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Natural convection heat transfer test for in-vessel retention at prototypic Rayleigh numbers – Results of COPRA experiments

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ABSTRACT

Large-scale COPRA experiments were performed to investigate the natural convection heat transfer in melt pools for the in-vessel retention during severe accidents in Chinese large-scale advanced PWRs. Both water and binary mixture of 20 mol% $NaNO_3$ – 80 mol% KNO_3 were used as the melt simulant material in performed tests. Due to the full scale geometry of the COPRA test section, the Rayleigh numbers of the melt pool could reach up to the prototypic magnitude of 10^{16}. Natural convection heat transfer tests at prototypic Rayleigh numbers have been performed to study the influence of the heat generation rate and melt simulant material on the melt pool temperature, heat flux distribution and heat transfer capability. The comparisons of the melt pool temperature and heat flux distribution from water experiments and molten binary salt experiments showed that the crust formation along the inner surface of the vessel wall could impact the heat transfer characteristics of the melt pool. And the heat flux distribution from COPRA water tests and molten salt tests were in good agreement with those from Jahn-Reineke water experiments and RASPLAV molten salt experiments, respectively. The heat transfer capability of the melt pool Nu_{dn} from COPRA molten salt tests were larger than those from water tests, but both were lower than those from ACOPO and BALI predictions within the same range of Rayleigh numbers (10^{15} – 10^{17}).

1. Introduction

In-vessel retention (IVR) of core melt is an important severe accident management strategy during a severe accident in Light Water Reactors (LWR). External reactor vessel cooling (ERVC), which involves flooding the reactor cavity to submerge the reactor vessel in an attempt to cool core debris relocated to the reactor pressure vessel (RPV) low head, is considered as one of the most promising severe accident management measures for IVR. The behavior and heat transfer characteristics of the melt pool in the RPV lower head directly affect thermal loads imposed on the vessel wall of the RPV lower head. The success of IVR-ERVC is determined by the melt pool natural convection heat transfer.

Heat transfer characteristics of the melt pool in the RPV lower plenum were investigated quite intensely in the last few decades. Some experiments based on IVR-ERVC concept were conducted to enhance this strategy, e.g. COPO (Kymäläinen et al., 1994; Helle et al., 1999), BALI (Bonnet and Seiler, 1999), SIMECO (Stepanyan et al., 2005), ACOPO (Theofanous et al., 1997a), and RASPLAV (Asmolov et al., 2000).

The thermal behavior of a single-phase melt pool during steady-state can be meanwhile well modeled by these experiments mentioned previously. However, the characteristics of the melt in the lower head, including the transient flow behavior, heat transfer, and chemical phenomena, are complicated. The uncertainties still exist in the description of the transient melt behavior, such as formation and growth of in-core melt pool, characteristics of corium arrival in the lower head, and molten pool behavior after debris melting. These phenomena or behaviors are plant and accident sequence dependent and have strong impacts on a potential termination of a severe accident (Asmolov et al., 2001). Karlsruhe Institute of Technology (KIT) performed a 1:5 scale tests in the LIVE program to investigate the melt pool behavior in the RPV lower head (Fluhrer et al., 2008; Miassoedov et al., 2007; Gaus-Liu et al., 2011). And Zhang et al. (2015) gave a state-of-the-art review of

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Nomenclature

H	vertical height of the vessel, m
$H_{\max}$	maximum height of the vessel, m
Nu_{dn}	Nusselt number for the downward heat transfer
q_{local}	local heat flux of the vessel wall, W/m^2
q_{mean}	mean heat flux the vessel wall, W/m^2
Ra'	internal Rayleigh number of the melt pool
T	melt temperature, °C
T_{mean}	mean temperature of melt in the melt pool, °C
Greek characters	
θ	angle from the bottom center of the vessel, degree
$\theta_{\max}$	maximum angle of the melt pool, degree

researches on natural convection heat transfer in melt pools with different geometry, different simulant materials, and different boundary conditions.

Furthermore, not many experimental data are available for full scale (1:1) geometry of the RPV. Based on this necessity, the experimental research program COPRA (COrium Pool Research Apparatus) with the full scale geometry at Xi'an Jiaotong University (XJTU) is being performed to investigate the natural convection heat transfer in melt pools for the IVR during severe accidents in Chinese large-scale advanced Pressurized Water Reactors (PWR). For the performed tests, both water and molten salt (binary mixture of 20 mol% $NaNO_3 - 80$ mol% KNO_3) were used as the melt simulant material. In this work, natural convection heat transfer tests at prototypic Rayleigh numbers have been performed to study the influence of the heat generation rate and melt simulant material on the melt pool temperature, heat flux distribution and heat transfer capability. Then, the correlations of the heat transfer capability of the melt pool Nu_{dn} from COPRA with the function of Rayleigh number Ra' were obtained, and these correlations can be used to calculate the heat rate on the RPV lower head wall form the in-vessel molten pool. And the research of this work can also be fundamental to understand the melt pool behaviors in the RPV lower head during the severe accident.

