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Mass transfer experiments on the natural convection heat transfer of the oxide pool in a three-layer configuration

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ABSTRACT

We investigated the heat load to the reactor vessel by the natural convection of the core melt in a hypothetical severe nuclear power plant accident condition. It is modeled as the natural convection heat transfer with the volumetric heat source in a chopped hemisphere. To achieve high Ra'_H ranging from 10^{11} to 10^{13}, mass transfer experiments were performed for three-layer configuration of the oxide pool with three different aspect ratios based on the analogy between heat and mass transfer. The local heat transfers to top, side, and bottom were measured, compared with the existing studies, and discussed phenomenologically. Major findings were that the side and bottom heat flux distributions are unaffected by the top plate cooling condition and that the angle dependent heat flux increases with the angle measured from the bottom. Three layer configuration is more conservative as its upward heat ratio was larger than that of two layer configuration. With the decrease of the aspect ratio, the upward heat ratios increased due to the reduced side wall cooling but with very small aspect ratio, multi-cell flow patterns were formed. The heat transfer around the edge of the bottom plate was impaired due to the formation of stagnant flows.

1. Introduction

Fukushima Dai-ichi nuclear power plant accident has raised the research interests for severe accident phenomena. Severe accidents are hypothetical nuclear power plant accidents that exceed the DBAs (Design Basis Accidents). They involve the damage of the fuel rods and resulting core degradation and have the potential risk of fission product release into the containment or even to the environment. In these accident conditions, two possibilities are possible: The reactor vessel maintains integrity and the core melt retains inside the reactor vessel or it breaks and the core melt leaks out to the containment atmosphere. If the molten core remains inside the reactor vessel, the severity of event is expected to be reduced. Therefore the IVR-ERVC (In-Vessel Retention of molten corium through External Reactor Vessel Cooling) is one of the desirable severe accident management strategy to maintain the integrity of reactor vessel during the severe accident. To implement this strategy, the integrity of the reactor vessel should be maintained and it is important to know the heat load to the reactor vessel by the core melts (Rempe et al., 2008; Theofanous et al., 1997; Park et al., 2012).

In general, it is assumed that molten core is stratified into two-layer (upper metal layer and lower oxide layer). However, MASCA experiment (Barrachin and Defoort, 2004) reported that the layer inversion may occur with an additional heavy metal layer below the oxide layer, resulting in a three-layer configuration. The three-layer formation is more conservative than two-layer formation as the thinner uppermost metal layer enhances the heat focusing to the vessel. However, there are only a few studies on the three-layer configuration as the possibility of the phenomena is recently discovered and the research interest had not been continued until Fukushima accident.

The height of each layer in the three-layer configuration depends on the reactor types and the accident scenarios as they determine the compositions of a U-Zr-Fe-O mixture from molten fuel and structures. Thus, we performed the natural convection experiments of the oxide layer varying the aspect ratios in the three-layer configuration. We measured heat transfer coefficient (h_h) at the top plate, the side wall and the bottom plate and compared these results for three different aspect ratios. Also we analyzed the flow patterns through local heat transfer measurements.

Based upon the analogy between heat and mass transfer, we performed the mass transfer experiments instead of heat transfer ones using a copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) electroplating system. By performing mass transfer experiments, high buoyancy was achieved with small facilities and an ideal isothermal temperature boundary condition was maintained without heat leakage to the environment with a uniform internal heat distribution.

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Nomenclature

C	Molar concentration [$kmole/m^3$]
D_m	Mass diffusivity [m^2/s]
Da	Damköhler number ($q'''H^2/k\Delta T$)
F	Faraday constant [96,485 $Coulomb/mole$]
g	Gravitational acceleration [9.8 m/s^2]
Gr_H	Grashof number ($g\beta\Delta TH^3/\nu^2$)
h_h	Heat transfer coefficient [$W/m^2{\cdot}K$]
h_m	Mass transfer coefficient [m/s]
H	Height [m]
I	Current density [A/m^2]
I'''	Current per volume [A/m^3]
I_{lim}	Limiting current density [A/m^2]
k	Thermal conductivity [$W/m{\cdot}K$]
n	Number of electrons in charge transfer reaction
Nu	Nusselt number (h_hH/k)
Pr	Prandtl number (ν/α)
Q	Heat quantity [W]
q	Heat generation rate [W]
q'''	Volumetric heat generation rate [W/m^3]
R	Radius corresponding to pool [m]
Ra_H	Rayleigh number ($GrPr$)
Ra'_H	Modified Rayleigh number (Ra_HDa)
Sc	Schmidt number (ν/D_m)
Sh	Sherwood number (h_mH/D_m)
T	Temperature [K]
$t_{Cu}{}^{2+}$	Transference number of Cu^{2+}
U_x	Uncertainty of x

