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DEVELOPMENT OF A BOILING MODEL FOR APPLICATION IN LUMPED-PARAMETER CODES FOR ASSESSMENT OF EXTERNAL REACTOR VESSEL COOLING

Ulf Schittek, Marco K. Koch
Ruhr-Universität Bochum (RUB), Germany
schittek@lee.rub.de, koch@lee.rub.de

Abstract

As a method for In-Vessel Retention (IVR) External Reactor Vessel Cooling (ERVC) might be an effective way for maintaining reactor vessel integrity during a severe accident with a core melt. For evaluating the ERVC as a severe accident management procedure simulation of cooling the Reactor Pressure Vessel (RPV) by flooding the reactor cavity is necessary and means simulation of heat transfer at a submerged heating surface. A model for simulation of the nucleate boiling during ERVC for lumped-parameter codes like ATHLET-CD based on a boiling model which was developed at the Renesselaer Polytechnical Institute (RPI) implemented in the CFD code ANSYS CFX 13.0 is under development at RUB.

Introduction

To assure a safe operation of nuclear power plants (NPP) requirements on reactor safety systems are very high. Although the probability is very low, under certain circumstances a severe accident could occur and could cause a core melt in the improbable case that the reactor cooling could not be restored by reactor cooling systems or emergency core cooling systems. In such a case parts of the melt could relocate to the lower head of the RPV as happened in Three Mile Island Unit2 (TMI-2) Accident. If so the integrity of the RPV is endangered by thermal loads of the core melt within the RPV so that the structural stability is jeopardized. [1], [2]

Taking into account a core melt scenario with relocation to the RPV lower head there are two different concepts restricting the consequences of such an accident to the plant site to avoid any hazards to the environment in Generation III reactor concepts. The core catcher concept provides an opportunity to catch melt from the RPV and spread it into a separate core catcher to cool it within the containment. Another concept is to avoid a failure of the RPV and retain the melt by cooling the RPV from outside. The ERVC is realized by flooding the reactor cavity with water and submerging the RPV. In this way the thermal load due to the decay heat from the core melt is removed. Due to the RPV wall temperatures, nucleate boiling processes are expected on the outer RPV wall. The feasibility of ERVC has been proven by several experiments for NPP concepts like e.g. the AP1000 [3] and has been implemented to Lovissa NPP [4].

1. Purpose

In the framework of a joint research project sponsored by the German Federal Ministry of Education and Research (BMBF) RUB is developing a model to simulate ERVC with the Lumped Parameter (LP) code ATHLET-CD (Analysis of Thermal-hydraulics of Leaks and Transients – Core Degradation) which is under development by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH in Germany. Based on the calculated wall temperature on the outer surface of the RPV by the ATHLET-CD module AIDA the heat transfer shall be simulated. Due to the RPV lower head geometry the regarded submerged heating surface is downward facing with different inclinations. The prediction of the heat flux is important in order to predict whether the heat flux exceeds the critical heat flux on the vessel surface or in other words if the RPV wall remain intact. Furthermore ERVC is an interface between reactor cooling circuit and containment so that data on the generated steam can be transferred as input parameter to containment codes like the containment code system COCOSYS.
This paper should give a brief overview on the concept of the running model development for simulations of ERVC with ATHLET-CD on the basis of a wall boiling model implemented to the CFD code ANSYS CFX 13.0.

2. External Reactor Vessel Cooling

The risk of a core melt towards the RPV consists in the high temperatures due to the decay heat which is released after scram and endangers the integrity of the RPV material. ERVC intends to remove the decay heat by flooding the RPV cavity with water and cooling due to downward facing boiling at the outside in order to avoid a failure of the RPV wall and retain the core melt. So the basic idea of IVR is that the thermal load from a core melt within the RPV is below the critical heat flux (CHF) of the boiling water at the outer surface of the RPV [3].
To realize ERVC some basic presumptions have to be fulfilled. First of all it is necessary that there is a sufficient supply of water with a direct access to the cavity and the vessel surface. Because of the expected temperatures at the RPV wall nucleate boiling regime is expected so that a removal of steam is required in order to avoid a pressure build-up in the Containment.
The feasibility of decay heat removal by ERVC is limited by the following factors: As explained above the CHF at the RPV surface is the first factor. Based on the water/vapor two phase flow the choking limit for steam venting (CLSV) is a second limiting factor. The buoyancy driven upward flow of the arising vapour is entrained by water so that a two phase flow is evolved. The resulting flow could choke the steam removal at bottleneck so that steam could not be led away anymore. As a consequence steam is accumulating and there is no supply of liquid water to the heating surface. [1] Depending on the size of the NPP the focusing effect could be a third liming factor. Due to density differences the configuration of the core melt within the RPV lower head can be divided in an oxide pool and a metallic layer above (see Figure 1). Because of the good heat conductivity characteristics the heat from the melt might be focussed directly to the RPV wall in the region of the metallic layer.

