NENE
International Conference
Nuclear Energy for New Europe

EXPERIMENTAL INVESTIGATION OF THERMAL WAVE FLOW METER FOR MOLTEN SALT APPLICATIONS

Tomas Korinek
Czech Technical University in Prague
Jugoslavskych partyzanu 1580/3
160 00, Prague, Czech Republic
tomas.korinek@cvut.cz

Jan Skarohlid, Radek Skoda
Czech Technical University in Prague
Jugoslavskych partyzanu 1580/3
160 00, Prague, Czech Republic
jan.skarohlid@cvut.cz, radek.skoda@cvut.cz

ABSTRACT

Flow measurement of molten salts is a challenging task due to high temperatures and high corrosion of salts. A simple and reliable flow meter capable to withstand harsh conditions of molten salt is a key feature for the safe operation of molten salt reactors. The present study experimentally investigates the potential of a thermal wave flow meter for flow measurement of molten salt. Experimental investigations were conducted with water on an experimental flow meter platform with a reference magnetic-inductive flow meter. Several flow and thermal wave parameters were tested in order to study the behavior of thermal waves.

1 INTRODUCTION

Molten salts have found applications in several areas, such as fourth-generation nuclear reactors [1-3], concentration solar power plants [4], and high-temperature heat storage [5]. Their use in these applications is due to specific properties, such as high thermal stability, high boiling point at atmospheric pressure, and relatively high heat capacity. One of the critical parameters monitored in these applications is the determination of the flow rate of molten salt. Conventional flow measurement methods are not applicable to molten salts due to the high temperatures and corrosive environment [6].

One of the available methods for flow measurement is through an ultrasonic flow meter based on the time-of-flight principle, which has found application particularly in solar concentrator power plants and heat storage. However, a drawback of this flow measurement method is the low maximum temperature on ultrasonic probes. To measure the flow of fluids at higher temperatures, this limitation is addressed by positioning the probe away from the pipeline using an inserted plate, called a wave injector.

Another method for flow measurement using the time-of-flight principle is through a heat pulse. The principle of flow measurement using the heat pulse is based on determining the time delay of the thermal wave between two measuring points. This method of measurement has been previously studied for measuring the velocity of turbulent flow [7]. However, with the development of more precise methods, this velocity measurement approach has not become widely adopted. The flow measurement method using a heat pulse has found application in medical applications [8] or in the field of gas mixture flow [9]. The flow meter is not limited only to molten salt reactors but can be applied in other applications such as flow measurement in concentrating solar power plants, and thermal storages.

The present paper focuses on verifying the flow measurement method of molten salts using a heat pulse. To validate the method, an experimental setup was constructed, and initial measurements were carried out with water.

2 FLOW METER

The principle of flow measurement is based on a heat pulse which creates a thermal wave in fluid. The thermal wave travels in the flow meter and is measured on at least on two locations. The time delay of the thermal wave between two measuring points is used to calculate velocity and corresponding flow rate.

The time delay of the thermal wave between two points is depicted in Fig. 1, where the blue and orange curves represent temperature signal from two sensors. Black dotes on this graph indicate peaks of the thermal wave. The peaks are further used to calculate the time delay (time-of-flight) and the corresponding flow rate.

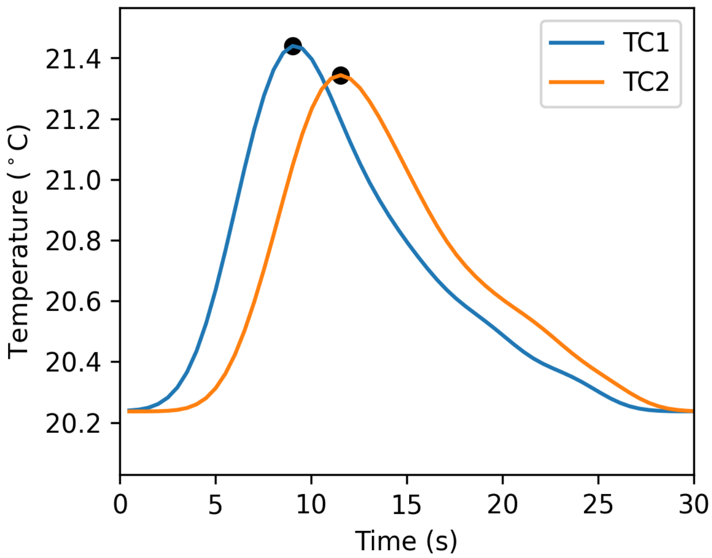

Figure 1: Sample of time delay of thermal wave between two thermocouples.

