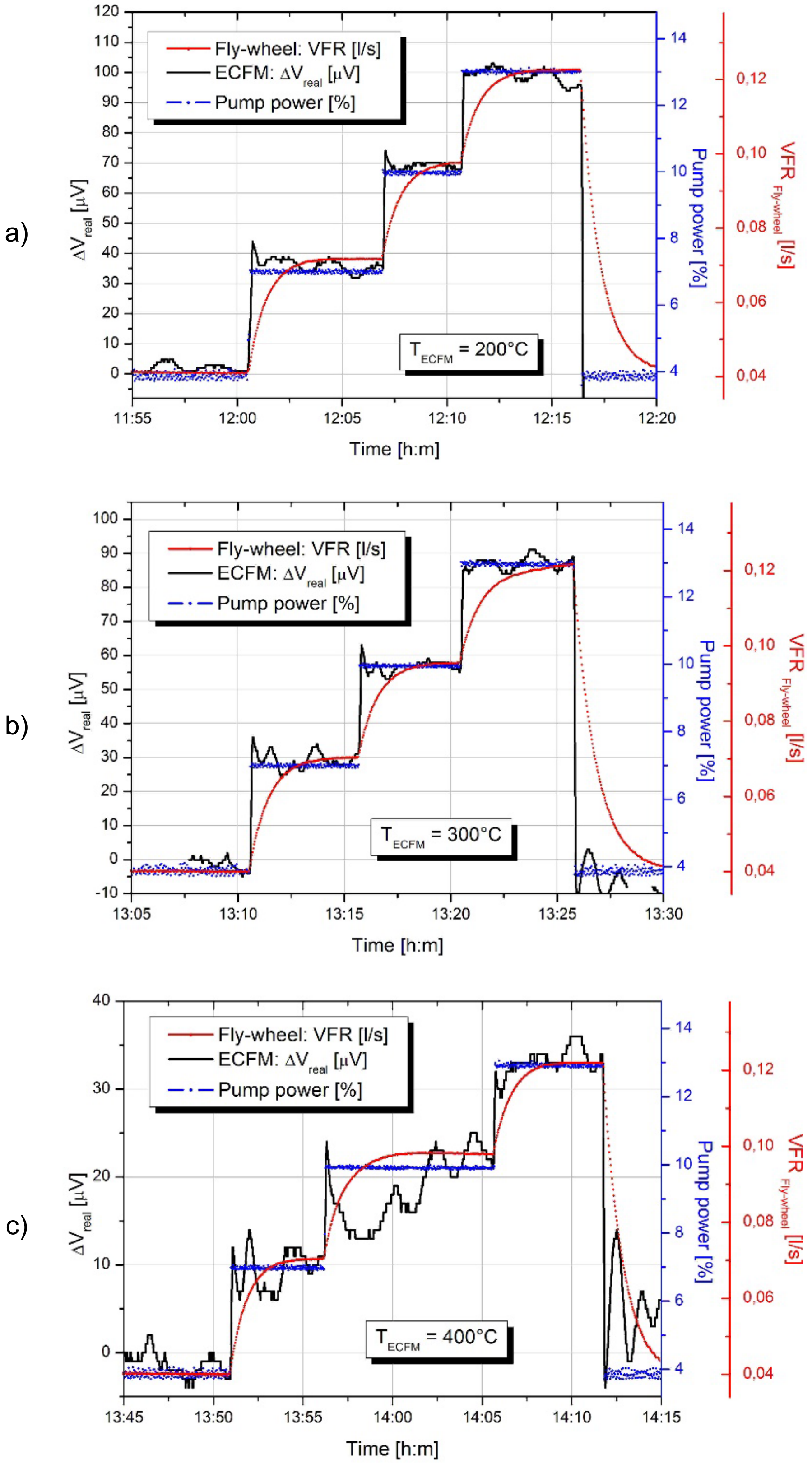


Figure 6. Comparison between the signals of the ECFM sensor and the fly-wheel sensor at ECFM temperatures of 200 °C (a), 300 °C (b) and 400 °C (c).

