

Chapter 57

A Simple Flowmeter for Fluids at High Temperature



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Abstract High temperature and corrosion are the challenging obstacles for any device to be used for molten salt flow measurement. Existing flow measuring devices have limitations due to operating temperatures above 550 °C, corrosion, maintenance, and high cost. We have introduced a simple and economical method of high-temperature flow measurement which involves measuring the time interval between changes in temperature of successive K-type thermocouples. The device is calibrated using cold and hot water, within the selected range of temperature 30–80 °C, and the non-dimensional thermophysical properties of molten salt and water are nearly matched. The results obtained show the device is capable of measuring the flow rates with less than 10% error.

Keywords Flow measurement · Molten salt · Flow measuring device · High temperature · Thermocouple

57.1 Introduction

Continuous and accurate flow measurement in high-temperature molten salt-based solar thermal plants on both energy collection and energy delivery sides is very important to control the temperature and other system parameters. High operating temperature, corrosive nature of salt, and high cost are the limitations of existing flowmeters. The various flowmeters including ultrasonic flowmeter, venturi, wedge element and orifice meters, vortex flow meter, turbine flowmeter, and magnetic flowmeter are used for high-temperature molten salt; however, each of them suffers from some limitations. Inline ultrasonic meters, orifice plate, or vortex meters are prone to clogging, making them unreliable [1]. Although magnetic flowmeters have been used at high temperatures (870 °C) for liquid metal systems, containment and low conductivity of molten salt prevent its use [2]. Ultrasonic flowmeters of Krohne make were tested at Molten Salt Test Loop (MSTL) facility, Sandia National Laboratory,

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in Albuquerque, NM, the USA [3]. The results show that meter worked accurately below the temperature limit of 535 °C, although SANDIA received special guarantee up to 585 °C [4]. Also, the insulation of ultrasonic flowmeter was prohibited and was exposed to the atmosphere and had to be trace heated. This consumed a large amount of energy during the non-flow period [3]. The Ultrasonic flowmeter with a bundle waveguide system suitable up to 600 °C is available from GE measurement and control [5] and Flexim [1]; however, minimum pipe sizes required are 3 inches and 1.5 inches, respectively. Ultrasonic flowmeters provide a noninvasive, high accuracy, and turn-down range option but they are extremely expensive. Hence, an alternative flow measurement method is needed which is reliable, economical, fairly accurate, and durable [2–4, 6]. Brito et al. [5] and Eckert et al. [6] have proposed an ultrasonic Doppler velocimetry for velocity measurement in liquid metals at 700–800 °C, but a significant loss in piezoelectric properties was observed. Also, an oxide formation in liquid metal scattered the ultra-sound making it impossible to propagate far enough. Mcenally et al. [7] have proposed and demonstrated thermocouple particle densitometry (TPD), a thermocouple-based method for measuring absolute soot volume fraction in flames.

A thermocouple-based blood flow sensor was invented and patented by Nelson et al. [8] which uses temperature difference sensed by thermocouple to measure blood flow. A simple and economic high-temperature flow measurement method is introduced here which uses K-type thermocouple temperature sensors. The proposed flow measuring device (FMD) consists of a vertical flow pipe with a set of K-type thermocouples placed centrally and vertically equidistant. A heat tracing element is externally wrapped around the flow section pipe. A bypass pipe section is also provided so that the flow can be continued during the operating cycle. The fluid initially trapped inside the flow pipe section is heated by the heat trace element and maintained at constant higher temperature than the colder fluid. During flow measurement, the hot fluid is allowed to be displaced by the colder fluid. As the cold front reaches to the thermocouple sensor, it records a drop in the temperature. The time recorded between the temperature drops of two successive thermocouples provides the flow velocity as the distance covered by the fluid front is known. Water is used to calibrate the FMD device as it provides the ease of operation, and also the temperature range of water 30–80 °C is so selected that it closely matches with non-dimensional thermophysical properties of molten salt like density ratio, viscosity ratio, and Atwood number.