Volumetric flow rate can be calculated based on the time delay of the thermal wave from:

$$\dot{V} = A \cdot \frac{L}{\Delta t}, \quad (1)$$

where A is inner pipe's cross-section, L is distance between sensors, $\dot{V}$ is volumetric flow rate and Δt is time delay. However, the formula in Eq. 1 does not consider pipes velocity profile [10]. To incorporate effect of the velocity profile into the flow rate formula, a correction factor has to be included. A modified version of flow rate calculation is in form

$$\dot{V} = C_{corr}(D, U, \nu) \cdot A \cdot \frac{L}{\Delta t}, \quad (2)$$

where C_{corr} is a correction factor which depends on pipe diameter D, velocity U and kinematic viscosity ν. The correction factor can be related to the Reynolds number, which is calculated as Re=DU/ν. The correction factor is in form:

$$C_{corr} = C_1 \cdot \mathrm{Re}^{C_2}, \tag{4}$$

where C_1 and C_2 are empirical constants obtained from experimental data.

3 EXPERIMENT

3.1 Experimental setup

To verify the flow measurement using a heat pulse, an experimental flow meter stand was constructed, which consisted of a reference flow meter, a throttle valve, temperature sensors, and heating cartridges. The experimental flow meter stand is schematically shown in Fig. 2 and Fig. 3 shows a picture from a measurement on the flow meter stand. This experimental stand was designed and dimensioned based on the experimental loop for molten salts located in the laboratory at CTU-CIIRC. The experimental flow meter will be later on installed on the loop after the verification.

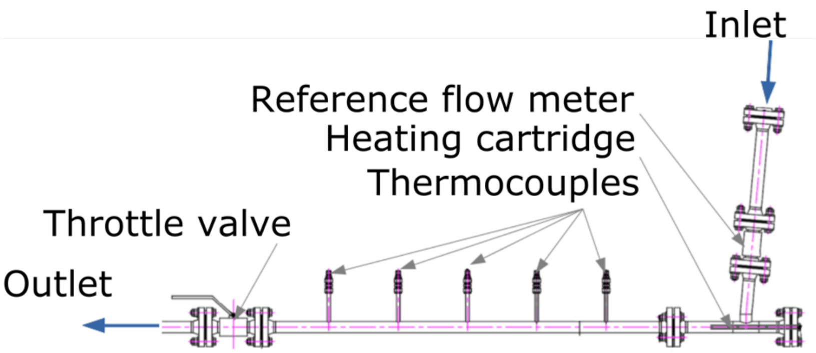

Figure 2: Scheme of experimental flow meter stand.

