Progress in Nuclear Energy 79 (2015) 167–181

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Review

Natural convection heat transfer in corium pools: A review work of experimental studies

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ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form
20 November 2014
Accepted 22 November 2014
Available online

Keywords:
Severe accident
Natural convection
Corium pool
IVR

ABSTRACT

During a severe accident in nuclear reactors, the core may melt and relocate into the lower head. The decay power in the accumulated melt pool will threaten the integrity of the reactor vessel if there is no effective cooling mechanism. Natural convection plays an important role in determining the heat flux distribution from the debris pool, which is directly relevant to the problem of retention of molten corium inside the lower plenum. Many experimental programs on natural convection heat transfer in corium pools have been performed under different conditions with multifarious research directions, thus a review work on this topic is necessary. Based on three different kinds of geometrical structures, this paper presents a comprehensive literature review of experimental methods and results. Influences of geometry, simulant material, heating method and layer stratification are also discussed. Conclusions and further research directions on natural convection heat transfer in corium pools are proposed.

1. Introduction

During a severe accident in light water reactors, the melt of the core may occur and then the corium melt may relocate into the lower plenum of the Reactor Pressure Vessel (RPV). The molten core material can form a hemispherical pool in the lower head with homogenous internal decay heat, as happened in the Three Mile Island Unit 2 (TMI-2) accident. If there is no effective cooling mechanism, the decay power will gradually heat up the melt pool and then the vessel wall, which will threaten the structural and thermal integrity of the reactor vessel.

External Reactor Vessel Cooling (ERVC) is regarded as a promising severe accident mitigation strategy for In-Vessel Retention (IVR) of core melt. The reactor cavity is flooded to submerge the reactor lower plenum in order to cool the melt pool relocated into the vessel lower head. The Westinghouse Advanced 600 MWe PWR (AP600), and subsequent advanced light water reactors AP1000, both adopted ERVC with a flooded reactor cavity as the enhanced safety strategy (Zhang et al., 2013). This will create a nearly isothermal boundary outside the vessel wall. The success of ERVC is determined by the heat removal capacity, because for a volumetrically heated pool, the heat generated in the melt must balance the energy removed from the pool boundaries to achieve steady states. The heat flux distribution towards the curved wall depends on many aspects in thermal-hydraulic transient and steady state: melt pool configuration, decay heat generation, crust formation, and insulated or cooling boundary conditions.

Natural convection plays an important role in determining the thermal-hydraulic phenomenon in the debris pool at high enough Rayleigh numbers, which is directly relevant to the problem of retention of a molten corium pool inside the lower head of reactor vessel. The heat transfer inside the corium pool can be characterized by buoyancy-induced flows arising from internal decay heating (Lee et al., 2007b). The Nusselt number *Nu* for natural convection heat transfer with internal heat generation is generally correlated with the modified Rayleigh number *Ra*' in terms of the volumetric heat rate and molecular viscosity, as well as the Prandtl number *Pr* (Lee and Suh, 2003; Theofanous and Angelini, 2000):

$$Nu = CRa'^{m}\mathrm{Pr}^{n} = C\left(\frac{g\beta q_v H^5}{\lambda\nu\alpha}\right)^{m}\left(\frac{\nu}{\alpha}\right)^{n} \quad (1)$$

where n is equal to 0 in some correlations to suggest a minor effect of *Pr*.

As summarized by Asmolov et al. (2001), our knowledge-base with respect to the IVR issue is divided into six categories: decay heat and fission products, melt thermal hydraulics, heat flux removal, melt composition and chemistry, vessel failure modes,

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http://dx.doi.org/10.1016/j.pnucene.2014.11.021
0149-1970/

and corresponding transient processes. Most of the experimental programs associated with IVR phenomenon in the past years paid interest to the research of melt thermal hydraulics and the corresponding knowledge base is good. To investigate the thermal hydraulic phenomena in corium pools accumulated in the lower head after melt relocation, a considerable number of experiments and analysis have been carried out in different geometrical facilities, such as fluid layer and rectangular cavities, elliptical and semicircular slice pools, hemispherical pools (Nourgaliev et al., 1997). These experimental programs were performed to study the fundamental behavior of the molten pool for both homogeneous and stratified configurations, providing evidence for the feasibility of retaining the core melt inside the reactor vessel as an accident management strategy. The results of these experiments will be applied to develop models, which can be implemented into severe accident computer codes, such as MAAP, MELCOR, SCADP/RELAP, ICARE/CATHARE and ASTEC. Some important experimental programs on this topic are:

- COPO experiments at Fortum Nuclear Services, Finland and CEA/DRN, France (Helle et al., 1999; Kymäläinen et al., 1994)
- UCLA experiments at UCLA, USA (Asfia and Dhir, 1996)
- ACOPO experiments at UCSB, USA (Theofanous and Angelini, 2000)
- BALI experiments at CEA, France (Bernaz et al., 1998; Bonnet and Seiler, 1999)
- RASPLAV experiments at the Kurchatov Institute, Russia (Asmolov et al., 1998, 2001)
- SIMECO experiments at KTH, Sweden (Sehgal et al., 1998; Stepanyan et al., 2005)
- SIGMA experiments at Seoul National University, Republic of Korea (Lee et al., 2014, 2007b, 2005)
- LIVE experiments at KIT, Germany (Gaus-Liu et al., 2010b)

