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Results of simulant effect on large corium pool behavior based on COPRA facility

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ABSTRACT

This paper presents the results from COPRA eutectic molten salt tests, which were carried out to investigate the simulant effect on corium pool natural convection heat transfer characteristics. A eutectic 50%$NaNO_3$-50%KNO_3 molten salt was used to simulate the prototypical corium. Compared with the previous non-eutectic 20% $NaNO_3$-80%KNO_3 molten salt experimental data, the effects caused by simulant composition on melt pool temperature, heat flux distribution and crust behavior were studied. The comparison showed that the temperature distribution of eutectic melt pool was lower than the non-eutectic one, while the heat flux was higher than that of non-eutectic melt pool. Applying the same pool height, heating power and boundary condition, smaller modified Rayleigh number was obtained in the eutectic case. It indicated that the mush zone effect of non-eutectic melt suppressed the thermal stratification and impeded the heat transfer through the vessel wall. These results can be expected to provide further data to understand the natural convection behavior of corium pool.

1. Introduction

In-vessel retention (IVR), adopted in some advanced light water reactors, is considered to be a crucial severe accident mitigation strategy to maintain the integrity of the reactor pressure vessel (RPV) (Theofanous et al., 1997a). For example, the Westinghouse AP1000 and the Korean APR1400 employed one of IVR safety enhancement measure known as external reactor vessel cooling (ERVC) (Zhang et al., 2015b). With the help of this method, the vessel wall local heat flux may below the critical heat flux (CHF) and vessel failure is going to be avoided sequentially. As a result, the strong radioactive and high temperature melt can be retained in the vessel. Note that the natural convection heat transfer of corium pool plays an important role in the success of IVR strategy, which directly determines the thermal load on RPV. The modified Rayleigh number (Ra'), or internal Rayleigh number, is usually used to describe the natural convection heat transfer phenomena involving internal heat generation. The Ra' number is given by

$$Ra' = \frac{g\beta q_v H^5}{\alpha\nu\lambda} \tag{1}$$

Where q_v is the volumetric heat generation rate, H is the pool height, g, β, λ, α and ν are the gravitational acceleration, thermal expansion coefficient, thermal conductivity, kinematic viscosity, and thermal diffusivity, respectively.

Many experimental work has been done on heat transfer characteristics of an internally heated pool with prototypical or simulant materials, e.g. COPO-I, COPO-II, UCLA, BALI, mini-ACOPO, ACOPO, RASPLAV, MASCA, SIMECO, SIGMA, LIVE and COPRA (Zhang et al., 2015a). The well-known COPO-I and COPO-II facilities presented the results on the heat flux distribution at the boundaries of volumetrically heated pools, a $ZnSO_4$-H_2O solution was chosen as the corium in the program (Helle et al., 1999; Kymalainen et al., 1997). In the UCLA experiments, Freon-113 was contained in a pyrex bell jars to examine the natural convection heat transfer in a hemispherical pool with external cooling (Asfia and Dhir, 1996). CEA (Commissariat a l'Energie Atomique) conducted the BALI program in a full-scale slice geometry with water as working fluid, which created a data base about heat transfer distribution of melt pool (Bonnet, 2000). The mini-ACOPO and ACOPO experiments at UCSB (University of California, Santa Barbara) employed a half-scale reactor lower head geometry and transient cooldown technique, aimed to simulate natural convection heat transfer from molten pools at high Rayleigh numbers (Theofanous and Angelini, 2000; Theofanous et al., 1997b). An international RASPLAV project was conducted in several facilities with prototypic materials (corium) and NaF-$NaBF_4$ mixtures (salt), provided significant data to the IVR severe accident management strategy (Asmolov et al., 2000, 2001). Similar to the RASPLAV experiments, the MASCA project was performed in Russia, focusing on stratifications and chemical interactions of real corium (Asmolov and Tsurikov, 2004). Royal Institute of Technology (KTH) performed a slice-type facility named as SIMECO, which paid

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more emphasis to the multidimensional heat transfer of stratified pool (Sehgal et al.). The Korean has employed SIGMA experiments to study high Rayleigh number natural convection inside different geometrical molten pools (Lee et al., 2007, 2014). The LIVE tests were designed to research the late in-vessel core melt behavior and the influence of water cooling, using a binary mixture of $NaNO_3$-KNO_3 to simulate the corium melt (Gaus-Liu et al., 2010; Miassoedov et al., 2013; Zhang et al., 2013, 2014). More recently, the COPRA experiments were conducted to investigate the turbulent natural convection in an internally heated melt pool, covered a prototypic Rayleigh number range from 10^{15} to 10^{16} (Zhang et al., 2016a; Zhang et al., 2016b; Zhang et al., 2016c; d). Some of these experimental results have been used for the development of mechanistic models in severe accident codes, such as MAAP, MELCOR and ASTEC. However, few studies have focused on the mush-zone effect of non-eutectic molten salt, which is essential for the heat transfer characteristics through the vessel curved wall. Results comparison between eutectic and non-eutectic molten salt tests will provide valuable data to understand the mush-zone effect on corium pool natural convection behavior and help to conduct the IVR analysis in the prototypic reactor situation.