Wetting of the sensor casing has a positive effect on the signal of the sensor. It leads to lower oscillations of the voltage signal, while the sensitivity to the flow changes is significantly improved. This effect has been observed in the experimental tests performed.

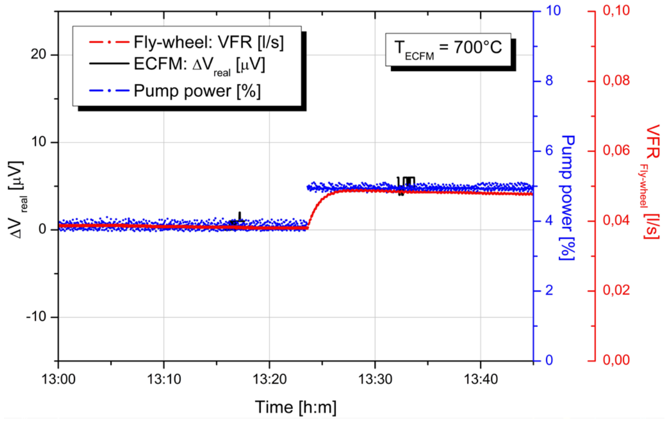


Figure 7. Comparison between the signals of the ECFM sensor and the magnetic fly-wheel sensor at ECFM temperature of 700 °C.

Despite the challenges occurring during the tests at higher temperatures, which are caused by the nickel migration and increased wire resistance, successful measurements denoting a good agreement with the fly-wheel sensor and the sodium pump power at 700 °C could be performed with the ECM sensor, as presented in Fig. 7. However, it should be noted that the magnitude of the sensor output voltage is significantly decreasing at this high temperature level, although, by adjusting the frequency or amplitude of the excitation current of the sensor, this effect can be counteracted [6].

6. Conclusions

The present study presents the results obtained with two flow rate sensors developed for high temperature liquid metal flows. A magnetic fly-wheel sensor and an eddy current flow sensor have been experimentally investigated in the 1000 K SOLTEC-2 facility. Generally a very good agreement has been obtained between the signals of both sensors, which were successfully compared also against the power level of the sodium pump used to drive the sodium in SOLTEC-2 loop. The main conclusions of the study are:

- The fly-wheel sensor exhibits an inertial behaviour and therefore a delay of several minutes by sudden flow changes and it can be applied therefore for steady-state flows, however is not recommended for fast transient flows.
- The eddy current flow sensor is sensitive to the changes in the flow, following practically instantaneously the changes in the flow rate. It can be therefore recommended for tracking fast transient flows.
- The fly-wheel sensor is restricted to an upper temperature of 500 °C for the driving fluid.
- For the eddy current flow sensor, successful measurements are reported in this study up to 700 °C. However, it should be noted that with increasing temperature and the nickel migration effect the wire resistance increases also, impacting the output voltage. This effect can be counteracted by appropriate adjustments of the frequency or amplitude of the excitation current.
- Due to the Curie temperature the use of the eddy current flow sensor in the temperature regime 345 ± 15 °C will produce unreliable measurements.

Author contributions

A. Onea: Conceptualization, Methodology, Investigation, Formal Analysis, Resources, Writing, Visualization, Project administration. N. Krauter: Investigation, Formal Analysis, Resources, Writing – Review and Editing. W. Hering: Term, Conceptualization, Supervision, Funding acquisition. S. Lenk: Formal Analysis, Resources. S. Ruck: Formal Analysis. R. Stieglitz: Term, Supervision. G. Gerbeth: Term, Conceptualization, Funding acquisition, Supervision.

Data availability statement

To access the data and the results presented in this article please contact the authors. The data generated is property of KIT and HZDR.

Competing interests

The authors declare no competing interests.

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