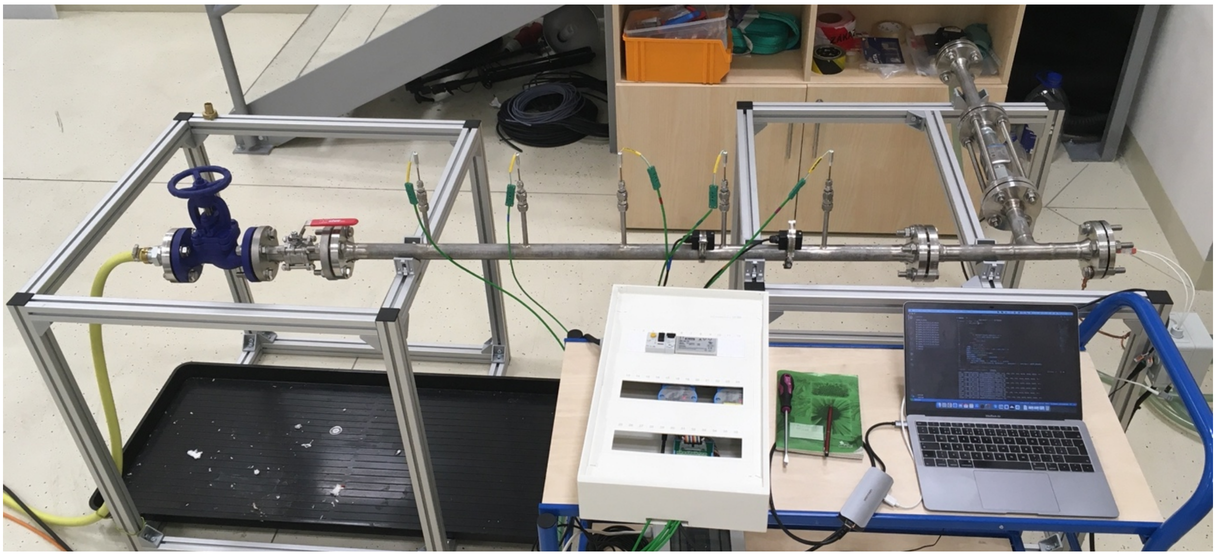

Figure 3: Measurement on the experimental flow meter stand.

Initial tests on the flow meter were performed on flow rate range 1-5 Liter Per Minute (LPM). Tests included two different time of heat pulses, 5 s and 10 s. The period of pulses was 30 s. Overview on performed tests is shown in Table 1.

Table 1: Overview of verification tests.

Case	Volumetric flow rate (Liter Per Minute)	Heat pulse	Reynolds number
FR-1-5	1 LPM	5 s	783
FR-1-10	1 LPM	10 s	783
FR-2.5-5	2.5 LPM	5 s	1 958
FR-2.5-10	2.5 LPM	10 s	1 958
FR-5-5	5 LPM	5 s	3 916
FR-5-10	5 LPM	10 s	3 916

4 RESULTS

The first test of the flow meter with water verified functionality of the measuring principle. The generated thermal waves were captured at all temperature measurement positions. A timeline of temperature for the first two sensors is shown in Fig. 4 left, where black dots mark position of peaks used for the calculation of volumetric flow rate. As the distance from the heating cartridge increased, the thermal wave flattened due to heat conduction and fluid mixing. Graph in Fig. 4 right illustrates how the thermal wave deformation/flattening occurred from the first to the fifth sensor location. This wave deformation led to deviations in the evaluating of thermal wave peaks.

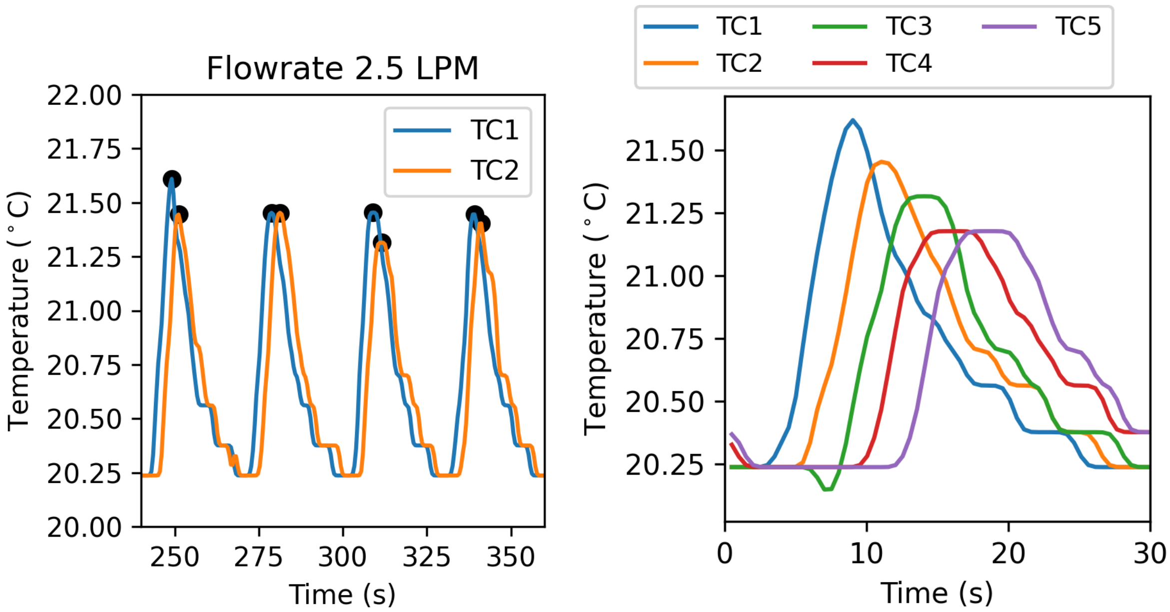

Figure 4: Measured thermal waves (left) and thermal wave deformations (right).

