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A Review of Measurement Technologies for Temperature, Pressure, Flow, and Level in Molten Salt Reactor Environments

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1. Introduction

MSR (Molten Salt Reactor) have garnered significant attention due to their safety and economic advantages, with active research being conducted both domestically and internationally. MSR operate in high-temperature (approximately 650°C) and high-radiation environments, conditions that differ significantly from those of conventional commercial reactors, making the application of existing measurement instruments challenging. Sensor materials can experience deformation, degradation, and corrosion in high-temperature environments, necessitating the use of sensors that remain reliable throughout the extended operational lifespan of MSR. This paper introduces the current state of sensor technologies for measuring temperature, pressure, level, and flow in MSR environments and proposes directions for the development of measurement technologies optimized for MSR conditions.

2. Methods and Results

In this section, we have investigated and selected measurement methods for temperature, pressure, flow, and level instruments from various reports that either meet or show potential to meet the environmental requirements of high temperature, corrosion, and high radiation, considering the unique operational conditions of MSR.

2.1 Thermometry

Thermocouples are advantageous for their ability to measure a wide range of temperatures, from -298 to 1650°C.They function by measuring the voltage differences that arise from different combinations of metals, leading to various types of thermocouples. Each type has a distinct maximum operating temperature and level of corrosion resistance. In the context of Molten Salt Reactor (MSR), Type N and Au-Pt thermocouples are particularly relevant.[1] Type N thermocouples can operate at temperatures up to 1300°C and are characterized by minimal performance degradation and de-calibration at this temperature. Au-Pt thermocouples, on the other hand, are suitable for temperatures up to 1000 °C and offer high accuracy, with a tolerance of ±10 mK below 1000°C. Typically, thermocouples are protected by sheaths and thermowells, preventing direct contact between the temperature sensors and molten salts, making them suitable for use in MSR environments.

As shown in Fig. 1, the Type B thermocouple, made of Pt-Rh, is known to have the widest temperature measurement range. According to the Rensselaer Polytechnic Institute, for temperature measurements in MSR, OMEGA's high-temperature platinum thermocouples, capable of operating up to 1650°C, are recommended.[4]

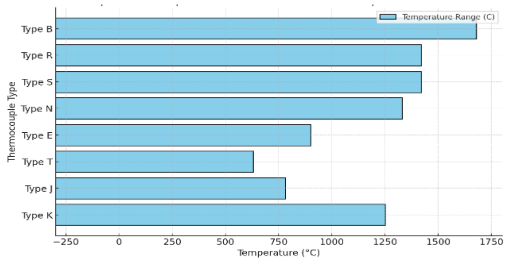

Fig. 1 Temperature Measurement Range by Thermocouple Material

2.2 Pressure measurement

Rensselaer Polytechnic Institute recommends Sporian's SmartCap 850 IM™ Isolated Media Pressure Sensor for measuring pressure in their MSR loop systems.[4] This sensor utilizes capacitive sensing principles to measure the pressure of gases and liquids, and it also integrates a K-type thermocouple for temperature measurement. Notably, it is capable of operating in extremely high-temperature environments, up to 850°C, and is highly compatible with corrosive media. Furthermore, its ability to withstand harsh molten salt environments makes it appear to be an ideal choice for such applications. However, additional investigation is needed as the information regarding radiation resistance is not clearly confirmed.

2.3 Flow measurement

The ultrasonic flow meter is a non-contact device that measures fluid flow by transmitting ultrasonic signals from the exterior of a pipe. This method offers the advantage of avoiding direct contact with the salt, thereby minimizing corrosion and radiation-induced damage. According to the Massachusetts Institute of Technology, experiments were conducted using an ultrasonic flow meter for flow measurement, specifically utilizing a product from FLEXIM.[2] Generally, the transducers in ultrasonic flow meters are challenging to operate at temperatures above 200 °C. Therefore, a Wave Injector is required for operation at 650°C, enabling the system to function at temperatures up to 750°C. Additionally, FLEXIM's transducers are designed to withstand radiation levels up to 5 × 10^5 Gy. The materials used in the transducers are selected for their radiation resistance, with the most sensitive material being Viton, which can also endure up to 5 × 10^5 Gy. (Table I) Thus, FLEXIM's ultrasonic flow meters show potential for withstanding the extreme conditions of MSR environments, including high temperatures, salt-induced corrosion, and high radiation levels. However, further testing and evaluation in MSR operational environments are necessary to advance the commercialization of this measurement method.

Table I: Radiation Resistance of Components in FLEXIM's Transducer [3]

Transducer Part	Material	Radiation Resistance [Gy]
Housing	Stainless Steel	Not Affected
Transducer Body	PEEK	10^7
Backing	**Viton**	**5 x 10^5**
Filler	Silicone Pottant RTV160, 6200LV	10^7 - 10^8
Inner Coupling Material	IS Fluid	10^6 - 10^7
Temperature Probe	Ceramic Substrate, Platinum	Not Affected
Acoustic Coupling Material	**Viton**	**5 x 10^5**

2.4 Level measurement

ORNL(Oak Ridge National Laboratory) recommends a Guided-Wave radar (level measurement method) that uses microwaves to measure the flight time from the radar gauge to the molten salt. This method provides continuous readings, allowing for real-time monitoring of the salt levels. Also, the transmitter is located outside the high-temperature zone, reducing potential damage from heat and radiation [5].
The radar level measurement method has also been applied in Terrapower's MCRE(Molten Chloride Reactor Experiment) and is identified as one of the models from VEGA's Radar sensor-VEGAPLUS 6X series. This model can operate at temperatures up to 450°C. However, a disadvantage is that salt vapor can accumulate on the transmitter, potentially shortening its lifespan. Furthermore, since the transmitter is located outside the high temperature environment, it is necessary to obtain temperature and radiation field data at this location to assess its suitability for use.

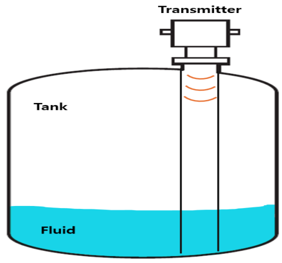

Fig. 2 Guided Wave Radar for Measuring Liquid Level in a Tank

3. Conclusions

This study reviewed various measurement methods that are suitable or show potential for the extreme conditions of MSR operation, such as high temperatures, corrosion, and high radiation. Specifically, based on MSR loop research data from multiple studies, temperature, pressure, flow, and level instruments were categorized according to their suitability for these environmental conditions. They were classified into stages such as 'Feasible,' 'Improvement needed,' and 'Testing required,' as shown in Table II. This indicates that, to ensure the reliability of measurements in extreme environments, including MSR, it is necessary not only to improve existing technologies but also to develop new approaches.

Table II: Applicability of Measurement Instruments by Environmental Conditions

Measurement instrument	High temperature	Corrosion	High radiation
Temperature(1) [4]	Feasible	Feasible	Testing required
Pressure(2) [4]	Feasible	Feasible	Testing required
Flow(3) [2]	Feasible	Feasible	Feasible
Level(4) [5]	Feasible	Improvement needed	Testing required

(1) Thermocouple(Type N,B), (2) Capacitive Sensor, (3) Ultrasonic Flow Meter, (4) Guided wave Radar

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