2. COPRA test program

2.1. Test vessel description

The test vessel of the COPRA program is a two-dimensional 1/4 circular slice test section to simulate the lower plenum of the reactor vessel at 1:1 scale for the Chinese large-scale advanced PWR. The test facility is composed of the central melt pool, cooling path and upper lid, as shown in Fig. 1. The inner radius of the vessel is 2200 mm and the inner width is 200 mm. All the vertical walls of the vessel have the thickness of 25 mm and are kept thermally insulated. The curved vessel wall has a thickness of 30 mm and was enclosed from outside with the cooling path to keep the boundary temperature nearly isothermal. The cooling water inlet and outlet are located at the bottom and top of the vessel respectively. There are two kinds of upper lid. The insulation lid and top cooling lid were designed to simulate insulation condition and top cooling condition, respectively. Two openings are designed in the upper lid to allow the melt pouring near the center and lateral of the RPV lower head wall, respectively. And the lateral melt pouring located at polar angle of 65° similar to the situation in the TMI-2 accident. The melt was pre-heated to about 350 °C in a custom-designed heating furnace before being pumped to the test vessel through the openings in the upper lid.

When scaling to the prototypical reactor case, in the conservative situation with 100% anticipated melting of the whole core inventory including both oxidic and metallic components, the surface of the melt pool could reach to the polar angle of 75°–82° (Gaus-Liu et al., 2011; Theofanous et al., 1997b). According to this estimation, the melt pool inside the COPRA facility could reach to the height of 1900 mm with the volume about 0.6 m^3. Due to the full scale (1:1) geometry of the COPRA test section, the Rayleigh numbers of the melt pool could reach up to the prototypic magnitude of 10^{16}. The volumetric heating system of 20 electrical heating rods was designed to simulate the homogeneous decay heat. The melt pool was divided into ten heating zones with the same zone height of 190 mm. In each heating zone, two parallel heating rods with the same length are mounted horizontally from the lateral vertical wall to the curved vessel wall. All the heating rods have a diameter of 16 mm and they can provide a maximum of 30 kW power to the melt pool. Based on the corresponding volume of each heating zone, homogenous internal heating could be achieved by adjusting the heating power of each group.

The locations of the heating rods and thermocouples in the test facility were schematically shown in Fig. 1. 79 K-type thermocouples (PT) were installed in the melt pool to measure the melt pool temperature field. 24 pairs of T-type thermocouples (IT/OT) are located inside the curved wall at the positions of 12 polar angles from both front and back sides of the vessel. These measuring points were designed at the middle position of the curved wall in each heating zone. IT/OT thermocouples, each with the diameter of 1 mm, were located 3 mm departure from the inner and outer surface of the curved wall. IT/OT were designed on both sides to grantee the effectiveness of local heat flux distribution along the curved wall. In the vessel cooling path, 3 T-type thermocouples (WT) are located at polar angles of 0°, 45°, and 90° to monitor the change of water temperature. Moreover, 6 multipoint thermocouples (CT), each with seven measuring points at different depth in the crust, were installed along the inside vessel wall to quantify the characteristics of crust behavior.

2.2. Simulant material

In the preliminary COPRA experiments, the water was used as melt simulant material to investigate the thermal behavior of the melt pool, as used in ACOPO (Theofanous et al., 1997a) and SIGMA (Lee et al., 2007). In order to study the effect of the crust formation on heat transfer characteristics of the melt pool under the condition of the vessel cooling, the molten salt was used as melt simulant material composed of a non-eutectic binary mixture of 20 mol% $NaNO_3 - 80$ mol% KNO_3 compositions, as used in KIT LIVE experiment (Gaus-Liu et al., 2011). The maximum temperature range between solidus and liquidus is about 60 K corresponding to a 20/80 mol% $NaNO_3$–KNO_3 mixture. And the solidus temperature and the liquidus temperature of the non-eutectic composition are about 225 °C and 284 °C, respectively. Therefore this kind of molten material can be used in a temperature range between 225 °C (solidification) and 370 °C (chemical decomposition) (Miassoedov et al., 2011). In addition, with this simulant material, a similar solidification behavior could occur as the prototypical corium due to the characteristics of multi-component and distinctive solidus–liquidus temperature range. More detailed information about properties of $NaNO_3$–KNO_3 mixture is available in literature (Berg and Kerridge, 2004; Janz et al., 1979; Zhang et al., 2003).