57.2 Flow Measuring Device (FMD)

Considering the limitations of flow measurement of high-temperature molten salt at and above 550 °C, a new and simple flow measuring device (FMD) is designed. The FMD consists of flow section and bypass section, each made up of an alloy steel pipe with an inner diameter of 80 mm and height of 500 mm. The five K-type thermocouples T_{h1} , T_{h2} , T_{h3} , T_{h4} , and T_{h5} were placed centrally at 100 mm apart

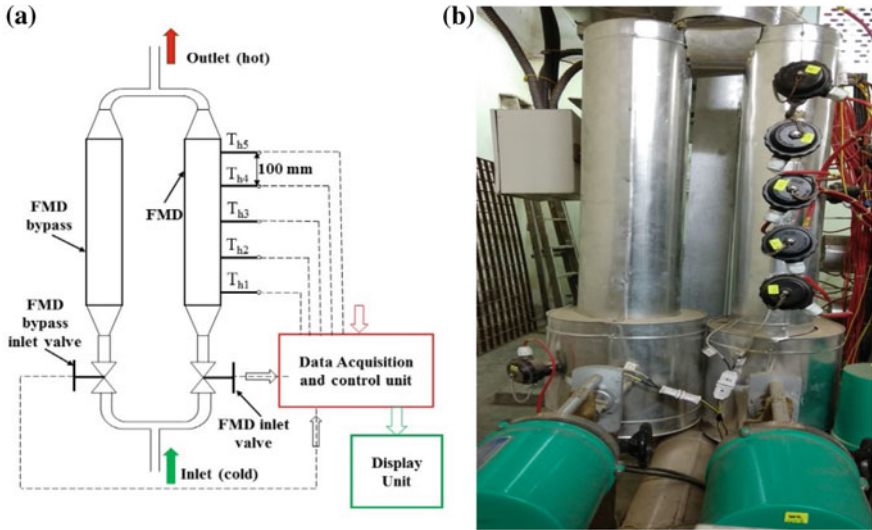


Fig. 57.1 Schematic of the flow measuring device (a), actual FMD device installed at laboratory scale molten salt loop (b)

vertically, as shown in Fig. 57.1. A heat trace element is externally coiled around the flow measuring section so as to provide a uniform high-temperature heating of the cold fluid inside the FMD section. The FMD section initially filled with a cold fluid is heated to a uniform high temperature and maintained constant so that each thermocouple displays the same high temperature. During flow measurement, colder fluid is introduced from the bottom of the FMD which displaces the hotter fluid upwards causing the cold temperature front to travel along the height. The time required for the temperature front to travel from bottom to top ($T_{h1}-T_{h5}$) is recorded. Volumetric flow rate can be estimated using Eq. (57.1), where ‘ Q_v ’ is volumetric flow rate, ‘ A_c ’ is an inner cross-sectional area of the FMD pipe, and ‘ x ’ is the successive distance between two thermocouples. This flow measuring device has a limitation that continuous flow measurement is not possible as it requires time for heating after every flow run measurement cycle.

$$Q_v = A_c \times x/t_a \tag{57.1}$$

57.2.1 Experimental Setup and Procedure for FMD Calibration

As shown in Fig. 57.2a, the water heater tank has a gravity head of around 2.3 m above the FMD inlet at the bottom. A hot water line from the bottom of the hot water

