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Original Article

Two- and three-dimensional experiments for oxide pool in in-vessel retention of core melts

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ABSTRACT

To investigate the heat loads imposed on a reactor vessel through the natural convection of core melts in severe accidents, mass transfer experiments were performed based on the heat transfer/mass transfer analogy, using two- (2-D) and three-dimensional (3-D) facilities of various heights. The modified Rayleigh numbers ranged from 10^{12} to 10^{15}, with a fixed Prandtl number of 2,014. The measured Nusselt numbers showed a trend similar to those of existing studies, but the absolute values showed discrepancies owing to the high Prandtl number of this system. The measured angle-dependent Nusselt numbers were analyzed for 2-D and 3-D geometries, and a multiplier was developed that enables the extrapolation of 2-D data into 3-D data. The definition of Ra'_H was specified for 2-D geometries, so that results could be extrapolated for 3-D geometries; also, heat transfer correlations were developed.

1. Introduction

In a severe accident, nuclear fuel may melt and stratify into upper metallic and lower mixture (oxide pool) layers according to density differences in the vessel lower head. The mixture layer contains uranium and fission products that continuously generate decay heat. In-vessel retention and external reactor vessel cooling (IVR-ERVC) is a power plant design strategy that allows the operator to maintain the reactor vessel integrity. To implement this strategy, it is important to know the heat load imposed on the reactor vessel by the natural convection of the oxide pool, the heat focusing on the reactor vessel in the upper metallic layer, and the external cooling capacity. This study aims to experimentally determine the heat load imposed on the reactor vessel.

Several experimental studies have been performed in two- (2-D) or three-dimensional (3-D) oxide pool geometries. Numerous volumetric heat sources have been devised to simulate the molten core decay heat. However, results from these studies have been reported without comparison with those of studies, nor have results been verified.

We simulated the IVR phenomena using semicircular (2-D) and hemispherical (3-D) facilities whose heights were 0.042 m, 0.1 m, and 0.167 m; these values correspond to Ra'_H values of 10^{12}–10^{15}. This work was performed with idealized simplified configurations assuming a homogeneous oxide pool, because complex severe accident phenomena cannot be considered all together.

To achieve these high buoyancies with compact test rigs, mass transfer experiments were performed using a copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) electroplating system based on the analogous natures of heat and mass transfer (MassTER-OP2 and MassTER-OP3, respectively).

2. Theoretical background

2.1. Phenomena

Typical flow patterns in the oxide pool are shown in Fig. 1 [1]. External cooling induces natural convection flows that run along the curved surface. The main downward flows merge at the bottom, move upward, and then disperse toward the edges at the top plate. There is a secondary natural convective flow beneath the top cooling plate. In a 3-D geometry, the main flows disperse radially beneath the top plate, and gather radially at the center of the bottom. However, these radial behaviors are not expected in a 2-D system.

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Nomenclature

A	area (m^2)
C	molar concentration ($kmol/m^3$)
d	width (m)
D_m	mass diffusivity (m^2/s)
Da	Damköhler number ($q'''H^2/k\Delta T$)
F	Faraday constant (96,485,000 Coulomb/kmol)
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 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 K)
n	number of electrons in charge transfer reaction
Nu	Nusselt number (h_hH/k)
Pr	Prandtl number (ν/α)
q	heat generation rate (W)
q'''	volumetric heat generation rate (W/m^3)
R_e	equivalent 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
δ	boundary layer thickness (m)
μ	viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

b	bulk
dn	lower head
h	heat transfer system
m	mass transfer system
T	thermal
up	top plate
2D	two-dimensional geometry
3D	three-dimensional geometry

2.2. Existing definition of Ra'_H

The buoyancy of a system is expressed by the Rayleigh number. In this system, because the mixture layer of molten fuels continuously emits decay heat, the internal heat generation should be incorporated into the definition of the Rayleigh number. The modified Rayleigh number, Ra'_H, is defined as the product of the conventional Ra_H and the Damköhler number (Da). Da is a dimensionless parameter that represents the volumetric heat generation (q'''), thus:

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

$$\text{where } Da = \frac{q'''H^2}{k\Delta T}. \tag{2}$$

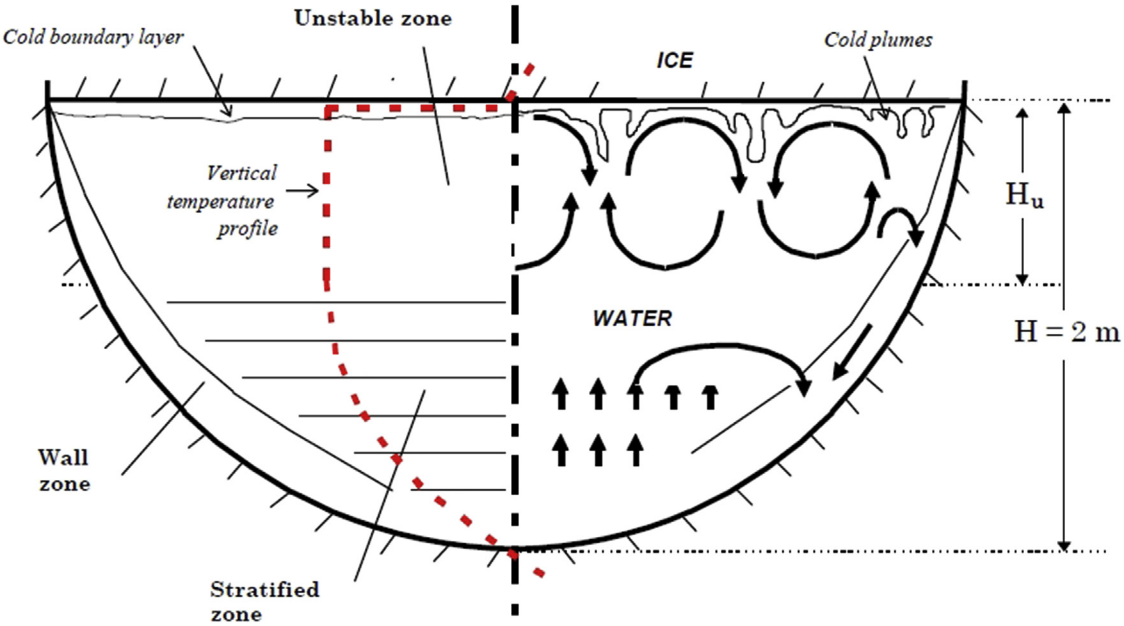

Fig. 1. General flows.

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