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Review

Review of experimental study on melt pool natural convection behavior

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ABSTRACT

In a hypothetical severe accident that happens in a light water reactor (LWR), the melt pool could be formed in the lower plenum of reactor pressure vessel (RPV). Remaining these molten materials inside RPV and preventing further leakage of these melt materials from RPV are treated as one of the severe accident management methods. In this aspect, one of the key issues is that the heat transfer from melt pool to RPV wall should be less than the corresponding critical heat flux (CHF) outside the vessel. The natural convection behavior in melt pools plays an important role in determining the heat flux from the melt pool to the RPV wall. Up to now, various experiments have been conducted to study the internally heated natural convection behavior in melt pools. In 1970s, several experiments were conducted, and mainly investigated the mechanism of internally heated natural convection phenomena. After TMI-2 and Chernobyl-4 severe accidents, such kinds of experiments were conducted worldwide, mainly aimed to further investigate the melt pool natural convection behavior in the lower plenum and conduct the experiment closer to the prototypical condition that may happen in a hypothetical severe accident. Some of these experiments were used to provide the data for severe accident management method assessment of their corresponding reactor types, and to solve the problems that were found or not solved by previous experiments. Especially the COPRA (COrium Pool Research Apparatus) experiment, of which the test section was the full scale and nitrate salt of which the physical properties are close to the prototypical material was used as the simulant material, improved the theoretical knowledge of the transient and steady-state phases of melt pool natural convection behavior. However, there are still uncertain and unclear phenomena related to the natural convection behavior in internally heated melt pools. This paper mainly summaries the melt pool natural convection experiments chronologically, and then points out the main remaining issues regarding the natural convection behavior in the melt pools in the RPV lower plenum.

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Nomenclature

C_p	Specific heat (J kg^{-1} K^{-1})
Gr	Grashof number
g	Gravitational acceleration (m s^{-2})
T	Temperature (K)
L	Pool depth (m)
Da	Damkohler number
Q	Volumetrical heat source (W m^{-3})
K	Thermal conductivity (W m^{-1} K^{-1})
Ra	Rayleigh number
Ra'	Modified (internal) Rayleigh number
R	Pool radius (m)
H	Pool height (m)

Greek symbols

α	Thermal diffusivity (m^2 s^{-1})
β	Thermal expansion coefficient (k^{-1})
v	Kinematic viscosity (m^2 s^{-1})
θ	Polar angle along the RPV wall (°)
ρ	Density (kg m^{-3})

1. Introduction

In a hypothetical severe accident of a light water reactor (LWR), lack of core cooling could cause core materials to melt by decay heat, and then the molten core materials could fall into the lower plenum, accumulate and form the melt pool, which could lead to the reactor pressure vessel (RPV) failure caused by thermal load, creep rupture or pressure load. From the nuclear safety aspect, how to maintain these melt materials inside RPV is essentially important for preventing the further severe accident progression. From the evaluation of RPV integrity aspect, one of the most important points is whether the heat removal by cooling is large enough compared to the heat transferred from melt pool to RPV wall (Sehgal, 2006, Zhang et al., 2015b, Ma et al., 2016). Thus, it is important to obtain the knowledge of melt pool characteristics in the RPV lower plenum, and the heat transfer correlations from melt pool to RPV wall. Up to now, various theoretical, numerical simulation and experimental works have been conducted to study the corresponding behavior, focusing on the melt pool configuration, crust formation, Nusselt-modified Rayleigh (Nu-Ra') number correlations, local heat flux and other related issues. Many research efforts have also been devoted to investigating melt pool behavior under different conditions, varying in facility geometrical types, simulant materials or using prototypical materials, boundary conditions, modified Rayleigh numbers, heating methods and so on. In general, the purpose of internally heated melt pool natural convection experiments is to investigate the associated phenomena that would happen but not understood yet in this aspect, and provide data for nuclear power plant severe accident management.

The natural convection characteristics inside the molten pool have significant effects on heat transfer from molten pool to the vessel and can also affect the temperature field inside molten pool. Fig. 1 shows natural convection behavior of molten pool in a typical hypothetical severe accident. The molten pool could be divided into two parts in the condition of uniform cooling. Temperature stratification phenomenon could be formed in the lower part, and unstable region could be found in the upper part (Bernaz et al. 2001).

The dimensionless parameters, such as internal Rayleigh number and Prandtl number, could be used to describe the internal heating melt pool natural convection heat transfer phenomenon (Theofanous et al., 1997b, Lee et al., 2014). Eqs. (1)–(3) show the definition of the Grashof number (Gr), the Prandtl number (Pr) and the Dammkohler number (Da). The Grashof number and the Prandtl number could be used to represent the natural convection phenomenon. The Dammkohler number could be used to represent the volumetric heat source condition. Eqs. (4) and (5) show the definition of the Rayleigh number (Ra) and the modified Rayleigh number (Ra'). The Rayleigh number can be used to describe the characteristics of external heated natural convection heat transfer behavior, while the modified Rayleigh number, which represents the effects of internal heat source and the buoyancy force, can be used to describe the characteristics of internal heated natural convection heat transfer behavior. The internal Rayleigh number has a significant effect on the molten pool natural convection behavior.

$$Gr = \frac{g\beta\Delta TL^3}{v^2} \tag{1}$$

$$\mathrm{Pr} = \frac{v}{\alpha} \tag{2}$$

$$Da = \frac{QL^2}{k\Delta T} \tag{3}$$

$$Ra = Gr\mathrm{Pr} = \frac{g\beta\Delta TL^3}{\alpha v},\ \alpha = \frac{k}{\rho C_p},\ v = \frac{\mu}{\rho} \tag{4}$$

$$Ra' = RaDa = Gr\mathrm{Pr}Da = \frac{g\beta QL^5}{\alpha vk} \tag{5}$$

For melt pool in reactor lower plenum, the driving force is generated by the internal heating from the radioactive materials decay behavior. Based on the previous research, the conduction behavior has little effect on such phenomena. Therefore, the modified Rayleigh number has significant effect on heat transfer behavior. As