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Shakedown Test of Molten Salt Spill and Spreading on a Flat Channel

Sang Mo An [a*], Jun-young Kang [a], Keun Sang Choi [a], Sung Il Kim [a]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: sangmoan@kaeri.re.kr*

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1. Introduction

This study was conducted as a part of the safety researches for the development of 100-MW_{th} maritime Korea molten salt reactor (K-MSR). In the past years, we have focused on the salt spill accident regarded as the maximum credible accident in MSR, and performed CFD simulations with MELTSPREAD code analyses on the spilled salt thermohydraulic behaviors [1-4]. It was found in the previous studies that the melt solidification model has a great influence on the spilled salt spreading dynamics which ultimately affects the amount of fission product release during the salt spill accident. In addition, it is needed to perform the salt vapor pressure measurement and the aerosol generation test by salt evaporation and splashing. This paper introduces the features of a new test facility to achieve those objectives and a brief summary of the shakedown test results.

2. Experimental Methods

2.1 Experimental Setup

A salt spill accident test facility is displayed in Fig. 1. A maximum about 5 kg of salt mixture is charged in the stainless-steel crucible surrounded by 6 kW heaters, and the molten salt is produced and heated up to 900 ℃. The thermocouple install locations and symbols are shown in Fig. 2. To control the heater temperature and monitor the melt temperatures, 5 K-type thermocouples are installed near the heaters (TF-01), inside the crucible (TF-02~TF-04) and at the melt delivery exit (TF-05). Once the salt pool is formed, compressed air or argon gas is supplied into the crucible though a hollow rod having several holes near the tip for uniform mixing and fume removal. When the molten salt reaches a target temperature, the heater power is turned off and the salt is delivered down into a rectangular parallelepiped spreading channel (L 976 mm × W 176 mm × H 88 mm) by tilting the crucible remotely. The channel is tilted up to 10° and equipped with 22 K-type thermocouples to monitor the ambient temperatures (TG-01, TG-02) and channel temperatures (TS-01~TS-20) for the evaluations of melt spreading velocity and heat transfer rate through the 12 mm channel bottom thickness. A metal block with a load cell at the center is installed under the channel to monitor the delivered salt mass. Infrared (IR) camera and camcorder are used to investigate the melt spreading behavior and measure the melt surface temperature distribution, which will be compared with the CFD simulations and code calculations for the relevant model validations.