In this study, the main experimental results of eutectic 50%$NaNO_3$-50%KNO_3 molten salt tests are addressed. Then a comparison is made with the data of previous non-eutectic 20%$NaNO_3$-80%KNO_3 molten salt tests to study the effects caused by simulant composition on melt pool temperature, heat flux distribution and crust behavior. Results of COPRA molten salt tests can be applied for further research of natural convection behavior within the corium pool.

2. Test program

2.1. Overview of COPRA facility

The COPRA experimental vessel is based on the RPV of a China advanced PWR, known as HPR1000. The test section fundamentally consists of a central melt pool, a cooling path and an upper lid, as shown in Fig. 1. The inner radius of the vessel is 2.2 m. Three vertical vessel walls, made of 25 mm thick stainless steel, are kept thermally insulated. The curved vessel wall, with a thickness of 30 mm, is enclosed in the cooling path to create nearly isothermal boundary. The cooling water inlet and outlet are positioned at the bottom and top of the cooling path, respectively. The melt pool is insulated or cooled at the top by different upper lid. Two openings are set in the upper lid to allow a pouring of the melt from central or lateral.

Direct electrical heating is applied in the experiment to simulate the volumetric decay heat. In order to achieve a uniform heating, the melt

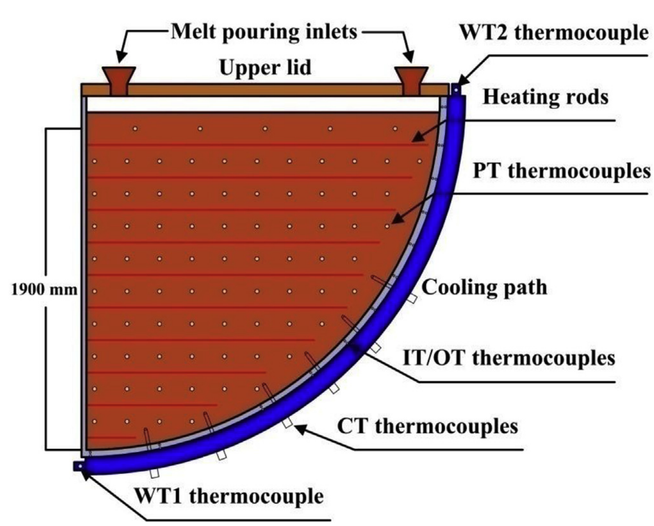

Fig. 1. Schematic of the COPRA test section.

pool is divided into ten parts. Each heating part has the same height of 190 mm and two heating rods are parallel located at the center. All these 20 rods have a diameter of 16 mm and they can supply up to a maximum power of 30 kW. According to the volume of each part, homogeneous internal heating can be realized by adjusting the power of heating rods individually. However, the maximum input power is limited to 28 kW due to voltage restriction of the shortest heating rod.

As shown in Fig. 1, the melt pool temperatures are comprehensively mapped by 79 PT thermocouples. Heat flux distribution through the vessel wall can be calculated based on the temperatures measured by 48 IT/OT thermocouples, which are mounted at 12 angular locations. These 1 mm diameter thermocouples are located at both front and back sides of the vessel to assure the effective measurement of local heat flux. The WT thermocouples are set in the cooling path to measure the inlet and outlet temperatures of the cooling water. In addition, 6 CT

Table 1
Parameters of the COPRA molten salt tests.

Test section	Geometry	1/4 circular slice
	Scale	1:1
	Inner radius	2.2 m
Material	Simulant	50%$NaNO_3$-50%KNO_3 20%$NaNO_3$-80%KNO_3
	Coolant	Water
Decay heat	Heating method	Direct electrical heating
	Heating power	0 kW–28 kW
	Number of heating rods	20
Melt pour	Pouring temperature	350 °C
	Poring position	Central/Lateral
	Hold time	2 min
	Number of pouring	1 time/2 times
Boundary conditions	Top	Insulated/Isothermal
	Side	Insulated
	Bottom	Isothermal
Measured parameters	Pool Temperature	79 K-type thermocouples
	Inner/Outer wall Temperature	48 T-type thermocouples
	Water Temperature	2 T-type thermocouples
	Crust Temperature	6 multipoint thermocouples
	Flow rate	2 electromagnetic flow meters

Table 2
Properties of non-eutectic and eutectic $NaNO_3$-KNO_3 mixture.

Material	20%$NaNO_3$-80%KNO_3		50%$NaNO_3$-50%KNO_3	
t, °C	300	350	300	350
c_p, J/(g·K)	1.369	1.369	1.320	1.320
ρ, kg/m^3	1897.78	1862.76	1903.12	1869.31
ν, m^2/s × 10^{-6}	1.75	1.35	1.68	1.24
λ, W/(m·K)	0.439	0.422	0.459	0.443
α, m^2/s × 10^{-7}	1.69	1.65	1.83	1.80
Pr	10.36	8.14	9.18	6.89
Liquidus temperature, °C	284		224	
Solidus temperature, °C	224		224	

Table 3
COPRA tests matrix.

Test	Working fluid	Relocation percentage	Pool height mm	Heating power kW
1	eutectic	100%	1900	15 - 10 - 15
2	eutectic	50%	1140	10–14
3	eutectic	50%→100%	1140 → 1900	14 → 15–10 - 15
4	non-eutectic	100%	1900	15 - 10 - 15
5	non-eutectic	50%	1140	10–14
6	non-eutectic	50%→100%	1140 → 1900	14 → 15–10 - 15