The graph of volumetric flow rate obtained from the thermal wave flowmeter is shown in Fig. 5. Results indicate a significant dispersion of evaluated flow rate values. This dispersion was caused by flow fluctuations in the experimental setup (±10 %) and by incorrect peak evaluations of individual pulses. The flow fluctuations in the experimental setup were recently dumped by installation of flow bypass for a better flow controlled. This improvement led to a reduction of fluctuations to 2 %.

The filtering of the measured temperatures using the Gaussian filter lowered the dispersion of calculated flow rate. Further, the average value of the flow rate obtained from the thermal wave evaluation is higher than the flow rate obtained from the reference flow meter. This overprediction is due to calculation of flow rate based on the velocity of the thermal wave. However, the obtained velocity corresponds to the velocity in the middle of the pipe which is higher than the mean velocity of fluid. To correct this overprediction, a correction has to be applied in order to incorporate the influence of the velocity profile. The correction is evaluated in the end of the results section.

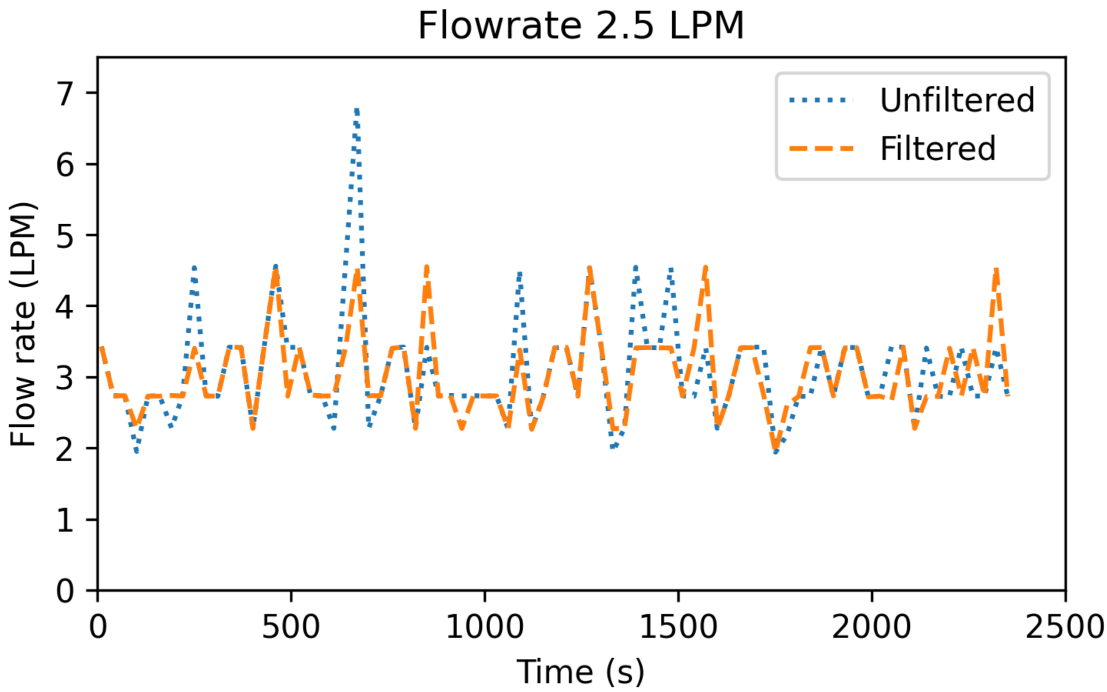

Figure 5: Calculated flow rate for unfiltered and filtered data.

Influence of the filtering process is shown in Fig. 6. The graph on the left shows deformation of the thermal wave due to the filtering. Greater the filter width is, a more peak flatten is created. The graph on the right side shows the influence of filtering on average flow rate. An increase of the filter width resulted in a decrease of standard deviation. The change of average flow rate remained within the order of percent.