Due to different research emphasis and limited experimental conditions, these experiments were carried out in different geometrical facilities with different simulant materials under different boundary conditions, and the melt pool natural convection covers different ranges of Rayleigh number. The uncertainty also comes from the variety of accident scenarios and the corresponding melt pool configurations, as well as from the applicability of the experimental results to the reactor case. In a word, experimental research of natural convection heat transfer in corium pools with volumetrically internal heat source are multifarious and have different emphasis points and analysis angles, a review work on this topic is necessary.

This paper aims to present a comprehensive literature review of previous experimental studies on heat transfer phenomena in corium pools in order to propose future work. The remaining part of this paper is organized as follows. Some representative experiments are introduced in Section 2 and the influencing factors and remaining uncertainties are discussed in Section 3. Section 4 further remarked the results mentioned in this paper and concluded this paper.

2. Experiments

Based on the different geometrical structures of experiments on natural convection heat transfer in corium pools, the review is divided into three parts: experiments in fluid layers or rectangular pools, two-dimensional slice pools and three-dimensional hemispherical pools. The basic experimental setup and main results are briefly introduced for each experimental program to provide a comprehensive grasp for the related phenomenon and will definitely help us understand the further discussions. A representative summary of natural convection heat transfer correlations obtained from previous experiments are listed in Table 1. Table 2 provides correlations for downward heat transfer distribution along the curved wall. More detailed information of some important experimental programs is summarized and compared in Table 3.

2.1. Experiments in fluid layers or rectangular pools

Many experiments in earlier times have been performed in fluid layers or rectangular cavities to obtain the basic knowledge of natural convection heat transfer phenomenon in heated pools. The heating methods (internal Joule heating) and boundary conditions (cooled or adiabatic boundary conditions on the upper and lower walls) in the experiments and the large relevant thermal-hydraulic database (relationship between upward/downward heat transfer and Ra'/Pr) have significant guidance to the future experiment design. So it's worth the effort to briefly describe the basic design and corresponding results of the experiments in fluid layers or rectangular cavities.

One of the earliest experimental studies on natural convection heat transfer in volumetrically heated horizontal layers is that of Kulacki and Goldstein (1972). A layer of dilute $AgNO_3$ solution was bounded with two rigid isothermal plates from above and below. The Ra' numbers examined in their experiments ranged from 2.8×10^4 to 2.4×10^7. According to the temperature field measured by an interferometer in steady states, the entire region can be divided into three parts: a thin and unstable upper boundary layer, an isothermal central region, a wider and stable lower boundary layer. Kulacki and Goldstein (1972) proposed that the upper region of the laminar regime was occupied by cellular structures. This cellular area shrank with an increase in Rayleigh numbers until the whole region transformed into turbulent regime. The experiment results are in terms of two Nu numbers (upper and lower surface heat transfer) as functions of the Ra' numbers based on the internal heat generation. The relations indicate that the upward heat transfer is larger than that on the lower surface and the difference grows with increasing Ra'.

Similarly, Kulacki and Emara (1975) conducted a series of natural convection experiments in a horizontal fluid layer of dilute aqueous electrolyte bounded with an isothermal upper plate and an adiabatic lower plate. Joule heating by an alternating current passing horizontally through the layer provides a uniformly distributed volumetric energy source. The Ra' numbers within the heated fluid layer was in the range up to 10^{12} and the Pr numbers was varied from 2.75 to 6.86 by adjusting test temperatures. The correlation for the upper heat transfer of Nu numbers in relation to Ra' numbers was developed. Moreover, when taking Pr effect into consideration, a correlation for Nu numbers dependence on both Ra' numbers and Pr numbers was proposed. Since the data were for a very narrow range of Pr numbers, relationship with dependence on Pr is considered to be of limited value (Asfia and Dhir, 1996). Combing data from Kulacki and Nagle (1975), the Nu numbers at the upper surface is found to be proportional to $Ra'^{0.227}$ in the range of $1.88 \times 10^3 - 2.15 \times 10^{12}$, which covers the laminar, transitional and turbulent flow regimes (Kulacki and Emara, 1977).

Later, Suo-Anttila and Catton (1977) performed an experimental study to measure the effect of unequal boundary temperatures on the heat transfer from a horizontal fluid layer with volumetric heating. The layer was bounded by two rigid plates maintained at different temperatures. Data were obtained for Rayleigh numbers up to 10^{12}. Similar to the previous studies, they found out the existence of a series of non-uniform fluctuations in the temperature field in the upper region of the pool with a stable and calm liquid layer in the lower region. They concluded that for a rectangular cavity, heat was transferred more effectively in the upper region as opposed to the lower.