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Research Paper

COPRA experiment and numerical research on the behavior of internally-heated melt pool with eutectic salt

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HIGHLIGHTS

- Eutectic salt was used for experimental research on the melt pool behavior.
- A sudden introduce of cooling and the melt pouring are the most dangerous transient.
- Power changing exerts obvious impacts on the crust growth below polar angle 30°.
- Steady-state correlations are qualified to analyze long-term cooling transient.
- Vortexes could form near the crust region, making an even temperature distribution.

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ABSTRACT

In-vessel retention (IVR) has been proposed as an effective mitigation strategy during severe accidents in pressurized water reactors (PWRs). To help understand better the application of IVR, the large-scale COPRA facility was used for experimental research and the eutectic salt, i.e. the binary mixture of 50 mol% $NaNO_3$ – 50 mol% KNO_3 was selected as the simulant material for corium. Besides, numerical studies were done to capture the detailed flow field information. The experiment studied the effects of a sudden change in boundary condition and the influences of power changes on the transient behaviors and the steady-state characteristics of melt pool. Experimental results show that a sudden introduction of sidewall cooling and the melt pouring are the most threatening factors to the reactor vessel safety, but which can be guaranteed as long as the vessel is kept undamaged during melt pouring phases. Also, power changing won't lead to rapid variation of sideward heat flux, so the correlations for steady state heat transfer calculation are basically qualified to evaluate the reactor safety in analysis of long time cooling. Besides, the power changing only exerts obvious impacts on the crust growth on the curved sidewall inner surface with polar angle below 30°, contrary to which the sideward heat flux is clearly influenced by different power densities only above the angle of 30°. Finally, the numerical simulation results show that vortexes could form near the region where the crust formed, and lead to a more homogeneous temperature distribution; generally, the convection happens between the lower part of melt pool and cooling boundary, with flow velocity at a magnitude of 0.01 m/s.

1. Introduction

In a postulated severe accident in light water reactors, the reactor may melt down and thereafter relocate into the lower plenum of the reactor pressure vessel, in which a melt pool could be formed, as happened in the well-known Three Mile Island Unit 2(TMI-2) accident. Without sufficient cooling capacity, the melt pool will be heated up continuously due to the homogenous internal decay heat, thereby threatening further the structure and thermal integrity of the reactor vessel. Therefore, since the TMI-2 accident, in-vessel retention (IVR) has been considered as one of the most important subjects of reactor severe accident mitigation [26].

External Reactor Vessel Cooling (ERVC) is an effective mitigation strategy for IVR to flood and submerge the reactor lower plenum [16,17,19,26]. And the key of this strategy is to keep the maximum heat flux from the melt pool to the curved wall lower than the critical heat flux (CHF) by providing a nearly isothermal boundary outside the vessel wall with external cooling. Based on IVR-ERVC concept, some typical experiments have been conducted to study the heat transfer characteristics of the melt pool in the RPV lower plenum, e.g. COPO [8,12],

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Nomenclature

c_p	specific heat, J/(kg K)
g	acceleration due to gravity, m/s^2
h	height of the each layer of melt pool, mm
H	total height of melt pool, m
i	the number of local heat flux zone
Nu	downward Nusselt number (Nu = qH/λΔT)
P	heating power, kW
q	local heat flux, W/m^2
q_{ave}	mean heat flux, W/m^2
Q_v	volumetric heat generation rate, W/m^3
Ra′	modified Rayleigh number ($Ra' = g\beta Q_v H^5/\lambda\nu\alpha$)
r_{in}	inner radius of the test vessel, m
r_{out}	outer radius of the test vessel, m
S_i	surface area of the local heat flux zone i, m^2
t	time, s
T	average melt temperature at different height, °C
T_{ave}	average temperature of the whole melt pool, °C
T_{in}	inner surface temperature of the vessel, °C
T_{int}	average temperature of the inner surface of the curved wall, °C
T_{max}	highest temperature in the melt pool, °C
T_{out}	outer surface temperature of the vessel, °C

Greek symbols

α	thermal diffusivity, (m^2/s)
β	thermal expansion coefficient (K^{-1})
λ	thermal conductivity of the melt, W/(m K)
λ_{wall}	thermal conductivity of the vessel wall, W/(m K)
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2/s
δ	thickness of the vessel wall, m
θ	polar angle along the curved wall, °

ACOPO [20], BALI [3], RASPLAV [1] and SIMECO [18]. These experiments can be used to model the thermal behavior in steady state of a single-phase corium pool, but they do not describe well the complicated transient melt behaviors, such as the melt pool evolution, the characteristics of corium arrival in the lower head, and melt pool behaviors after debris melting.