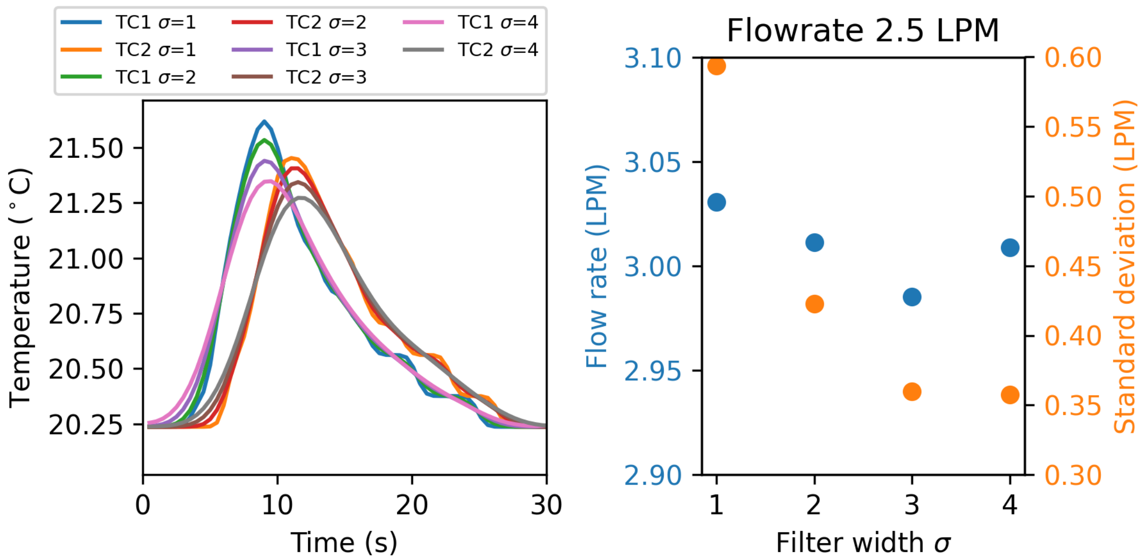

Figure 6: Influence of filter width on thermal wave (left) and calculated flow rate (right).

The influence of the filter width on the calculated flow rate is shown in Fig. 7. A wider filter window led to a decrease of overpredicted flow rates.

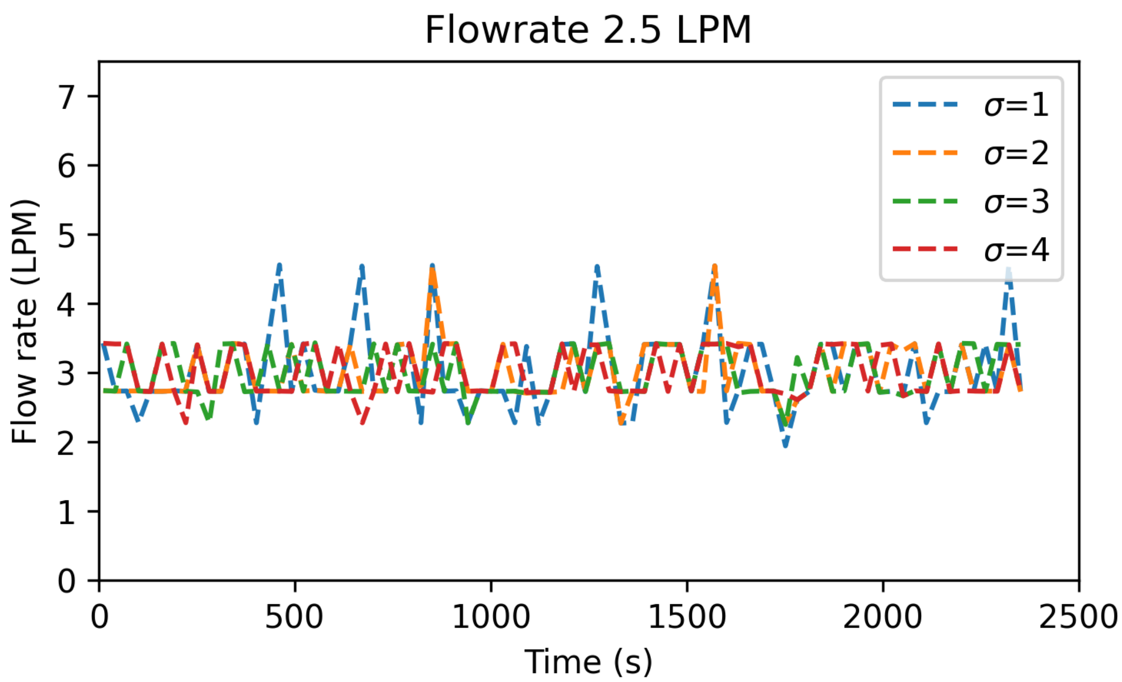

Figure 7: Influence of filter width on calculated flow rate.