In order to improve the efficiency of ERVC and enable it for reactors of sizes above 1000 MW_{el} enhancing and supporting measures like vessel coating to enhance the downward facing boiling or an enhanced vessel/insulation design to improve the steam removal are taken into account. [1], [5]

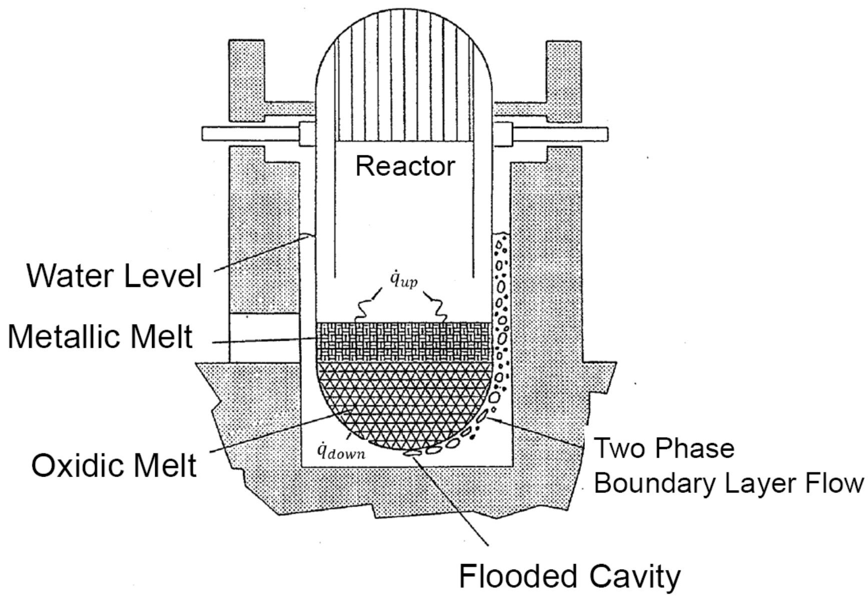

Figure 1: principle of nucleate boiling in ERVC [6]

3. Model development

The concept of model development is to adopt the effects of downward facing boiling to an existing wall boiling model approach. In the following nucleate boiling on downward facing surfaces and the chosen wall boiling model basis are described. In a next step a first calculation with the wall boiling model is compared to a correlation for ERVC.

3.1 Downward facing nucleate boiling

Nucleate boiling is characterized by a high frequency of generated steam bubbles. The steam generation in nucleate boiling is affected by the course of the ebullition cycle. Ebullition starts with the development of a vapor bubble at a nucleation site. In the following the bubble is growing until the size of the bubble reaches a certain size and departs from the heating surface. After departure a new bubble can arise at the nucleation site.
Depending on the hemispherical geometry of the RPV lower head the main heating surface is downward facing with different angles of inclination. The phenomenology of downward facing nucleate boiling has been studied in several studies [7] as well as boiling in the course of ERVC was analyzed investigating the feasibility and borders of ERVC as an IVR feature. After [8] the ex-vessel boiling process at the bottom center is divided in four distinct phases direct liquid-solid contact, bubble nucleation and growth, coalescence and vapor mass dispersion (ejection). The general direction of the

rising bubbles is in radial direction and gives rise to a regular progression from the bottom center upwards along the vessel radius. The characteristics of the flow appear like periodic waves of vapor although steam is generated on the entire vessel surface. [8]

3.2 RPI-Wall-boiling model

As a first approach for ERVC model development the RPI wall boiling model implemented in the CFD code ANSYS CFX13.0 is chosen. The model is named after the Renesselaer Polytechnical Institute (RPI) and goes back to a mechanistic heat partitioning of the Wall heat flux q_w as the sum of the heat flux components due to single-phase convection q_c, quenching q_q and evaporation q_e [9]:

$$q_w = q_c + q_q + q_e \ .$$

Figure 2 points out the heat fluxes during nucleate boiling as considered in the RPI wall boiling model. Also the time dependent course of ebullition is implied. The heating surface is separated into two parts in which the fraction A_2 is directly influenced by the development of the ebullition cycle and fraction A_1 (A_1=1-A_2) as the remaining wall area representing the wall surface which is not affected by the formation of bubbles (see Figure 2).

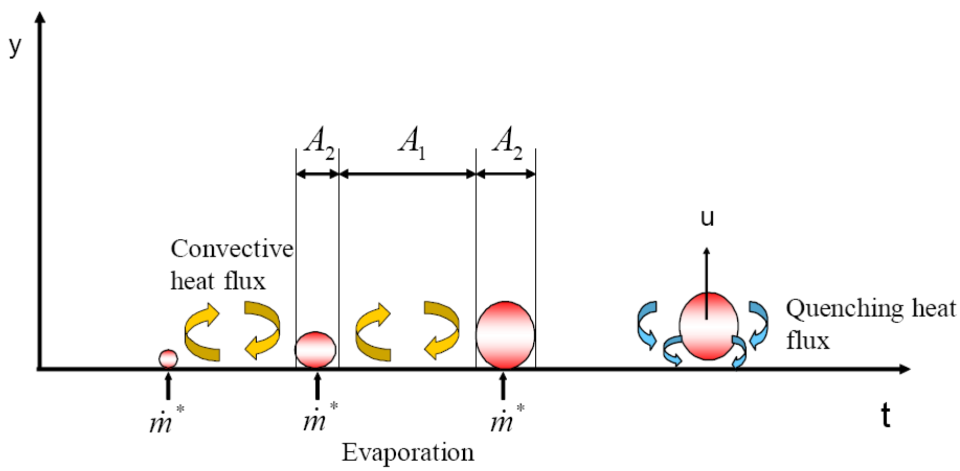

Figure 2: Heat fluxes of the RPI model [10]

The convective part of the total heat flux is calculated as

$$q_c = A_1 h_c (T_w - T_l).$$

Where the temperature of the wall is T_w, T_l is temperature of the liquid and h_c is the heat transfer coefficient, which is calculated using the temperature wall function.

In the transient conduction during the time period between the departure of a bubble and the next bubble formation at the same nucleation site the quenching part q_Q of the heat flux is given in terms of the quenching heat transfer coefficient h_Q and the temperatures of the wall and the fluid.

$$q_Q = A_2 h_Q (T_W - T_L).$$

The evaporation part q_E of the heat flux is correlated with the evaporation mass flux on the wall $\dot{m}_E$ and the evaporation enthalpy Δh_E as

$$q_E = \dot{m}_E \Delta h_E.$$

To close the correlations given above several sub models are available. The RPI model assumes, that the diameter of the bubble influence zone is twice as large as the bubble departure diameter d_W so that the non-dimensional area fraction influenced by the formations of bubbles is

$$A_2 = \min\left(\pi d_W^2 \cdot \frac{n}{4}, 1\right).$$

The bubble departure diameter d_W is adopted by [11]

$$d_W = \min\left(1.4\,mm, 0.6\,mm \cdot \exp\left(-\frac{T_{sat} - T_L}{45\,K}\right)\right).$$

The nucleation site density n according to [12] depends on the difference between the temperature of the wall and the saturation temperature T_{sat}

$$n = 185 (T_W - T_{sat})^{1.805}.$$

The quenching heat transfer coefficient is recommended by [13] as

$$h_Q = 2 f \sqrt{\frac{t_W \lambda_L \rho_L c_{pL}}{\pi}}.$$

In which t_W is the waiting time between bubble departure and nucleation of a new bubble at the same nucleation site with

$$t_W = \frac{0.8}{f}.$$

Dependent on the gravitational acceleration g, the bubble departure diameter and the densities ρ_L and ρ_G for the liquid and the gas phase respectively the bubble departure frequency f is adopted here from [14] in the form

$$f = \sqrt{\frac{4 g (\rho_L - \rho_G)}{3 \rho_L d_W}}.$$

Furthermore λ_L is the liquid heat conductivity and c_{pL} is the specific heat capacity of the liquid.

In order to calculate the evaporation heat flux the evaporation mass flux is given by [15]

$$\dot{m}_E = \rho_G \frac{\pi d_W^3}{6} f n.$$

In order to enable calculations on the heat transfer during ERVC with the RPI model influence factors on the process have to be taken into account. Besides, boundary conditions have to be considered. The influence of inclination which characterizes the heating surface in ERVC is the most obvious aspect which has to be included for simulations of ERVC. In addition, the characteristics of the external heating surface affect the boiling process by the nucleation site density.

To estimate the prospects of the RPI model for ERVC a calculation on the heat flux is compared to a correlation from ERVC experiments in the SBLB test facility. At the Subscale Boundary Layer Boiling (SBLB) test facility several experiments concerning ERVC have been realized investigating the effects of vessel coatings or enhanced insulation structures. [16] In dependence of the inclination different correlations have been set up. Figure 3 shows the Heat transfer calculated with the SBLB correlation for an inclination of 56° and the calculations with the RPI model without any regard to the inclination. Although the graphs show a similar overall progression the inclination of the SBLB correlation exceeds the increase of the RPI calculation until the graphs converge.

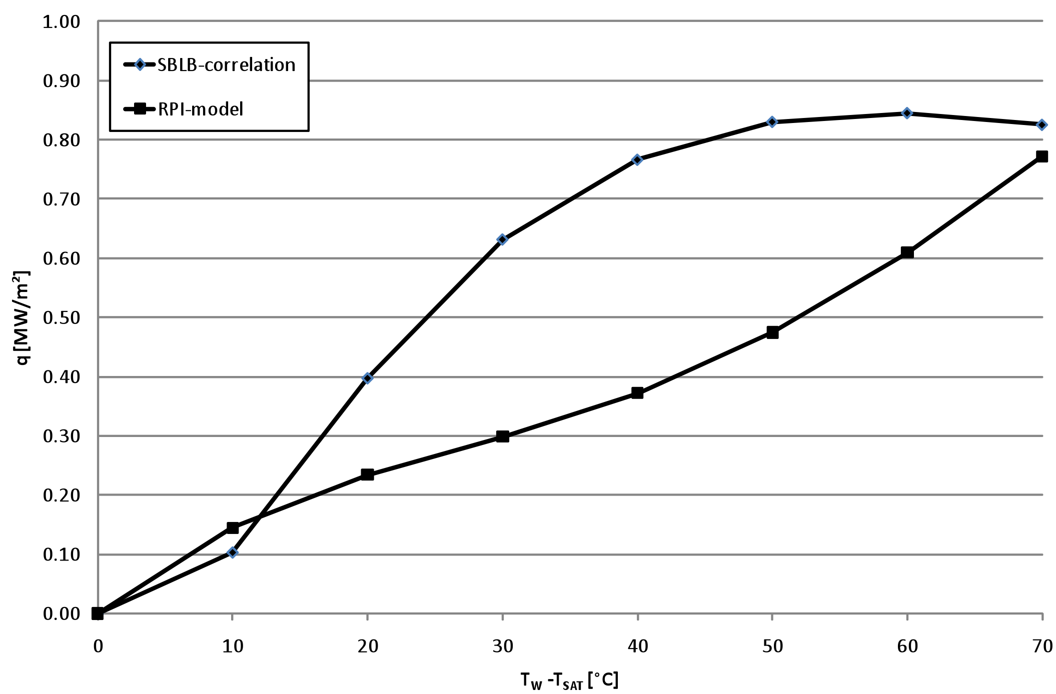

Figure 3: Prediction of heat flux in ERVC

4. Outlook

To enlarge the presented wall boiling approach in order to recognize the effect of inclination of the heated surface the presented sub models which are used in the RPI wall boiling model have to be modified. The most obvious effect of inclination of a heated surface is the coalescence of bubbles due to the interference of bubble departure by the configuration of the heating surface. That has a direct effect on the bubble departure diameter and the ratio of the area fractions influenced by the generated steam. Further steps contain work on the bubble departure in dependence of the inclination angle on the heated surface.

5. Conclusion

To assess ERVC with the LP-Code ATHLET-CD a model is under development to calculate the heat transfer in nucleate boiling on an inclined surface as a RPV lower head. As basic approach the heat flux partitioning approach of the RPI wall boiling model adopted from the CFD Code CFX 13.0 is used. In comparison to ERVC correlations the calculated heat fluxes show the necessity to improve differences which have to be taken into account in the sub models of the RPI wall boiling model. The accomplishment of model development is still in progress so that results will be introduced in the presentation at NURETH-14.

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