More recently, LIVE program was launched in Karlsruhe Institute of Technology (KIT) to investigate the melt pool behavior in a 1:5 scale three dimensional test section [4,7,15]. And COPRA (Corium Pool Research Apparatus) experiments were performed at Xi'an Jiaotong University to study the natural convection heat transfer in a full scale (1:1) geometry of the RPV similar to Chinese large-scale advanced Pressurized Water Reactors [28]. More details about the research on the behavior of melt pools with different geometry, simulant materials and boundary conditions can refer to the review work by Zhang et al. [24].

In both LIVE and COPRA experiments, the non-eutectic molten salt (binary mixture of 20 mol% $NaNO_3$ – 80 mol% KNO_3) was used as the simulant material, with which the effects were studied of different initial pouring masses, pouring positions and boundary conditions on the melt pool. In this research, however, eutectic salt, i.e. the binary mixture of 50 mol% $NaNO_3$ – 50 mol% KNO_3 was chosen as the simulant material, and this research was aimed at the transient behavior of melt pool under a sudden change in boundary condition, and its steady-state characteristics. Further, in order to obtain the flow field inside the melt pool, numerical simulations were done here. This work can help understand better the application of EVRC strategy after a postulated severe accident.

2. Experimental studies

2.1. Experimental facility

This chapter focuses on the experimental facility and working fluid that was used. Then, the important experimental procedure will be given in detail.

2.1.1. Test section description

The experimental facility COPRA (Corium Pool Research Apparatus) is a two-dimensional 1/4 circular slice, composed of a central melt pool, a sidewall cooling path and an upper lid, as shown in Fig. 1. This vessel can simulate the reactor vessel lower head for the Chinese advanced PWR at full scale, with an inner radius of 2200 mm and an inner width of 200 mm. Its vertical walls are 25 mm thick and kept thermally insulated. The curved wall, however, has a thickness of 30 mm and is enclosed from outside with a cooling path to maintain a nearly isothermal boundary. The lid put on the top surface of the vessel is used for an adiabatic upper boundary. In the insulated lid, an opening is designed for the melt pouring at a polar angle of 65°, which is similar to the situation in the Three Mile Island Unit 2 (TMI-2) accident. Due to the full scale of COPRA facility, a melt pool higher than 1900 mm can be simulated, and the Rayleigh numbers can reach up to 10^{16}. Therefore, COPRA facility has an advantage of simulating the behavior of melt pool matching those in the prototypical situation for PWR.

For the simulation of homogeneous decay heat in real reactors, a volumetric heating system is designed, which consists of 20 electrical heating rods divided into ten heating zones with an even height of 190 mm. In each heating zone, two parallel heating rods of same length are installed horizontally from the lateral vertical wall to the curved vessel wall. The rods can provide a maximum of 30 kW heating power to the melt pool. During the experiment, homogenous internal heating could be easily simulated by adjusting the heating power of each group according to the corresponding volume of each zone at different heights. The detailed parameters of the heating zones and heating rods are given in Tables 1 and 2, respectively.

One of the most important parts in the experiment is temperature measurement. In the experiment, the National Instruments acquisition system with an interface panel based on Labview was used to monitor and save test data. To obtain the temperature field of the melt pool and

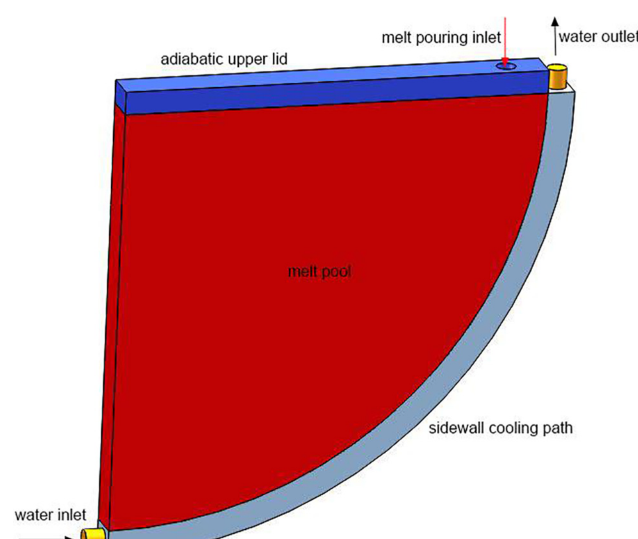

Fig. 1. The schematic of the COPRA test section.

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