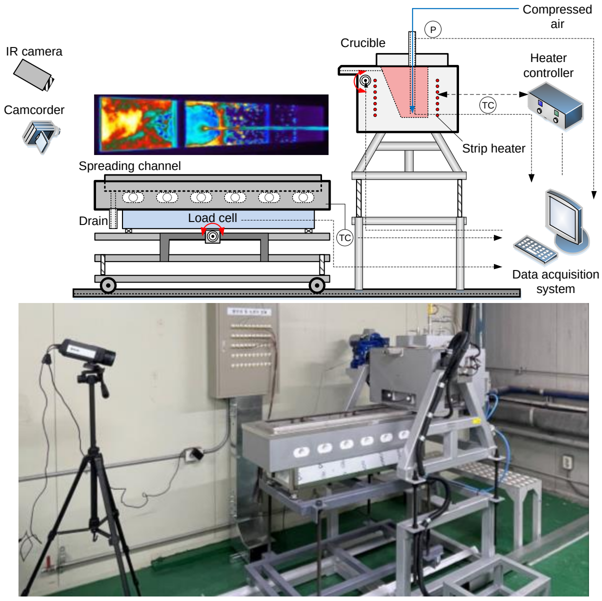

Fig. 1. Test facility

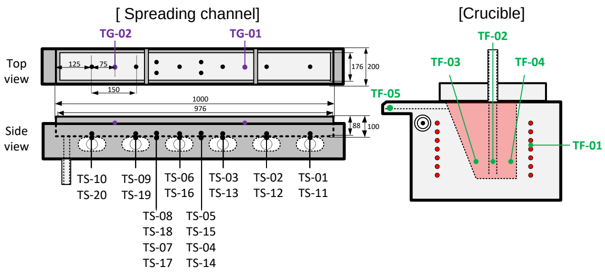

Fig. 2. Thermocouple install locations

2.2 Simulant Salt Mixture

NaCl-KCl-UCl_3 was adopted as a fuel salt in K-MSR under development [1, 3, 4]. Several salt mixtures such as LiF-NaF-KF(FLiNaK), NaCl-KCl, LiCl-KCl, NaCl-KCl-$MgCl_2$, NaCl-KCl-$ZnCl_2$ and NaCl-KCl-$CaCl_2$ were considered as the candidates of fuel salt simulant. Among them, NaCl-KCl was selected temporarily in considerations of similar thermophysical properties to the fuel salt, economic feasibility, and also chemical stability without hazard gas production like HCl due to dehydration in high temperature ranges. The thermophysical properties between NaCl-KCl-UCl_3 and NaCl-KCl is compared in Table I, where the values of NaCl-KCl-UCl_3 were obtained from [4] while those of NaCl-KCl from several references [5-8].

Table I: Thermophysical properties of NaCl-KCl-UCl_3 and NaCl-KCl

Property	K-MSR fuel salt (NaCl-KCl-UCl_3)	Simulant (NaCl-KCl)
Composition (mole frac.)	0.429-0.203-0.368	0.5-0.5
Melting temp. [℃]	470.15	656.85 [5]
Fusion heat [kJ/kg]	145	312.80±22.56 [5]
Density [g/cm^3]	3.476-3.228 (470.15-700 ℃)	1.588-1.469 (686.85-96.85 ℃) [6]
Heat capacity [J/(g·K)]	0.609-0.564 (470.15-700 ℃)	1.22-1.41 (656.85-826.85 ℃)[5]
Thermal conductivity [W/(m·K)]	0.407-0.373 (470.15-700 ℃)	0.53-0.44 (740-1025 ℃) [7]
Viscosity [kg/(m·s)]	5.015-2.025 (470.15-700 ℃)	1.318 (740 ℃) [8]
Surface tension [N/m]	0.127-0.11 (470.15-700 ℃)	0.108 - 0.946 (706.85-896.85 ℃)[6]

3. Shakedown Test Results

3.1 Molten Salt Generation

Figure 3 shows the evolutions of crucible near the heater (TF-01) and salt temperatures (TF-02~TF-04) according to the control of heater temperature (set value). 5 kg of NaCl-KCl mixture power was charged in the crucible and heater temperature was controlled to increase gradually up to 890 °C for about 5 hours (17551 s). As the salt pool being produced, the salt temperatures at the center (TF-02) and near the crucible inner wall (TF-03, TF-04) became close from each other and reached the target salt temperature (850 °C). In order to the investigate the molten salt composition in the post analysis, the heater power was turned off at 14840 s and a small amount of melt sample was taken from the salt pool. Then, we reheated the salt pool and maintained the salt temperature at about 850 °C for a few minutes for stabilization.

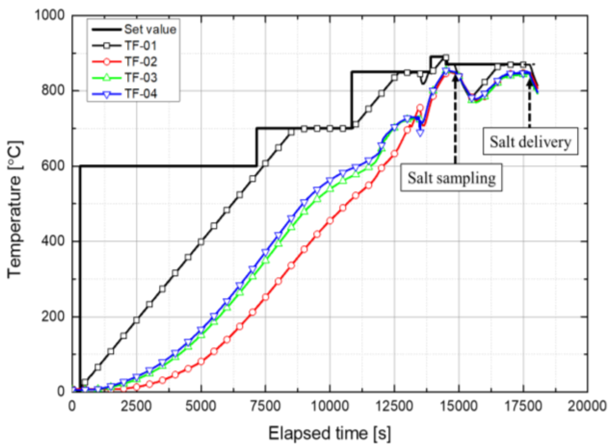

Fig. 3. Salt and crucible temperatures during the melting and delivery process

3.2 Salt Delivery

After the power shutdown again for safety, about 3.2 kg of 850 °C molten NaCl-KCl was delivered successfully into the spreading channel for about 20 seconds. In the present shakedown test, the channel angle was set 0° (i.e., flat channel) without salt drainage so that all amount of salt remains in the channel.

The channel upper surface temperatures along the downstream are shown in Fig. 4. The sequential images obtained from IR camera and camcorder snap shots are displayed in Figs. 5 and 6, respectively. In Fig. 5, the accurate temperature measurements by IR camera were not possible due to unknown molten salt emissivity which will be obtained in the near future, so just refer to the rough temperature distribution between red (850°C) and blue (room temperature). The molten salt jet impinged near the TS-02 so the TS-02 showed the earliest and rapidest temperature increase. As the molten salt flowed downstream like water, the channel surface temperatures exhibited sequential and rapid temperature increases for about longer than 10 seconds. Small amount of salt drops was produced due to the jet impingement on the bare channel surface and salt pool.

