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Thermal Wave Flow Meter for Molten Salts Flow Measurements

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Abstract. Flow measurements in molten salt are generally challenging task due high operating temperatures, corrosive environment and salt tendencies to solidify in cold parts. Flow rate measurement using a thermal wave flow meter is a simple and reliable flow rate measurement not limited only to molten salts. The present study focuses on verifying and analyzing the thermal wave flow meter. Several flow meter settings were tested to evaluate flow meter accuracy and reliability. The flow meter was verified on a testing loop with water where an electromagnetic flow meter was used for a reference. First tests showed sensitivity of flow meter on heat pulse length and accuracy of peak location searching for a time delay evaluation.

Keywords: Molten Salt, Thermal Wave, Time-Of-Flight, Flow Measurement

1. Introduction

Molten salts have garnered attention for their diverse applications, including fourth-generation nuclear reactors [1] concentrated solar power plants [2-4] and high-temperature heat storage systems [5-7]. Their utility in these contexts arises from their unique properties, including remarkable thermal stability, high boiling points at atmospheric pressure, and relatively substantial heat capacity. A critical parameter in these applications is the precise measurement of molten salt flow rates, a challenge due to the high temperature and corrosive environments involved [8,9].

While a wide range of commercially available flow meters were used for high-temperature applications, few flow meter designs/methods were introduced for molten salt applications. One viable method for measuring molten salt flow is using an ultrasonic flow meter based on the time-of-flight principle. This flow meter is commonly employed in concentrated solar power plants and heat storage facilities. However, a limitation of this method is its reduced tolerance for high temperatures, which is often overcome by positioning the probe away from the pipeline using an inserted plate [10]. This exposes the flow meter to its surroundings and increases the risk of damaging the sensor. Further, the flow meter`s sensitive probes (wave transmitter and receiver) will be influenced by ionized radiation in case of application for molten salt reactors. Flow measurement using an ultrasonic flow meter was successfully used in the natural circulation loop for FLiBe molten salt [11].

Another commercially available flow meter is a thermal mass flow meter. The principle is based techniques which either measure the rate of heat loss from a heated body in the flow stream or measure the rise in temperature of the flowing medium downstream the heater. [12]. However, the flow meter requires either a long distance between temperature sensors or small flow rates for accurate flow rate measurements. Additionally, heating and measurement blocks with multiple holes were introduced to overcome such limitations [13]. Further, the installation of thermal probes instead of blocks with holes resulted in accuracy improvement [14].

A different approach to flow measurement is based on the time-of-flight principle which is utilizing a heat pulse. This method relies on the determination of the time delay of the thermal wave between two or more measuring points. Although this approach has been explored previously for measuring turbulent flow velocities [15,16], its adoption has been limited due to the emergence of more precise measurement techniques. Nonetheless, the heat pulse flow measurement method has found applications in medical contexts [17] and in the study of gas mixture flows [18]. Another application was an experimental measurement of flow velocity using thermal wave for air and carbon dioxide mixture [19].

The present study is dedicated to validating the flow measurement technique for molten salts using a heat pulse approach. An experimental setup was designed to assess the method's effectiveness, and preliminary measurements were conducted using water as a test medium. The flow meter was tested for several flow rates and thermal pulse conditions to evaluate the influence of settings on flow meter accuracy.

2. Problem formulation

2.1 Flow meter principle

The thermal-wave flow meter investigated in the present study is based on the time-of-flight principle, where the flow rate is calculated from the cross-flow area and measured velocity, which is obtained from the delay of the thermal wave between two positions as is shown in Figure 1. The thermal wave can be detected by temperature sensors such as resistance temperature detectors, thermocouples, etc.