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Volume expansion coefficient [$1/K$]
γ	Dispersion coefficient
μ	Viscosity [$kg/m{\cdot}s$]
ν	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]

Subscripts

b	Bulk
dn	Downward
Lc	Characteristic length
lim	Limiting current condition
h	Heat transfer system
m	Mass transfer system
T	Thermal
tot	Total
up	Upward

2. Theoretical background

2.1. Problem description

The DBAs (Design Basis Accidents) are the postulated set of accidents that the nuclear power plant must be designed to withstand. Severe accidents are worse than DBAs, which lead core degradation. When the fuels are no longer covered by coolant and heated up by the decay heats, they melt and relocate to the lower vessel. The IVR (In-Vessel Retention) retains the molten core in the reactor vessel and is an effective strategy to mitigate the severe accident, as it prevents the radioactive material emission to the containment atmosphere. As the molten fuels generate the decay heat continuously, it should be cooled properly to maintain the integrity of the reactor vessel. The ERVC (External Reactor Vessel Cooling) provides the cooling by flooding the reactor vessel with water outside.

This strategy has been applied to small sized nuclear power plants less than 1000 MWe such as AP600, AP1000 and Loviisa plants. On the other hand, large sized nuclear power plants such as EPR of 1800MWe couldn't rely on the IVR as its surface-to-volume ratio is small. The IVR strategy for the middle sized plant such as APR1400 needs to be further verified.

2.2. Phenomena

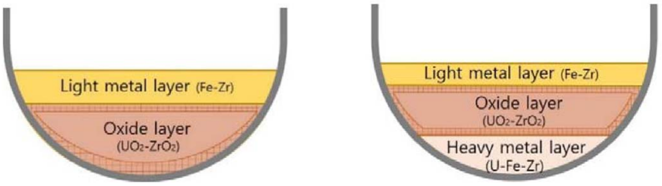
The molten core is believed to be stratified into two-layer by density difference in a severe accident. Upper layer consists of metallic materials such as Fe and Zr, and lower layer consists of oxidized materials such as UO_2 and ZrO_2 as shown in Fig. 1(a). However MASCA experiments (Barrachin and Defoort, 2004) showed that the layer inversion may occur with an additional heavy metal layer below the oxide layer, resulting in a three-layer configuration. They reported that when Zr is not oxidized sufficiently, the U migrates to the metal layer, increasing the metal layer density and then heavy metal layer is formed at the bottom as shown in Fig. 1(b). The top light metal layer contains Fe and Zr. The middle oxide layer contains UO_2, ZrO_2 and most of the fission products. The bottom heavy metal layer consists of U, Fe, Zr and some metallic fission products. In the three-layer configuration, the thickness of the upper light metal layer reduces due to heavy metal layer formation, intensifying the heat focusing to the reactor vessel at the light metal layer. Table 1 summarizes the approximate density of each layer in the two-layer and the three-layer configurations.

Fig. 2 shows the oxide layers among the stratified layers in Fig. 1. We simulated the oxide layer assuming the idealized conditions where there is no interaction between each layer and there are no penetrations at the bottom of the reactor vessel. Fig. 2(a) and (b) present the flow patterns of oxide layer in the two-layer configuration (Bonnet and Seiler, 1999) and the three-layer configuration. In both configurations, the downward flows by natural convection run down along the curved surface and merge at the center. Then they rise upward and disperse towards the edge of top plate. There are also natural convective flows underneath the top plate.

2.3. Definition of Ra'_H

As the oxide layer generates decay heat continuously, the modified Rayleigh number (Ra'_H) is used instead of the conventional Rayleigh number (Ra_H) so as to consider the internal heat generation. The Ra'_H is calculated by multiplying the Ra_H and Da. The Da is a dimensionless parameter which converts the temperature difference (ΔT) into the volumetric heat generation (q'''). Thus the Ra'_H is expressed by

$$Ra'_H = Ra_H \times Da = \frac{g\beta\Delta TH^3}{\alpha\nu} \times \frac{q'''H^2}{k\Delta T} = \frac{g\beta q'''H^5}{\alpha\nu k}, \tag{1}$$



(a) Two-layer (b) Three-layer

Fig. 1. Stratified molten pool configuration.