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Infrared thermometry for molten salt application

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1. Introduction

The use of infrared thermometry for non-contact temperature measurement is an important tool in various industrial fields. This technology allows for quantitative evaluation by comparing it with contact methods such as thermocouples. While the emissivity and transmissivity, which are typical uncertainty factors, are well-known for infrared thermometry on metal surfaces, there is significant uncertainty in measuring the temperature of molten salts during spreading phenomena that involve phase change and fluid flow. For typical molten salts like NaCl and KCl, values for these properties are clearly known in their solid state. However, they vary as functions of temperature and surface properties under the conditions of fluid flow and phase change.

Molten salt cannot be approximated as a gray body because its radiation behavior is governed by wavelength-dependent ionic vibrational modes rather than free-electron dynamics [1]. In contrast to metals, where abundant conduction electrons respond broadly to infrared radiation and yield relatively weak spectral dependence of emissivity, molten salts remain electronically insulating even in the liquid state. Their infrared interaction originates from collective ionic oscillations and short-range structural correlations, which produce resonance-type absorption bands analogous to broadened Reststrahlen features [2]. As a result, the complex dielectric function varies strongly with wavelength, leading to pronounced spectral dependence of emissivity and partial transparency in certain band of wavelength [3]. Therefore, infrared thermometry of molten salt exhibits significant band-dependent deviations, reflecting the fundamentally non-gray and non-Drude nature of ionic molten salts. This study presents experimental results on the assessment of infrared thermometry for evaluating the spreading phenomenon of molten salts according to the wavelength band.

2. Methods and Results

2.1 Review of literatures

Argonne national laboratory conducted the infrared thermometry about two types of molten salt (FLiNaK, NaCl-UCl3) for molten salt reactor application [4,5]. FLIR T540 (LWIR, 7.5-14 micron) measured the salt temperature in the molten pool and spreading channel. They reported that LWIR underestimated the temperature of molten salt in the molten salt pool compared to the thermocouple because of its high transmissivity. Thin layer of salt during spreading does not represent the actual salt temperature with infrared thermometry.

Pacific northwest national laboratory conducted the infrared thermometry to evaluate the emissivity of NaCl-KCl binary salt [6]. Williamson pyrometer (SWIR, 1.3 micron) measured the salt temperature in the molten pool and it is compared to the thermocouple to find actual emissivity using infrared thermometry. From 850 to 550C, emissivity of NaCl-KCl is from 0.78 to 0.90, which is function of temperature. Based on the literature survey, it is summarized that (i) transmissivity of the molten salt is high and makes it difficult to measure the salt temperature of thin layer during spreading and (ii) determination of wavelength is important to apply the infrared thermometry because molten salt behaves non-gray body whose emissivity varies with wavelength and temperature.

2.2 Test condition

Present study conducted the experiment with two types of molten salt condition: static pool and spreading channel. Temperature range is 600, 650, 700, and 800 C, which is the based on the melting temperature of NaCl-KCl (5:5), 645 C in the static pool. Especially, it is hard to select the wavelength criteria when the infrared camera is used. Present study tested three types of infrared camera: SWIR (Short Wavelength InfraRed, 0.9-1.7 um), MWIR (Medium Wavelength InfraRed, 3-5 um) and LWIR (Long Wavelength InfraRed, 7.5-14 micron). It is assumed that all test for infrared thermometry are used 1.0 for salt emissivity. In the test for SWIR, pyrometer (1.45-1.8 micron) is used together for the reference.

2.3 Static pool

Through the penetration port located at the top of the furnace, the temperature of the molten salt was measured. The results showed that, compared with LWIR and MWIR, the SWIR exhibited a relatively smaller temperature difference with respect to the thermocouple and demonstrated higher accuracy. In the case of LWIR, a temperature difference of approximately 50°C was observed compared to the thermocouple. However, analysis of the count value (raw data) revealed a linear dependence on temperature. This indicates that the discrepancy is not due to an intrinsic error of the LWIR camera itself, but rather reflects the uncertainty associated with molten salt temperature analysis within the corresponding wavelength range (7.5–14 μm).

