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In- and ex-vessel coupled analysis for in-vessel retention

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ABSTRACT

In-vessel retention (IVR) in the manner of external reactor vessel cooling (ERVC) is an important severe accident mitigation strategy, which has been applied to some advanced light water reactors, e.g. AP1000. This main assessment method on the effectiveness of IVR is the lumped parameter (LP) model, which has been applied to assess the safety margin of IVR-ERVC for decades. However, this model deals with the safety margin analysis with several isolated processes, without considering the strong coupled relations about the heat transfer processes in the internal and external reactor pressure vessel (RPV). This paper addresses this coupled issue based on modified lumped parameter model using an iterative method, which focuses on the relations between the inner wall surface temperature of the reactor pressure vessel lower head and the heat flux through the RPV inner wall with a modified heat transfer method. The method has been applied to analyze the molten pool behaviour of LIVE-L4 tests. Comparison between the experimental data and the calculation results is performed to validate the accuracy of the coupled analysis method. High attention is paid to some important parameters, e.g. the heat flux through vessel, the inner and outer wall surface temperatures of the RVP lower head and the crust thickness. In addition, the paper analyzes the effectiveness of IVR for AP600 based on the modified method and compares with the UCSB assumed Final Bounding State (FIBS) benchmark calculation results to verify the modified coupled method. This method is applied to conduct the sensitivity analysis for some design parameters of AP600.

1. Introduction

In-vessel retention (IVR) in the manner of external reactor vessel cooling (ERVC) is a key severe accident mitigation strategy for some newly designed nuclear power plants, which has been applied to the Louisa plant a few years ago. At present, the IVR-ERVC concept is applied to some advanced light water reactors (LWRs), e.g. AP600, AP1000 (Westinghouse design), APR1400 (Knudson et al., 2004). As an effective method for the of mitigation severe accident, also, the IVR-ERVC is applied to Chinese advanced LWRs designs, like CAP1400.

As for IVR-ERVC, the accident mitigation strategy is flooding reactor cavity before the relocation of molten debris, and making the reactor pressure vessel (RPV) submerged. The concept is mainly based upon the opinion that the lower head which gets cooled externally, will be able to accommodate the downward relocation of the degraded core. In this situation, it is required to assure that the integrity of the RPV lower head could be maintained under thermal mechanical loads, which mainly from the high temperature of molten pool (about 3000 K for oxide pool and about 1800K for metallic layer). Theofanous et al. (1997a) deemed that the boiling crisis (BC) is the necessary and sufficient conditions for the integrity of RPV lower head, meaning that if the heat flux along the angles through RPV wall exceeds local critical heat flux, the RPV will fail (Theofanous et al., 1997b).

As known, the phenomena of severe accident are full of uncertainties and very complicated. For molten pool, a number of complex phenomena such as highly turbulent natural convection, crust formulation, heat transfer for the ERVC and so on should be considered carefully. At present, extensive numerical and experimental researches have been performed. Some classical and important researches have been conducted by Theofanous et al. (1997a, 1997b); Zhang et al. (2010); Esmaili and Khatib-Rahbar (2004); Henry and Fauske (1993); Rempe et al. (1997) and Cao et al. (2015).

The concept has been developed by numerous researchers step by step. Theofanous (1989) first demonstrated the technical feasibility of the IVR concept for VVER-440 in Finland. Theofanous et al. (2004) demonstrated the effectiveness of the IVR-ERVC concept for an AP600-like design and provided a readily adaptable oath for other designs. Theofanous et al. (2004) suggested that it was reasonable to apply the IVR-ERVC strategy to higher power density reactors, such as AP1000.

For the natural convection heat transfer of molten pool, there are numbers of experimental analyses. Based on the experimental data, correlations characterizing the natural convection in form of

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Nomenclature

Gr	Grashof number
c_p	specific heat capacity, j/kg.K
Nu	Nusselt number
Pr	Prandtl number
H	height, m
k	thermal conductivity, W/(m.K)
Q	volumetric heat generation rate, W/m^3
q	heat flux, W/m^2
r	radius, m
S	area, m^2
Ra	Rayleigh number
T	temperature, K
V	volume of the molten pool, m^3
t	time, s
Ra’	internal Rayleigh number