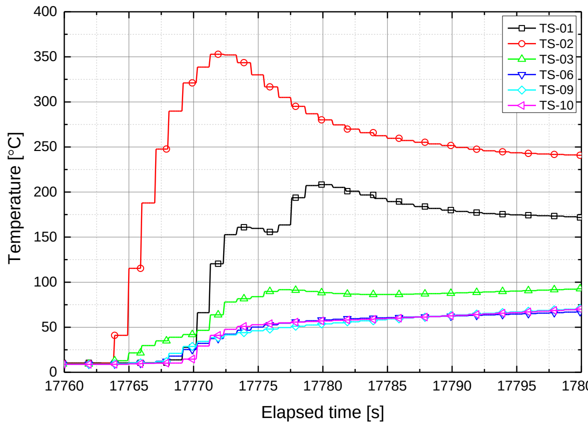

Fig. 4. Upper surface temperatures of the spreading channel

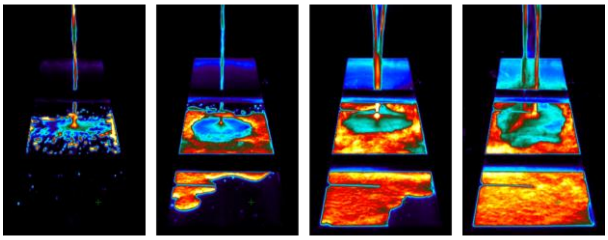

Fig. 5. IR camera images during the salt delivery

Fig. 6. Camcorder images during the salt delivery

After the salt delivery, the salt pool surface in the channel was cooled down in the room temperature and solidified rapidly within a few minutes, and accordingly cracked into two large chunks as shown in Fig. 7(a). The solidified salt in the channel was easily removed and crashed into several pieces for the posttest analysis (Fig. 7(b)). The upper surface of the solidified salt looked like light pink (Fig. 7(c)) while its lower surface showed a gray color (Fig. 7(d)). After salt cooling to the ambient temperature, additional four samples were taken for the chemical composition analysis, of which three are from the solidified salt in the channel and one from the remained salt in the crucible. The posttest analyses including the chemical composition analysis of the salt samples is now in progress.

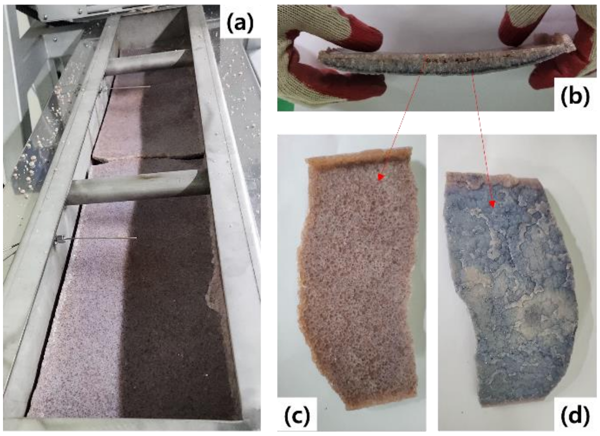

Fig. 7. Solidified NaCl-KCl salt in the spreading channel

Even though the present shakedown test including the molten salt generation and delivery was performed successfully, we need lots of improvements of the test facility. For example, the salt delivery rate and its location should be controlled to have a uniform jet diameter and falling height should be fixed for the model validations. In addition, we need to control the channel temperature boundary conditions and modify the channel shape for the model validations.

4. Conclusions

We constructed a new test facility for the investigations of spilled salt thermohydraulic behaviors during a salt spill accident and model validations in CFD and code analyses. A shakedown test was performed using NaCl-KCl mixture as the simulant of NaCl-KCl-UCl_3 fuel salt of K-MSR. 5 kg of 850 °C molten salt was produced and about 3.2 kg was delivered into the flat spreading channel successfully. We observed a series of processes of salt melting, delivery, spreading and cooling in the channel, and also obtained temperature and image recording data with the solidified salt samples for the chemical composition analysis. This was the first attempt to check the operation performance of all the facility components and data acquisition system, and we found that many improvements are necessary for the model validations. Furthermore, it will be improved to perform the tests of salt vapor pressure measurement and aerosol generation by salt evaporation and splashing.

ACKNOWLEDGMENTS

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