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Heat & mass transfer and interface temperature during simulated melt-concrete interaction with composition variation in ARTEMIS 2D experiment

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HIGHLIGHTS

- 0D modelling of heat and mass transfer during molten corium-concrete process (MCCI).
- Application of developed model for validation of experimental data of ARTEMIS 2D.
- Evolution of interface temperature for eutectic and non-eutectic coriums.
- Interface temperature stay at eutectic temperature for eutectic corium.
- Interface temperature can be predicted using TIM for non-eutectic corium.

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ABSTRACT

In a severe accident involving a water-cooled nuclear reactor, the core containing a mixture of oxides ($U0_2$ and ZrO_2) heats up under the influence of decay heat. Within several hours from the start of the accident, core melting occurs and liquid materials (named corium) flow into the lower head and, ultimately, may relocate in the reactor pit. Thus, interaction between Molten Corium and Concrete (MCCI) occurs. Since containment integrity is a key objective in severe accident management, knowledge of the concrete ablation rate is required. Ablation rate and shape of concrete cavity depends on heat flux distribution. During MCCI concrete is melting between 1200 °C and 1800 °C and refractory solid species from the corium (UO_2, ZrO_2) may precipitate at the concrete interface due to the elevated liquidus temperature of the corium (Liquidus temperature is typically between 2200 °C and 2500 °C). Several complex phenomena (solidification, gas release, concrete entrainment) at the melt-concrete interface influence the interface temperature, and consequently the evolution of the heat flux distribution at the melt boundaries. In this framework, ARTEMIS 2D simulation tests were performed at CEA Grenoble (France) to investigate the non-eutectic material on the 2D transient melt-concrete interaction phenomena, focusing on the determination of the heat flux distribution along the corium cavity wall for non-eutectic mixtures. The present work contributes to a determination of the controlling phenomenology at the interface for both hydraulic and chemical aspects, during transient as well as in steady state. A model has been developed allowing predictions of corium-concrete interface temperature and heat & mass transfer evolutions during the ablation process in ARTEMIS 2D. This model proposes a single and consistent approach for various reactor situations involving In-Vessel-Retention, Ceramic Ablation and Corium-Concrete Interaction.

1. Introduction

In a severe accident involving water-cooled nuclear reactors the core, containing a mixture of oxides ($U0_2$ and ZrO_2), heats up under the influence of decay power. Within several hours from the start of the accident, core melting can occur and liquid materials (called: corium) flow into the lower head and, ultimately, may relocate in the reactor pit. Molten Corium - Concrete Interaction (MCCI) then

Abbreviations: IVR, In-Vessel Retention; LCS, Limestone Common Sand concrete; MCCI, Molten Corium-Concrete Interaction; TIM, Transient Interface temperature Model for Multi-component systems (TIM).

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Nomenclature

a, b	coefficients in $Nu = \alpha\, Ra^b$
C	mass concentration of solute (kg/kg)
Csp	specific heat of bulk liquid (J kg^{-1} K^{-1})
D	mass diffusion coefficient of solute (m^2 s^{-1})
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
j	superficial velocity of entrained liquid in the boundary layer (m/s)
k_M	mass transfer coefficient (m/s)
L	latent heat of melting (J kg^{-1})
$L' = [L_w + C_{sp,w}(T_{BL} - T_w)]$ (J kg^{-1})	
m_L	slope of the liquidus curve in the phase diagram (K)
T	temperature (°C)
V_{abl}	ablation velocity of wall (concrete) (m s^{-1})
Greek	
ϱ	density (kg m^{-3})
$\Delta\rho$	density difference between boundary layer and bulk (due to temperature, composition and void fraction effects)
α	thermal diffusivity of the melt (m^2 s^{-1})
β_T	thermal expansion coefficient of the melt (K^{-1})
υ	kinematic viscosity of the melt (m^2 s^{-1})
Gr	Grashof number, $Gr = \frac{g\frac{\Delta\rho_{bulk}H^3}{\rho_{bulk}}}{\nu^2}$
Ra	Rayleigh number $Ra = Gr\, Pr$
Nu	Nusselt number, $Nu = a\,Ra_{ex}^b = a(Gr\,Pr)^b$
Sh	Sherwood number $Sh = \frac{k_M H}{D}$
Sc	Schmidt number, $Sc = \frac{\nu}{D}$
Pr	Prandl number $Sc = \frac{\nu}{\alpha}$
Indices	
bulk	bulk or melt
i	interface
BL	boundary layer
w	relative to wall material (concrete)

occurs. Since containment integrity is a key objective in severe accident management, knowledge of the concrete ablation rate is required. Ablation rate and shape of the concrete cavity depends on the heat flux distribution. During corium – concrete interaction (concrete melts between 1200 °C and 1800 °C), refractory solid species may precipitate in front of the concrete interface due to the elevated liquidus temperature of the corium (liquidus temperature is typically between 2200 °C and 2500 °C). Several phenomena (solidification, gas release, concrete entrainment) at the melt-concrete interface influence the interface temperature, and consequently the heat flux distribution at the melt boundaries.