Data from experiments shows that not only the filtering process influences the thermal wave. Another large contributor on measured flow rate is the heat pulse itself. A longer time of heat pulse creates a larger thermal wave as it can be seen in Fig. 8 left. The longer heat pulses resulted in a larger value of calculated flow rate and a greater standard deviation.

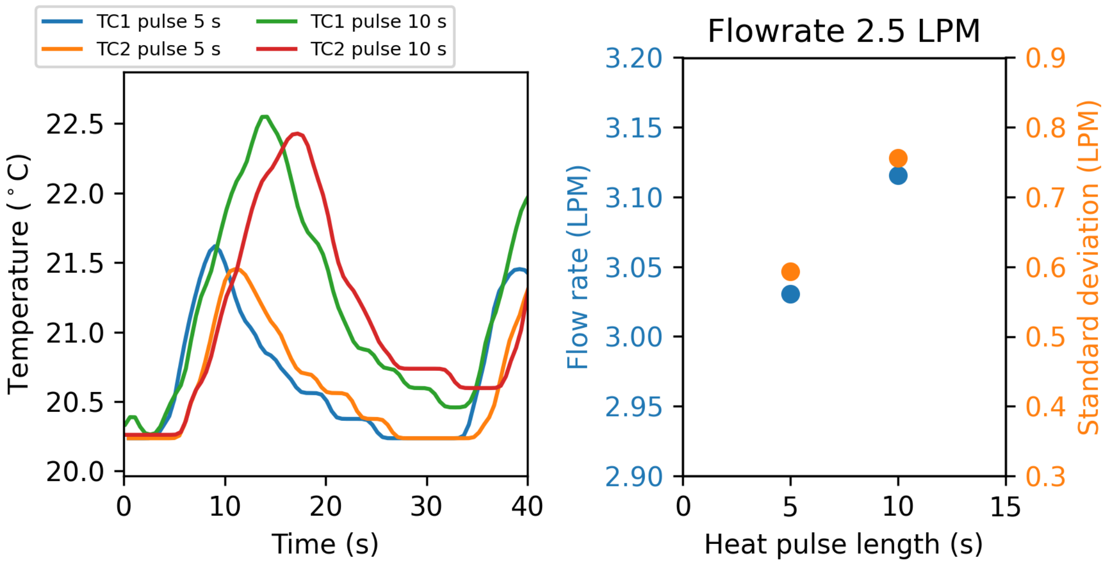

Figure 8: Influence of heat pulse on thermal wave (left) and calculated flow rate (right).

Flow meter tests were performed on three different flow rates. Fig. 8 shows comparison of the measured and reference flow rate for heat pulse 5 s. Further, the graph includes the uncertainty of experimental flow meter stand (light blue area).

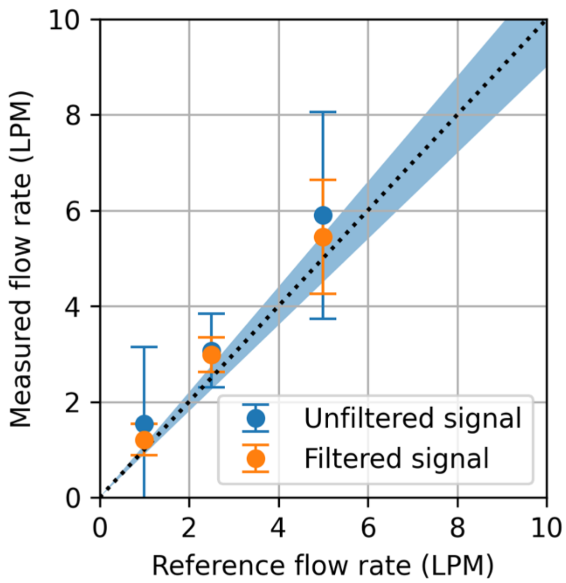

Figure 8: Comparison of measured and reference flow rate.

The uncorrected measured flow rate was higher than the reference flow rate. To overcome such an overprediction, a correction factor based on Reynolds number was applied and correction constants were estimated from the experimental data. The corrected flow rate formula is in form

$$\dot{V} = C_1 \cdot \mathrm{Re}^{C_2} \cdot A \cdot \frac{L}{\Delta t}, \tag{5}$$

where C_1=0.542 and C_2=0.0639. The corrected results are show in Fig. 9.