Table.I IR thermometry for molten salt according to wavelength

	LWIR	MWIR	SWIR	SWIR*
Temp_TC [C]	829	-	833	833
Temp_IR [C]	871	-	820	839
Temp_TC [C]	750	750	783	783
Temp_IR [C]	772	790	780	790
Temp_TC [C]	656	-	676	676
Temp_IR [C]	698	-	685	691
Temp_TC [C]	590	-	633	633
Temp_IR [C]	649	-	643	650

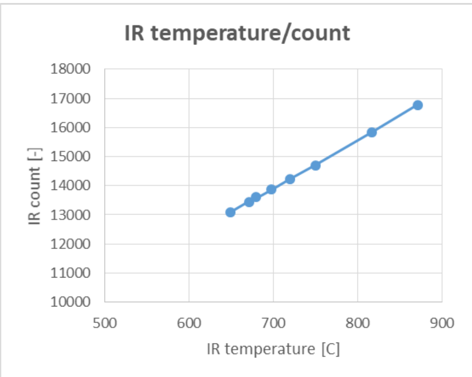

Fig.1 Count-temperature relation of LWIR camera

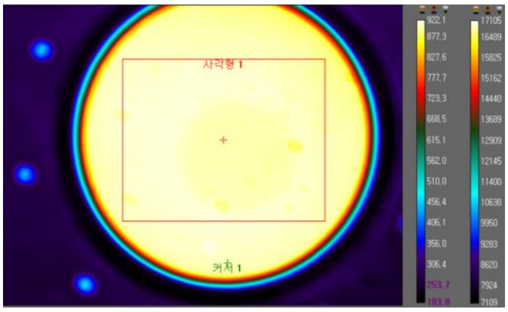

Fig.2 Snapshot of molten salt temperature (LWIR, Temp_TC : 829C)

2.4 Spreading channel

The temperature of the molten salt in the spreading channel was measured at two primary locations: the channel inlet nozzle and the molten spreading channel surface. Compared with LWIR and MWIR, SWIR showed temperature measurement results at the channel inlet that were consistent with the thermocouple; peak temperature is 710 and 647C for thermocouple and SWIR, respectively). Across all wavelength bands—LWIR, MWIR, and SWIR—significantly lower temperatures were observed at the molten spreading channel surface. Averaged temperature of same field of view on the channel surface is 238, 331, 498 C for LWIR, MWIR and SWIR, respectively. This is significantly different to the thermocouple measurement at the channel surface.

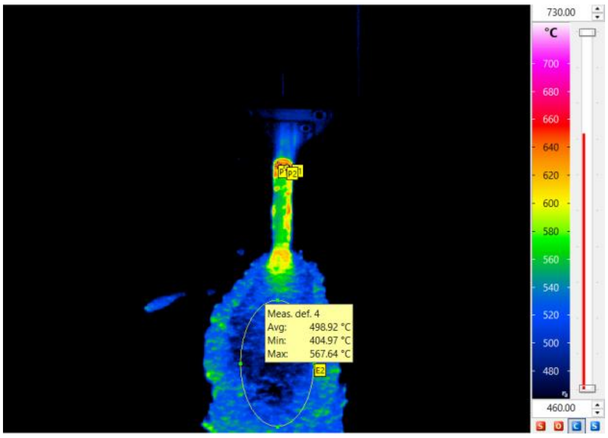

Fig.3 Snapshot of molten salt temperature during spreading (SWIR)

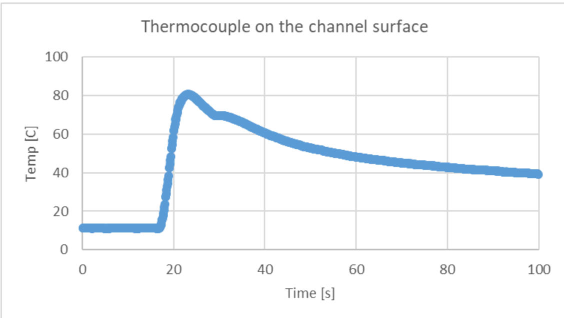

Fig.4 Temperature on channel surface during spreading (thermocouple)