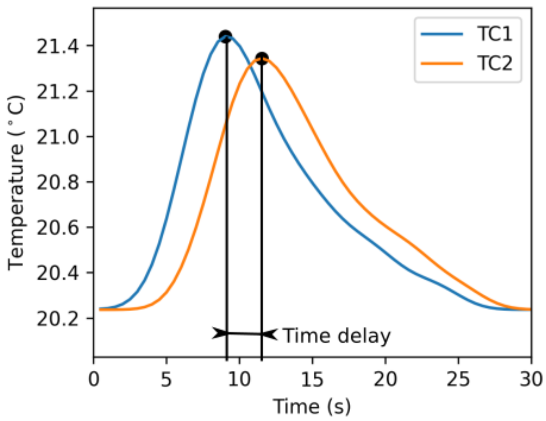

Figure 1. *Time delay of thermal wave between two positions*

The flow rate is calculated from a simple formula:

$$\dot{V} = A\frac{L}{\Delta t} \tag{1}$$

Where A is a flowrate cross-section, K is distance between sensors and Δt is time delay of thermal wave.

However, Δt will depend on the thermocouple position in the flow. Thermocouples located close to the pipe wall would measure a greater time delay of a thermal wave than thermocouples located on the pipe axis. Thus, the equation (1) would only work with inviscid flow. In order to overcome such limitation, a correction has to be applied to incorporate the influence of velocity profile across the pipe on the flow rate. The correction factor should depend on flow parameters such as pipe diameter, temperature, velocity, and fluid properties, thus can be related to the Reynolds number, which is calculated as

$$Re = \frac{DU}{\nu} \tag{2}$$

where D is the pipe`s inner diameter, U is velocity, and ν is kinematic viscosity.

The correction factor will be in the form:

$$C_{corr} = C_1 Re^{C_2} \tag{3}$$

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

The flow rate will be in the form:

$$\dot{V} = C_1 Re^{C_2} A \frac{L}{\Delta t} \tag{4}$$

The distance between measuring points is one of the key factors. A short distance between sensors would require an accurate low-latency acquisition system. A large distance might result in a wave deformation due to thermal mixing and thus, would require a higher power of a heating cartridge.

2.2 Experimental apparatus

An experimental measurement stand was built for the verification and first tests of the flow meter. The flow meter has geometry and dimensions to fit on the natural circulation molten salt loop for further tests with molten salts. The experimental stand was placed in a testing loop, which consisted of one cubic meter water tank, a centrifugal pump, a bypass leg for coarse flow control, and a testing section with reference and thermal-wave flow meters and two additional control valves. The testing section of the loop with the thermal-wave flow meter is shown in Figure 2.

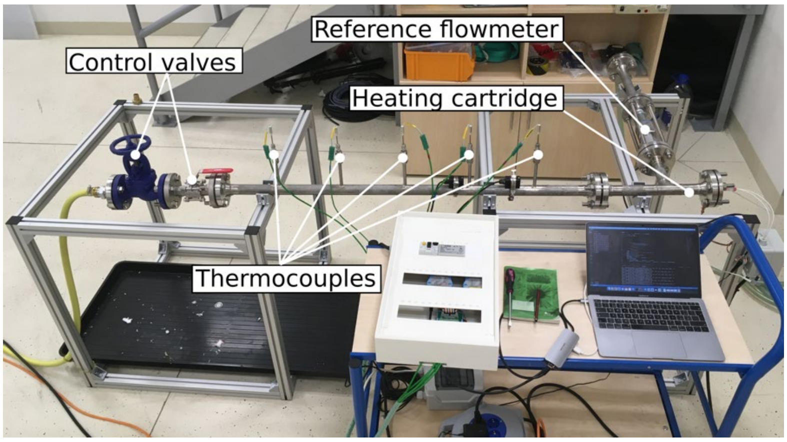

Figure 2. *Flow meter experimental stand setup*

The thermal-wave flow meter was compared against a reference electromagnetic flow meter Endress+Hauser Picomag DMA25 with measurement error ±0.8 \% of reading. The reference flow meter was used to set up a desired flow rate in the test section. The flow rate was set up by three control valves. The first valve was located on the bypass leg for a coarse flow control, and two additional control valves were located downstream of the flow meter for a precise flow rate set up. Five K-type thermocouples were used to capture the traveling thermal wave. Thermocouples were placed along the testing section with a 200 mm spacing where the thermocouple tips were positioned in the middle of the pipe cross-section.