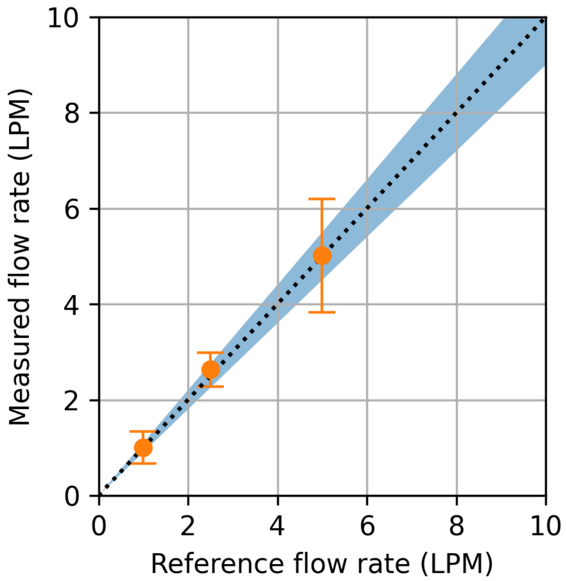

Figure 9: Flow rate from thermal-wave flow meter after the correction.

5 CONCLUSION

This study aimed to verify the thermal-wave flow meter for measurement of molten salt flow. Initial results from experiments with water confirmed the concept of flow measurement using a heat pulse which created a thermal wave and the flow rate was measured based on the time delay of the thermal wave between two sensors. A filtering of the measured signal resulted in a better match with the reference flow rate value. Additionally, a smaller deviation was achieved on the filtered signal. A wider filter window led to a smaller deviation without compromising measured flow rate. Further, a correction based on Reynolds number was introduced in order to incorporate influence of velocity profile on calculated flow rates.

In the future, the flow meter will be installed on the molten salt natural circulation loop, where further tests will be conducted. Additionally, further efforts will be dedicated to the method of evaluating the time delay, specifically the processing of signals from the temperature sensors as a better processing would lead to an increase of flow meter accuracy.

ACKNOWLEDGMENTS

Authors would like to acknowledge support of Technological Agency of the Czech Republic TK03030109.

REFERENCES

[1] Ch. W. Forsberg, P. F. Peterson, P. S. Pickard, Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity. Nuclear Technology, 144, 2003, pp. 289-302.

[2] M. Ruscak, T. Melichar, J. Syblik, O. Frybort, D. Harut, E. Losa, M. Marecek, G. Mazzini, M. Reungoat, J. Pilat, M. Bencik, P. Kral, Energy Well: Concept of 20 MW Microreactor Cooled by Molten Salts. Journal of Nuclear Engineering and Radiation Science, 7, 2021.

[3] M. C. Kahraman, S. Şentürk Lüle, Numerical Investigation of Behaviour of Small Modular Molten Salt Reactor Freeze Plug Under Various Reactor Operation Conditions. Numerical Heat Transfer, Part A: Applications, 20, 2023.

[4] R. I. Dunn, P. J. Hearps, M. N. Wright, Molten-Salt Power Towers: Newly Commercial Concentrating Solar Storage. Proc. of the IEEE, vol. 100, no. 2, Feb. 2012, pp. 504-515.

[5] T. Bauer, Ch. Odenthal, A. Bonk, Molten Salt Storage for Power Generation. Chemie Ingenieur Technik, 93, 2021, pp. 534-546.

[6] J. Spacek, Liquid Salt Flow Measurement Technologies. Czech Technical University in Prague, Master's thesis, 2022.

[7] L. J. S. Bradbury, I. P. A. Castro, A Pulsed-Wire Technique for Velocity Measurements in Highly Turbulent Flows. Journal of Fluid Mechanics, 49, 1971, pp. 657-691.

[8] A. Al-Salaymeh, J. Jovanovic, F. Durst, Bi-directional Flow Sensor with a Wide Dynamic Range for Medical Applications. Medical Engineering & Physics, 26, 2004, pp. 623-637.

[9] T. S. J. Lammerink, F. Dijkstra, Z. Houkes, J. Van Kuijk, Intelligent Gas-Mixture Flow Sensor. Sensors and Actuators A: Physical, 47, 1995, pp. 380-384.

[10] L. W. B. Browne, A. Dinkelacker, Turbulent Pipe Flow: Pressure and Velocities. Fluid Dynamics Research, 15, 1995, pp. 177-204.