2.5 Discussion

Two questions remain. First, why is the temperature measured near the channel surface during the spreading process significantly lower? In the spreading experiments, the initial temperature of the metal plate was at room temperature (approximately 20 °C). When high-temperature molten salt at 800 °C comes into contact with the plate, the initial interfacial temperature can be estimated using the heat conduction between semi-infinite medium. Based on transient thermal contact analysis, the instantaneous interface temperature, T_{int}, formed upon contact between 800 °C molten salt and a 20 °C steel plate at t = 0 sec is calculated to be approximately 100 °C. This value is comparable to the surface temperature measured by thermocouple installed in the metal plate, which is significantly low temperature.

$$T_{int} = [T_1\sqrt{(\rho C_p k)_1} + T_2\sqrt{(\rho C_p k)_2}] \,/\, [\sqrt{(\rho C_p k)_1} + \sqrt{(\rho C_p k)_2}]$$

Interestingly, the molten salt surface temperature measured in the experiment appeared to be below the solidification temperature of the salt even though it flows. Under spreading, a very thin molten salt layer - on the order of a few millimeters or less - is formed. Due to rapid heat transfer to the metal plate, steep temperature gradient is expected within the molten salt. In particular, NaCl–KCl molten salts exhibit a certain degree of transparency in the infrared region. Therefore, the infrared camera is unlikely to measure the true surface temperature alone; rather, it likely detects a radiatively averaged temperature that represents a mixture of radiation intensity from the low-temperature boundary layer adjacent to the metal substrate and the higher-temperature upper region exposed to the atmosphere. Consequently, even if the measured temperature falls below the solidification point, this does not necessarily indicate that the entire molten salt has solidified. Instead, the internal temperature distribution and radiation characteristics must be considered.

Second, why do temperature measurements differ depending on the wavelength band of the infrared camera? Regardless of material properties, the radiative characteristics at a given temperature are described by Planck's law;

$$B(\lambda,T) = (2hc^2/\lambda^5)\{1/[\exp(hc/\lambda kT)-1]\}$$

where B, h, c, λ, k, T, is radiation intensity, Planck constant ($6.626*10^{-34}$ J-s), speed of light, wavelength, Boltzmann constant ($1.381*10^{-23}$ J/K), and absolute temperature, respectively. At 800 °C (1073 K), the maximum spectral radiation intensity occurs at approximately 2.7 µm, which lies in the short-wavelength infrared (SWIR) region. As temperature decreases, Wien's displacement law ($\lambda_{max} * T = 2.898 \times 10^{-3}$ m-K) indicates that the peak wavelength shifts toward longer wavelengths, reaching approximately 10 µm in the long-wavelength infrared (LWIR) region at room temperature.

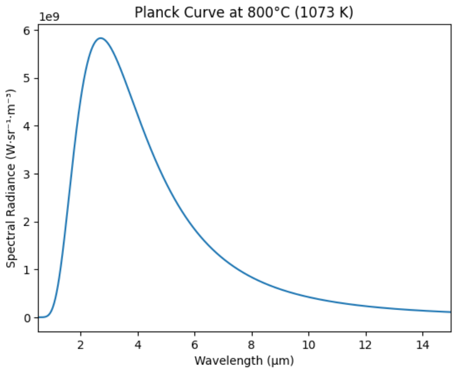

Fig. 5. Planck curve at 800C

Molten salt spreading is a transient process accompanied by phase change and fluid flow. Accordingly, in the initial high-temperature state, the SWIR or MWIR regions exhibit relatively higher radiative intensity and temperature sensitivity. However, as cooling progresses, the dominant radiation energy gradually shifts toward longer wavelengths. Also, the non-gray behavior of molten salt, wavelength-dependent emissivity, partial transmissivity, and reflections from the metal substrate together amplify wavelength-dependent measurement discrepancies.

3. Conclusions

Present study shows that SWIR is appropriate to measure temperature of the molten salt (NaCl-KCl) in the static pool or spreading situation. Even though spreading condition is complicated to clarify the exact salt temperature because of time-dependent flow with thin-layer, phase-change heat transfer, and high transmissivity, the salt temperature is able to be evaluated by the averaged across the salt thickness and is capable to apply the salt spill accident in MSR.

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