2.3 Flow rate measurements

Measurements were conducted on various flow rates and lengths of heat pulses. The period of heat pulses was 30 seconds to ensure that bulk temperature would reach the initial state and waves would not overlap. Initial tests were performed for relatively low flow rates which are expected in the molten salt loop. An overview of tested variants is in Table 1.

Table 1. *Overview of tested flow conditions and flow meter settings.*

Case	Flow rate (L/MIN)	Reynolds number (1)
Flow rate	1	783
	2	1566
	3	2349
	5	3915
	7.5	5873
	10	7830
	Heat pulse length (s)	**Period (s)**
Heat pulse	2.5	30
	5	30
	10	30

2.4 Signal filtering

Initial results indicated the necessity for data filtering due to a poor resolution of the thermal wave and the corresponding wave`s peak location. The filtering process was done using the Gaussian filter.

$$h_\sigma(i) = \sum_{u=-z}^{z} \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{u^2}{2\sigma^2}\right) f(i-u) \quad (5)$$

where f is the discrete unfiltered value, h is the value after filtration, i is an index of the actual filtered value, u is a discrete index, and z is half of the filter window.

The influence of filtering on temperature signal is shown in Figure 3.

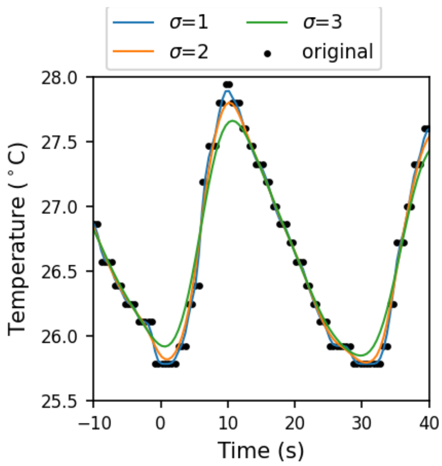

Figure 3. *A sample of filtering effect on measured signal.*

2.5 Uncertainty analysis

Flow rate in the testing section was not constant during the experiment and thus influenced thermal flow meter accuracy. Uncertainty of the flow rate in the testing loop was evaluated based on flow rate variations and reference flow meter accuracy.

$$u_{FR} = 1.96\frac{s_{FR}}{\sqrt{n}} \quad (6)$$

where coverage factor 1.95 corresponds to the 95 % confidence interval, s_{FR} standard deviation of the flow rate measurement and n is number of flow rate readings. The total uncertainty of the flow rate during the experiment was calculated as a combination of flow rate measurement uncertainty u_{FR} and the reference flow meter uncertainty u_{FM}

$$u_{loop} = \sqrt{{u_{FR}}^2 + {u_{FM}}^2} \quad (7)$$

The maximum flow rate uncertainty was achieved for the flow rate of 5 L/MIN, and the lowest uncertainty was for 10 L/MIN. Relatively high uncertainty in the region 2.5-5 L/MIN corresponds to the laminar-turbulent transition in the testing loop, where flow rates above 5 L/MIN are in fully turbulent flow. Results from testing loop uncertainty analyses are shown in Table 2.

Table 2. *Uncertainty analyses of flow rate in the testing loop.*

Flow rate (L/MIN)	Standard deviation (L/MIN)	Flow rate uncertainty (L/MIN)
1	0.081	0.051
2	0.110	0.068
5	0.121	0.076
10	0.064	0.04

3. Results

Results of averaged flow rates obtained from the thermal wave flow meter are shown in Figure 4 and the corresponding relative error is shown in Figure 5. All three tested pulses led to a close match of the calculated flow rate with a reference flow rate of up to 5 L/MIN. Measurements for the flow rate of 10 L/MIN evinced a significant error among all tested heat pulses and the current flow meter design seems to be inappropriate for higher flow rates. Further, the 2.5-second pulse was too short to capture the wave accurately, and the signal was rather full of noise than period waves, thus, no reasonable value was measured. The filtering process resulted in a lower flow rate deviation. The optimal filtering window is 3-4 σ as it evinced the lowest deviation for flow rates up to 7.5 L/MIN. A higher filtering window led to an ambiguous result as for some flow rates, it led to an improvement and for others to worse results.

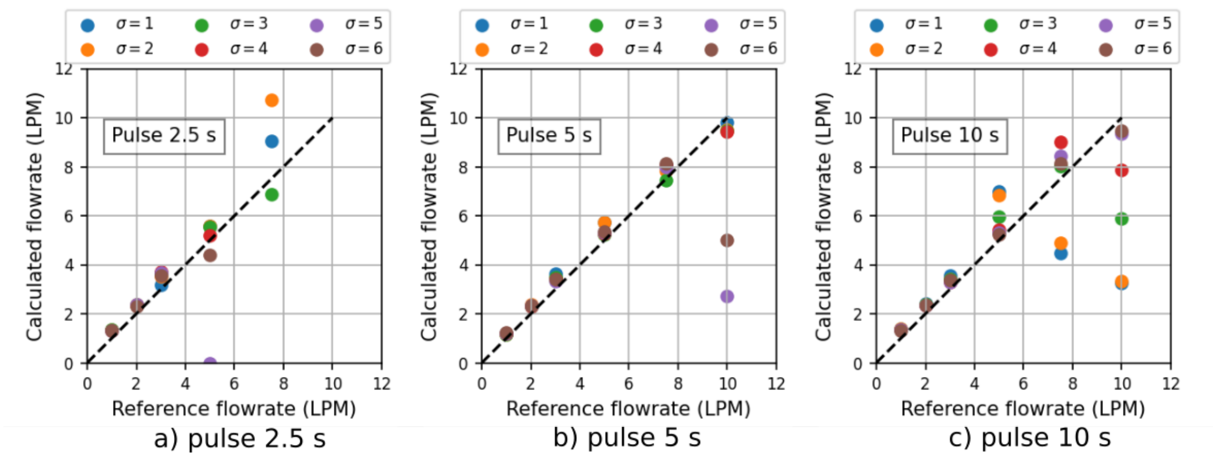

Figure 4. *Comparison of calculated uncorrected flow rates against reference value; influence of heat pulse length and filtering window* σ*.*