Experimental investigations have been performed in the last 20 years to study the molten corium-concrete interaction (MCCI) under prototypic conditions of severe accidents (ACE, MACE, CCI, VULCANO and others) (Sehgal, 2012). The objectives of MCCI studies include: Concrete ablation kinetics with corium cavity evolution in 1D and 2D geometries, the effect of concrete material on concrete erosion, heat transfer from the melt to the concrete and liquid-solid interface conditions (composition and temperature), melt solidification, ejection of gas and fission product release.

This work aims at studying the 2D molten corium-concrete interaction by means of ARTEMIS 2D experiments performed at CEA Grenoble with simulant eutectic and non-eutectic materials. A detailed analysis of experimental data from two representative tests (ARTEMIS 11 with eutectic melt and ARTEMIS 10 with non-eutectic melt) will be presented in order to derive the main physical phenomena controlling the heat and mass transfer at the melt-solid interface as well as the concrete ablation kinetics.

2. State of the art

For corium - concrete interactions, the approach initially adopted in the 1970 – 1980 s basically located the interface at the physical limit formed by the solid concrete wall. With this approach the mushy zone was treated as thermal resistance, which reduces the heat-transfer between the bulk of the melt and this interface. The mushy zone was a highly viscous layer which affected gas flow (resulting from the decomposition of concrete); gas accumulation at the interface could also affect heat transfer (Bradley et al., 1993; Foit et al., 1995). In the 90's the interface condition $T_i = T_{liquidus}$, assuming the existence of a refractory crust at the interface, was applied to the corium–concrete interaction (Seiler, 1996; Seiler and Froment, 2000). The physical justification for this was based on the fact that MCCI is a slow transient (the typical ablation rate is $\sim 10^{-5}$ m/s) which could be approximated as a succession of steady-state situations. This approach was first used to recalculate the ACE and MACE experiments (Spindler et al., 2005, 2006; Vandroux Koenig et al., 1999). This modelling approach yielded the following results (Seiler and Froment, 2000):

- The melt temperature tends to decrease as does the liquidus temperature (the melt liquidus temperature decreases as the concrete mass fraction increases). Quantitatively, the later efforts concluded that the melt temperature is close to the liquidus temperature for limestone-common sand (LCS) concrete, but stays below the liquidus for siliceous and concrete with iron oxides (ACE L5) (Vandroux Koenig et al., 1999);
- A higher mass fraction of refractory species was found near to the bottom interface in experiments with (LCS) concrete (Seiler and Froment, 2000), but not with siliceous concrete (Farmer et al., 2007a,b). The thickness of the layer enriched in refractory species was two to five times greater than the calculated thickness (on the basis of conduction heat transfer in the crust);
- For LCS concrete, the fact that the melt temperature is linked to the liquidus temperature explains that the melt temperature is only slightly affected by substantial power variations (MACE M3B test);
- The existence of a solid deposit at the interface was postulated to be a cause of ablation instabilities (Seiler and Froment, 2000).

A specific development concerning the modelling of corium–concrete melt viscosities, taking into account the melt physico-chemical behavior, was carried out at this point (Seiler and Ganzhorn, 1997; Cognet et al., 1999). Codes were developed taking into account the physico-chemical effects (TOLBIAC (Spindler et al., 2005, 2006; COSACO (Nie and Fischer, 2002), CORQUENCH (Farmer and Spencer, 1999; Farmer, 2001), MEDICIS (Cranga et al., 1999, 2005, 2010) and an interface temperature more or less linked to the liquidus temperature. More recently, analysis of 2D concrete ablation tests (CCI test series at ANL (Farmer and Lomperski, 2005; Farmer et al., 2006, 2007ab,c); and VULCANO tests at CEA (Journeau et al., 2009)) led to the following conclusions: