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Towards the accurate numerical prediction of thermal hydraulic phenomena in corium pools

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ABSTRACT

The knowledge of heat transfer in corium pools is one of the important issues for corium retention, as it defines the safety margin for vessel integrity. In this regard, in the 90's the BALI experimental program was performed at the CEA, France. The principal idea was to create a database regarding the heat transfer distribution at corium pool boundaries for in-vessel and ex-vessel configurations at high internal Rayleigh number (10^{15} to 10^{17}). One of the tasks within the ongoing IVMR project, part of the HORIZON 2020 program, is to assess the up-to-date CFD turbulence models over a wide range of Rayleigh number for the homogenous pool tests of the BALI experiments. In the present study, the assessment of three different turbulence models is performed for two BALI test cases. These turbulence models include a linear k-ε model, a non-linear Reynolds stress model and an advanced turbulent heat flux model known as the AHFM-NRG. After an extensive and careful assessment it has been found that none of the previous models is able to correctly predict the complex heat transfer phenomena appearing in natural convection flow regimes at such high Rayleigh numbers. Hence, a new model is proposed to deal with a wide range of Rayleigh number flow regimes. Accordingly, the results obtained using this new approach are found to be in a very good agreement with the available experimental data.

1. Introduction

The numerical prediction of turbulent natural convection flows requires a special attention with respect to the selection of the turbulence model. The limitations of the most commonly used turbulence models within the Eddy Diffusivity approach have become more evident, particularly for natural and mixed convection flows (OECD/NEA, 2007). There exist a number of situations in the nuclear industry where turbulent natural convection heat transfer occurs. One such situation corresponds to a hypothetical severe accident scenario in a light water reactor, in which the melt core may relocate and accumulate in the lower plenum of the reactor pressure vessel (RPV). The decay heat in the core melt may cause the formation of a core melt pool (corium) and the subsequent onset of natural convection. This turbulent natural convection in the corium pool could have a profound impact on the thermal loading in the vessel. A proper knowledge of the heat transfer in corium pools is one of the important issues for corium retention, as it defines the safety margin for the vessel integrity (Gaus-Liu et al., 2010), (Theofanous et al., 1996). In this regard, in 1993, the BALI experiment has been designed to create a database of the heat transfer distribution at the boundaries of corium pools (Bonnet, 1999). In the BALI experimental a series of different pool configurations were studied, such as homogenous, stratified and porous pools.

The BALI homogeneous pool test has been designed to simulate the natural convection flow and heat transfer phenomena in corium pools: in the lower head of the RPV (Bonnet, 1999). The test section is a full-scale 2D slice of a typical hemispherical pressurized water reactor (PWR) lower head, see Fig. 1. A water-salt solution is used as a simulant fluid. The BALI tests considered prototypical values of the internal Rayleigh number ranging from 10^{15} to over 10^{16}. The experiments were equipped with Particle Image Velocimetry (PIV), yielding information on the structure of the flow, as shown in Fig. 2. In principle, three major zones can be distinguished. Starting from the bottom part of the pool, a thermally stratified zone appears with low ascending velocities. In the upper part, an *iso*-thermal, unstable zone develops with sizeable eddies caused by cold plumes descending from the upper cooled surface. Lastly, a downward flow region along the cooled curved wall appears, where the velocity reaches its maximum values.

A number of CFD studies have been performed in the past in order to reproduce similar experiments and to provide an insight of the phenomena associated with the molten core (Le Guennic et al., 2017a,b; Fukasawa et al., 2008). However, it is certain that

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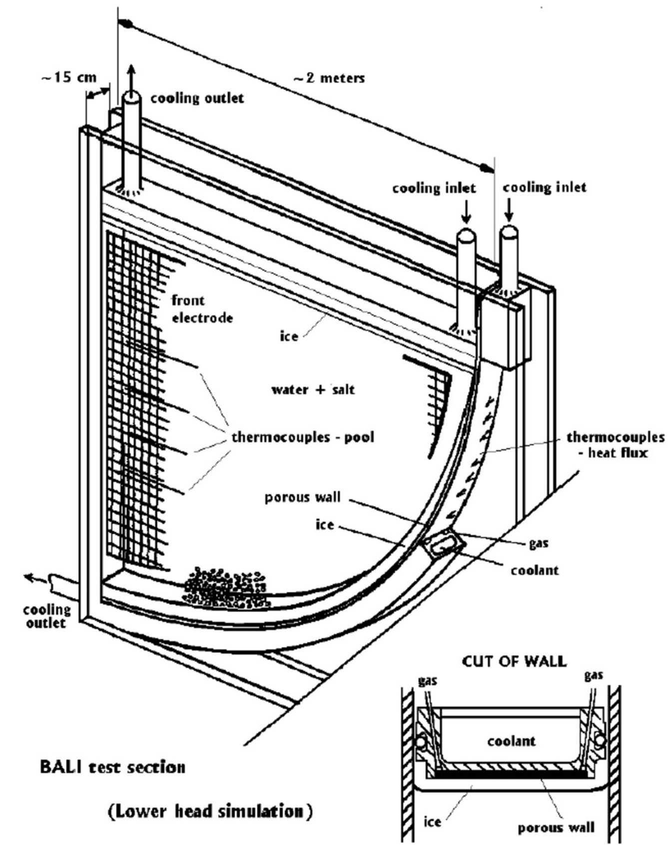

Fig. 1. BALI experiment test section (Bonnet, 1999).

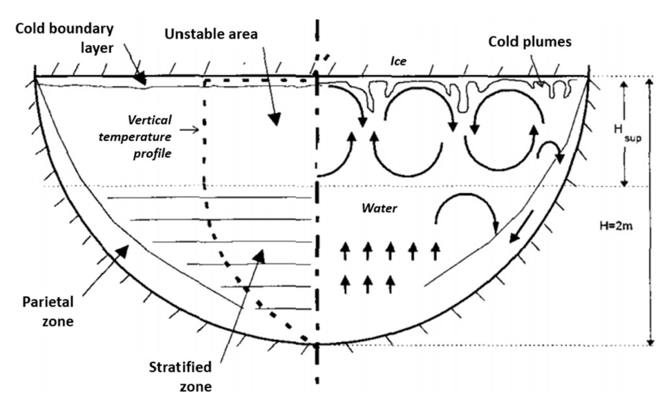

Fig. 2. Temperature profile and flow structure observed in the BALI tests (Bonnet, 1999).

numerical simulations for such a flow configuration are challenging. In particular, several efforts have been dedicated to assess different RANS turbulence models for their application to molten core and/or similar natural convection flow configurations. Dol and Hanjalic (2001) performed 2D and full 3D computations with low Reynolds k-ε models to simulate the natural convection in a side-heated near-cubic enclosure containing dry air (Pr = 0.71) at a Rayleigh number (Ra) equal to 4.9×10^{10}. Aounallah et al. (2007) performed the validation study of the k-ε and the k-ω SST models for a turbulent natural convection flow in a differentially heated cavity containing a fluid with Pr = 0.71 and at Rayleigh numbers ranging from 1.58×10^{9} to 10^{12}. The authors concluded that the k-ω SST model provided superior results compared to the considered k-ε model. Nevertheless, none of the models were able to correctly reproduce the mean flow. Similarly, Nourgaliev et al. (1997) have shown that the standard low Reynolds k-ε models are not suitable for such high Ra flows in a nuclear reactor. However, a modification of these models with anisotropic buoyancy effects could improve the accuracy of the analysis. Fukasawa et al. (2008) have performed the assessment of several turbulence models for one of the homogenous BALI test cases. They found similar conclusions as Nourgaliev et al. (1997). In a nutshell, CFD may help in gaining more detailed knowledge on in-vessel corium pool behaviour, which cannot be provided by integral/one-dimensional severe accident codes such as MELCOR, MAAP, RELAP, ICARE, and ASTEC. In this context, CFD can play an important role to predict the thermal-hydraulic phenomena of the various zones appearing in the corium pool and accordingly provide important qualitative information, which can be useful to improve the modelling in integral severe accident codes. However, despite several CFD studies, the available CFD codes are neither developed nor validated for corium pool applications. In this regard, the present work is a step forward in which a new CFD turbulence model is proposed and validated for the flow and heat transfer in a homogeneous corium pool at high Rayleigh number. As a next step, this model will be applied for corium pool applications.

In the present study, an assessment of four different turbulence models is performed for two BALI test cases. These turbulence models include: i) a linear k-ε model, ii) a non-linear Reynolds stress model, iii) an advanced turbulent heat flux model developed by NRG, known as AHFM-NRG (Shams et al., 2014), and iv) a newly proposed model, which is a modification of the AHFM-NRG model and is called as AHFM-NRG+. Details regarding the flow configuration and the adopted numerical strategies are reported in Section 2. In Section 3, the obtained results are extensively discussed and compared with the experimental data. This section is followed by conclusions in Section 4.

2. Flow configuration and numerical methodology

2.1. Selection of the test cases

The BALI experimental program comprised four test series. The first three test series were dedicated to the homogenous corium pools in order to study the effect of the Rayleigh and the Prandtl numbers, and to assess the heat transfer in a porous medium. The fourth series was performed on a different test section. Nevertheless, the main focus of the present study is to assess different RANS turbulence models for the homogenous pool. In this regard, two of the available BALI tests are considered and details are given in Table 1. The test case BALI-I has a pool depth of 1 m and employs a uniform temperature boundary conditions, whereas the case BALI-II has a pool depth of 2 m and a higher internal Rayleigh number compared to BALI-I.

2.2. Flow configuration

Following the BALI experiments, the selected flow configuration is a half slice of a hemisphere with two parallel walls representing a three dimensional geometric configuration, as shown in Fig. 3 (left). In the present study, the focus is on single phase computations; hence the ice formation, which was observed in the experiments, is not taken into account. Accordingly, based on the approximate thickness of the ice formed at the bottom of the pool, the resulting computational domain has been modified (see Fig. 3: right). It is worthwhile to mention that the thickness of the ice formation has been approximated based on the experimental results.