Greek characters

ρ	density, kg/m^3
θ	angle
δ	thickness, m

Subscript

b	bottom of the molten pool
c	center of the molten pool
chf	critical heat flux
cr	crust
dn	downward
eq	equivalent
f	fluid of the ERVC channel
in	inner of the structure
l	metallic layer
m	melting
max	maximum value
out	outer of the structure
p	oxide pool
s	other structures
t	top of the molten pool
w	vessel wall
up	upward
ves	vessel

dimensional parameters and some other parameters were obtained. The COPO experiments dealt with the Rayleigh number about 1.5×10^{15} (Theofanous et al., 1997a). The UCLA experiments (Asfia and Dhir, 1996) utilized Freon ($Pr \sim 8$) as measuring material. The mini-ACPO experiments (Theofanous and Liu, 1995) have been conducted to address the issues about the independent effects of Prandtl number and the range of Ra’ number has been extended. (Theofanous et al., 1997b) summarized some available results aiming at natural convection heat transfer in metallic layer, and finally, obtained the heat transfer correlations of metallic layer conservatively, which were also supported by some simple simulant experiments.

However, all of these experiments discussed above mainly focused on the natural convective heat transfer in metallic layer and oxide pool to obtain the natural convective heat transfer correlations that are applied to theoretical analysis, except the LIVE tests, which were conducted to study the core melting behaviour and the effects of external cooling water (Fluhrer et al., 2005). Generally speaking, this experiment has focused on the coupled effects between the molten pool and external water cooling. At this study, these correlations discussed above have also been applied to assess the natural convective heat transfer in molten pool, but these results have been validated with the LIVE tests and verified with the AP600 benchmark results.

For Westinghouse designs on IVR-ERVC of AP600, the University of California - Santa Barbara (UCSB) has completed plenty of researches and produced peer-reviewed report, DOE/ID-10460. The Idaho National Engineering and Environmental Laboratory (INEEL) has been arranged to review the UCSB study independently. For the UCSB study, the key assumption was that the two debris configurations “bound” the thermal loads from all other debris configurations that can “reasonably expected”. One configuration was dominated by transient forced convection and jet impingement effects, and the other was dominated by natural convection in the “Final Bounding State” or the “FIBS”, and the analyses suggested that their assumed-FIBS were more challenging. The INEEL applied other relevant experimental data and severe accident analysis code to quantify uncertainties in UCSB study, and noted that the UCSB-assumed FIBS was not a bounding configuration.

Both the UCSB study Theofanous et al. (2004) and the INEEL study (Rempe et al., 1997) employed a lumped parameter model to analyze the energy balance of the steady state for molten pool, which dealt with the thermal response of the RPV lower head with a one-dimensional method. They also summarized the natural convective heat transfer correlations in oxide pool and metallic layer. Besides, Zhang et al. (2010) completed a code for AP600 and applied it to AP1000. For these codes, they were mainly based on one-dimensional and haven't considered the ERVC heat transfer in detail, generally with constant boundary conditions, such as constant temperatures or constant heat transfer coefficients.

Buck et al. (2010) and Palagin et al. (2012) has analyzed the LIVE-L1 and LIVE-L6 test respectively, both using CONV, ATHLET-CD, ASTEC and PECM model. In these models, the two-dimensional heat conduction in vessel wall and natural heat convection inside molten pool has been considered. However, there are also many challenges, such as lack of consideration of varying thermal conductivity via temperature in vessel, lack of the convective effects in molten vessel and detailed convective correlations at outer vessel wall surface.

Cao et al. (2015) analyzed merits and demerits of the relevant system codes, such as ATHLET-CD, SCDAP-RELAP, MELCOR and MAAP, and completed a code mainly considering the two-dimensional heat conduction, varying thermal conductivity via temperature in vessel, the convective effects in molten vessel and the convective heat transfer which dealt with the heat transfer process between inner and outer RPV wall surface, and finally validated the code with the experimental data from LIVE tests. For the study of Cao et al. (2015), it utilized the known heat flux through the inner RPV wall surface as input condition, meaning that it only focused on the 2-D heat conduction and ERVC convective heat transfer, ignoring the effects of natural convective heat transfer in molten pool.

According to the above summary, it can be seen that the issue has been divided into independent part, such as, the convective heat transfer between RPV outer wall surface and the ERVC fluid, the heat conduction in RPV lower head and the natural convective heat transfer in molten pool. Usually, the convective heat transfer has obvious influences on the molten pool, especially the curst thickness. Therefore, it is necessary to reconsider the issue with a comprehensive method, an iterative method to address the coupled analysis between the molten pool and the ERVC fluid. For verification and validation calculation, this paper selected the LIVE tests and the AP600 benchmark calculation results as comparison object.

This paper is made up of three main sections. The first section presents the couple analysis method based the modified lumped parameter model and the convective heat transfer of ERVC. The second section validates the modified model with the LIVE-L4 experimental