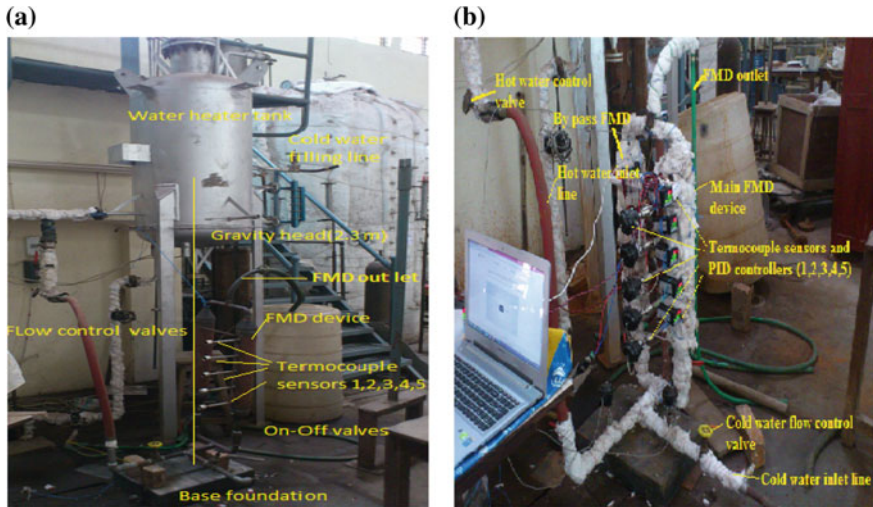


Fig. 57.2 Experimental setup for FMD calibration without insulation (a), with insulation and data logging (b)

tank and the cold water line are connected to the bottom of the FMD section with a tee connector. The hot water is allowed to flow under gravity through the FMD. The cold water is controlled using a ball valve. Five K-type calibrated thermocouples connected with PID display and SCADA data logging system are used to record the temperature data as shown in Fig. 57.2b. A calibrated measuring container was used to collect the flow from FMD outlet to measure flow rate during calibration test.

The water heating tank initially filled with cold water at 30 °C is heated to a temperature of 80 °C by an electric heater, and all the valves are kept closed. The hot water is allowed to flow under gravity through the FMD section by opening the hot water valve. The FMD section is filled with hot water and is allowed to remain at a uniform temperature of around 70 °C along the height. The bypass FMD section is filled with cold water during the test. As the FMD section attains a constant temperature, hot water valve closed and cold water at 28–30 °C is allowed to flow through the FMD section by marginally opening the cold water valve at bottom of FMD. As the cold waterfront moves upwards, a temperature drop along the height of the FMD section was observed and recorded. The hot water displaced by cold water flows out from the outlet of FMD at the top. The flow rate is manually measured collecting outlet in a measuring container and the time required to fill it. The procedure was repeated for different flow rates by adjusting the cold water valve.

57.3 Results and Discussion

Considering the difficulties of operating molten salt at a high temperature nearly 400–450 °C, water was selected as fluid for FMD calibration. Water temperature range is selected so that it nearly matches the non-dimensional thermophysical properties of molten salt like density ratio, viscosity ratio, and Atwood number. Table 57.1 provides the comparative analysis of non-dimensional thermophysical parameters for a selected range of temperatures [9, 10].

57.3.1 Calibration and Error Estimation

Calibration and error estimation were carried out for this new FMD using hot and cold water. The hot water was displaced by the cold water and was collected in a measuring container. The time required to collect a certain quantity of fluid in the container provides the flow rate. Temperature change per second was recorded using SCADA system. The temperature profile for 0.86 LPM flow is plotted in Fig. 57.3 which shows the temperature drop recorded by each thermocouple as the temperature front passes through.

The time difference ‘ Δt ’ required to displace hot water through fixed volume between the sections of each sensor by cold water is recorded to estimate volumetric flow rate, liter per minute (LPM) using the Eq. (57.2)

$$\text{Volumetric flow rate (FR)} = \frac{\rho_w * V * 60}{\Delta t} \quad (57.2)$$

where ρ_w is the cold water density (Kg/m³), V is the section volume between two successive sensors (approximately 0.000468 m³), and Δt is the time (seconds) difference for temperature drop between successive temperature sensors ($T_{h1} - T_{h2}$, $T_{h2} - T_{h3}$, $T_{h3} - T_{h4}$, $T_{h4} - T_{h5}$). The standard deviation error in the measurement is calculated using Eq. (57.3).

$$\sigma_x = \sqrt{\frac{1}{n-1}} * \sum_{i=1}^n (x_i - x')^2, x' = \frac{\sum x_i}{n} \quad (57.3)$$