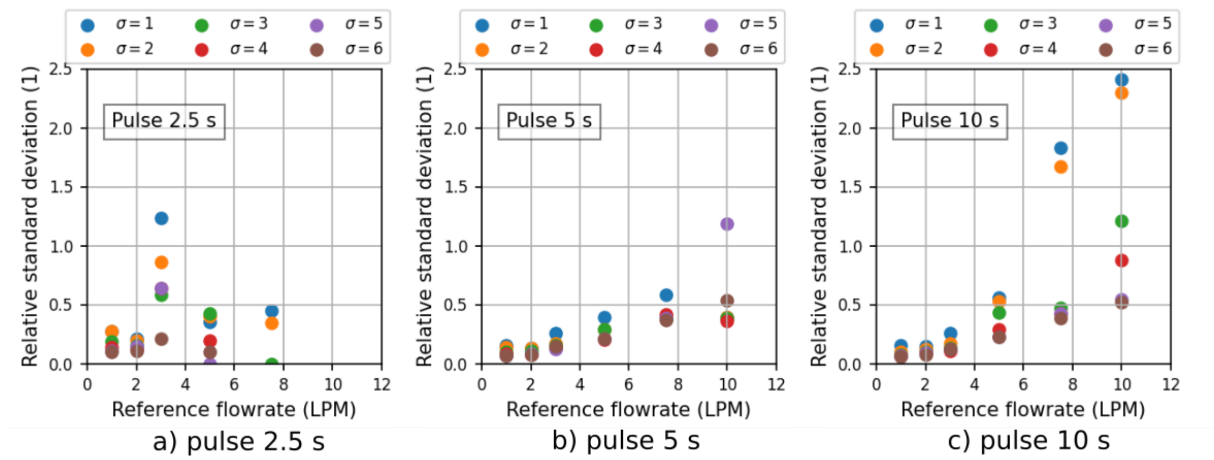

Figure 5. *Relative standard deviation of calculated uncorrected flow rates.*

Thermal wave traveling through the flow meter is affected by thermal mixing and it becomes flatter and wider. The deformation of the thermal wave is visible from temperature signals shown in Figure 6. The thermal wave captured in the first two sensors has a visible peak location. However, a flattened wave is captured further downstream. This deformation influences the peak search algorithm as the wave`s peak is ambiguous, which results in a significant deviation of the calculated flow rate. Further, the increase of flow rate leads to a more intensive mixing, and the wave becomes flatter earlier than in the case of small flow rates. The filtering process with a broader window led to a reduction of the wave`s flat top; however, it resulted in a slight time shift of the peak due to the asymmetry of the peak. The average time shift was 7.6 % in comparison with unfiltered data, which led to a reduction of the average calculated flow rate from 5.9 L/MIN to 5.45 L/MIN. Further, flow analyses showed that the velocity in the middle of the pipe is 26 % and 22 % higher than the average velocity for TC-1 and TC-2 locations.

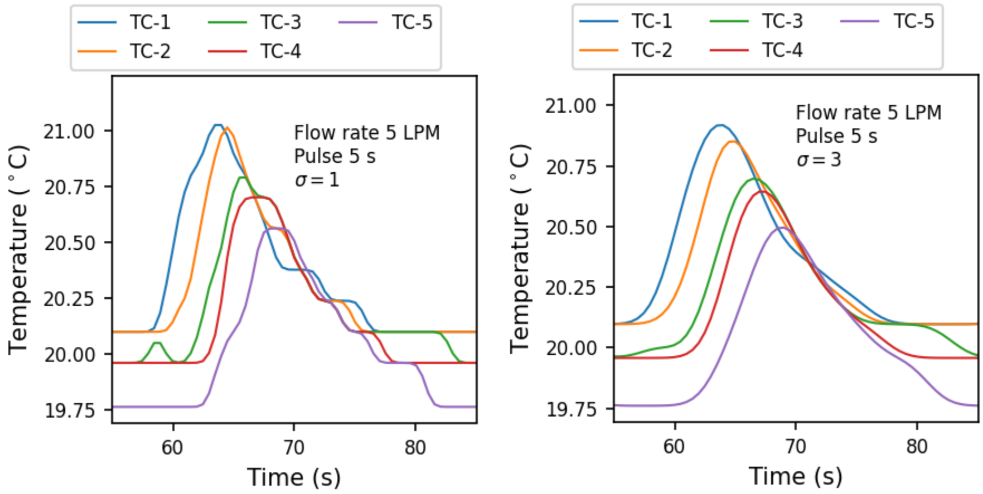

Figure 6. *Thermal wave deformation in flow meter; left: filter width σ=1, right filter width σ=2.*

4. Conclusions

The present study focused on the experimental of the thermal wave flow meter. Several flow rates and heat pulse setups were experimentally measured and measured flow rates were compared against flow rates from the reference flow meter. The outcomes of the study are:

- The thermal-wave flow meter design was successfully validated on low temperature medium (water) with sufficient accuracy on low flow rates.
- Thermal mixing downstream of the heating cartridge resulted in the deformation of thermal waves and higher uncertainty of calculated flow rates.
- A poor resolution of the acquisition system resulted in higher results deviations on higher flow rates.

Data availability statement

Data are available upon request.

Author contributions

Jan Škarohlíd: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing – review & editing; Tomáš Kořínek: Data curation, Formal Analysis, Software, Validation, Visualization, Writing – original draft ; Radek Škoda: Funding acquisition, Supervision.

Competing interests

The authors declare that they have no competing interests.

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