Table 57.1 Comparative parameter for water and molten salt on the basis of the temperature range

Fluid type	Low temperature (°C)	High temperature (°C)	Temperature difference (°C)	Density ratio	Viscosity ratio	Atwood number
Molten salt	200	300	100	1.03	2.63	0.019
Water	30	80	50	1.02	2.24	0.012

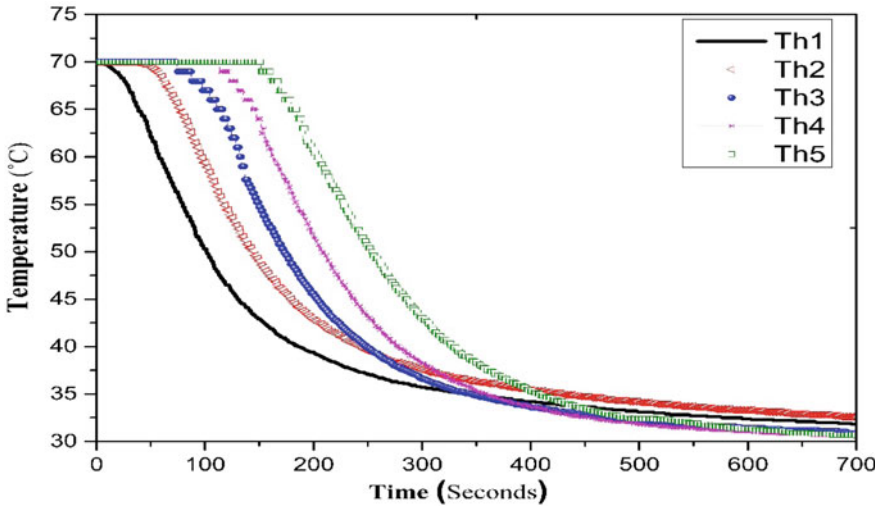


Fig. 57.3 Temperature plot per unit time for flow rate of 0.86 LPM

As in Eq. (57.3), ‘ σ_x ’ is the standard deviation, ‘ n ’ is the number of sample values, ‘ x_i ’ is the sample value, and \bar{x} is the average sample value. Table 57.2 gives a comparative analysis of flow rate measurement for FMD and measuring container. Estimated error in flow measurement was approximately $\pm 4.8\%$ and $\pm 9.5\%$ for corresponding flow rates of 0.86 LPM and 1.95 LPM. At lower flow rates, measured error decreases which indicates that the FMD is suitable for low flow rate measurements. As the cold fluid front reaches the sequential thermocouples, temperature trend lines bend downwards. At higher flow rates, the measurement error increases but is still less than 10%.

Table 57.2 Comparative analysis of flow measurement

Measuring container (LPM) (a)	FMD (LPM) (b)	Measured error (LPM) (a – b)	% error	Standard deviation	Standard error bar
0.86	0.803	0.057	5.7	0.0032	± 4.8
	0.901	-0.041	-4.1		
	0.762	0.098	9.8		
	0.782	0.078	7.8		
1.95	1.85	0.1	10	0.00098	± 9.5
	1.98	-0.03	-3		
	1.74	0.21	21		
	1.85	0.1	10		

Table 57.3 Molten salt pump power and corresponding FMD flow rate correlation

Pump power VFD (Hz)	Pump (RPM)	Mass flow rate (kg/min) or (LPM)	Velocity (m/sec) inside		Standard deviation	% error of mean
			Inlet pipe	Tank		
8	180	0.64	0.027	5.8×10^{-5}	0.0007	10.97
10	206	0.877	0.036	7.8×10^{-5}	0.0030	7.28
12	232	1.06	0.044	9.5×10^{-5}	0.0037	7.98
15	306	1.26	0.052	1.02×10^{-4}	0.0011	5.27
18	376	1.35	0.076	1.06×10^{-4}	0.001	5.77
20	405	1.71	0.081	1.2×10^{-4}	0.0016	6.52
22	457	2.02	0.089	1.9×10^{-4}	0.0072	4.85
25	504	2.65	0.115	2.4×10^{-4}	0.0017	6.25
30	604	3.31	0.139	2.9×10^{-4}	0.0006	2.87

57.3.2 FMD Flow Rate Correlation with High-Temperature Molten Salt Pump in Molten Salt Setup

The flow rate measurement by FMD section fitted in the 30 kWh molten salt setup is correlated with the molten salt pump speed variation. In order to set the flow rate, a variable-frequency drive (VFD) input was calibrated with FMD. Pump power frequency (Hz) to flow rate correlation was established as given in Table 57.3. The data for varying flows through FMD was collected. Average mean, standard deviation, and standard error of mean were identified using Eq. (57.4), where ' σ_m ' is the standard error of the mean, ' σ_x ' is a standard deviation, and ' n ' stands for a number of samples. Figure 57.4 illustrates the pump speed to flow rate correlation. Flow rate linearly increases with increasing pump power and speed.

$$\sigma_m = \sigma_x / \sqrt{n} \quad (57.4)$$

57.4 Conclusion

A simple and economical device for intermittent measurement of volumetric flow rate of hot and corrosive fluids is designed. The FMD is calibrated, and estimated error identified in flow measurement is less than 10%. FMD flow rate correlated with molten salt pump corresponding speed shows almost linear progression. The result obtained can be scaled to predict molten salt flow measurement. The device is installed in a laboratory scale molten salt loop.

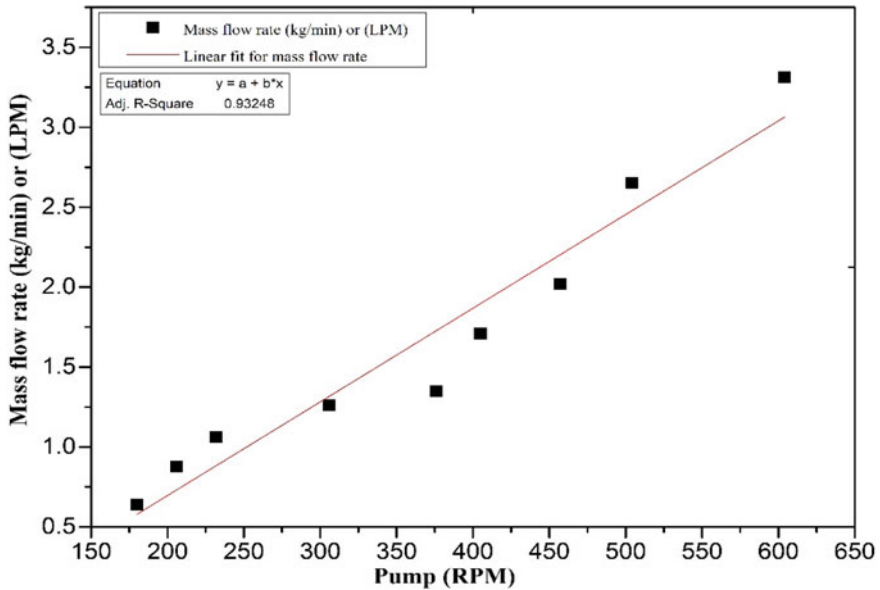


Fig. 57.4 The graph plotted for varying pump speed (RPM) against fluid flow rate measured by FMD

Nomenclature

A_c	Cross-sectional area
Q_v	Volumetric flow rate
V	Section volume between two successive thermocouples
X	Distance between two successive thermocouples
T	Local temperature ($^{\circ}\text{C}$)
t_a	Average time (sec)
T_h	Thermocouple
Δt	Time difference
FMD	Flow measuring device
FR	Flow rate
HTF	Heat transfer fluid
PID	Proportional integral derivative
VFD	Variable frequency drive
ρ_w	Water density
σ_x	Standard deviation
σ_m	Standard error of mean

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