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Review on the PhD thesis of Luc Favre on

Modeling and simulation of the boiling crisis within PWR at CFD scale

Subject and significance of the thesis

The work is dedicated to CFD modeling of wall boiling processes under conditions typical for pressurized water reactors (PWRs). The detailed understanding of the complex physical processes is of high relevance for nuclear reactor safety, since the occurrence of the boiling crisis has to be safely avoided. During the boiling crisis the heat removal from the fuel rods is strongly reduced what may lead to a damage of the fuel elements. Because of its importance, the subject has been intensively investigated for decades. The application of CFD methods to describe the processes has also been a long-standing research topic. Despite all this work, the predictive capability of today's CFD methods is not satisfactory with respect to important parameters, such as the wall temperature that establishes for a given heat flux (as it is the case in PWR). The main reasons are the complexity of the processes, the influence of phenomena on multiple scales and the high number of influencing parameters.

This PhD thesis analyzes the previous work very thoroughly. The most important achievement is the establishment of a new wall heat flux partitioning model. This represents an important step towards improved modeling. The work is dedicated to a relevant topic and is original.

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Content

In the Introduction the background regarding PWRs and boiling phenomena including the boiling crisis is well explained. This provides clear motivation and shows that an accurate modelling of the boiling phenomena is relevant and a topic of high importance.

In the first part of the thesis (chapters 2 - 4), the state of the art is demonstrated using the example of the wall boiling models implemented in the CFD code NEPTUNE_CFD and their validation on the basis of DEBORA data.

For this purpose, Chapter 2 first presents the basic equations and the main closure models applied in NEPTUNE_CFD. In particular, the equations for the wall boiling model are introduced. This is based on the heat flux partitioning model of Kurul and Podowski with an additional term to account for the convective heat flux towards vapor.

The third chapter is dedicated to the DEBORA experiments. After the description of the experiments and measurement techniques, the selection of the measurement series suitable for the present purpose is made. A selection of important data is presented. Different consistency tests are carried out. Since the data basis is not new, the question arises here whether such a detailed analysis, interpretation and examination of the data has actually been carried out for the first time in the context of the work and what was already available.

In Chapter 4, the validation of the NEPTUNE_CFD models is performed using the DEBORA data discussed in Chapter 3. For this purpose, the simulation setup is first presented and a grid study is performed. The results show that the present modeling for wall boiling leads to partly significant deviations in important parameters such as the gas fraction, the bubble diameter and the wall temperature. The influence of the parameters of the heat flux partitioning model is particularly evident for the wall temperature, while the bulk parameters are less affected. From the results, it is concluded that the heat flux partitioning model in particular needs to be updated. Therefore, a new wall heat flux partitioning model is developed in the second part of this thesis.

This second part (chapters 5 to 9) is the most important part of the thesis, which contains actual new developments within the framework of the dissertation.

In chapter 5, the most important existing heat flux partitioning models are presented. The most frequently used is the one by Kurul and Podowski, which is usually also the starting point for extended models. However, it does not take into account bubble sliding, which is important for vertical flows. Therefore, it is only suitable to a limited extent for application to the boiling processes in PWR, as was also shown by the discrepancies between the simulations with NEPTUNE_CFD, which uses this model, and the Debora experiments in chapter 4. Bubble sliding adds a high degree of complexity to the modelling, as various assumptions have to be made about the sliding length and thus about the interaction with other bubbles. The model of Basu et al. provides some approaches for this, other models take into account additional phenomena such as microlayer evaporation or simplify some models.

The construction of the new model then begins in chapter 6. An important part of this is the establishment of a balance of forces. This is nothing fundamentally new, but the choice of models for the individual forces is not trivial. However, it is done very thoroughly here and findings and correlations from recent work are used. Different approaches and correlations are compared and their suitability is critically discussed. In this way, a new selection is made for the individual forces. Finally, the corresponding equations are compared to those of existing models.

For the description of the bubble growth, an analytical model is proposed which assumes an established single-phase thermal boundary layer of a given thickness. In comparison with DNS data and experiments, it shows good results especially for the low pressure range, but one problem of the model is the uncertainty of the boundary layer thickness (needed as an input parameter), on which the results sensitively depend. Although the model itself is more detailed, it does not bring real advantages for the desired application due to this uncertainty and is therefore not used in the new overall model. The ability to critically assess the advantage of the candidate's own derivations and model developments over existing approaches and to draw the appropriate conclusions should be noted positively here.

The bubble sliding is again considered based on the force balance. The bubble departure diameter, i.e. the bubble size at which sliding starts, is a result as well as the bubble growth during the sliding phase and the sliding speed of the bubble. Critical parameters here are the contact angles at the base of the bubble at the front and the back with regard to sliding. However, the lift-off diameter cannot be determined from the single bubble force balance, as it only provides resulting forces directed towards the wall. Therefore, it is assumed that lift-off takes place when coalescence occurs and a correlation between lift-off diameter and sliding length is proposed. It was obtained from a multi-dimensional regression of a large amount of experimental data.

In chapter 7, the actual construction of the new heat flux partitioning model takes place. For this purpose, the most suitable correlations are identified for further parameters, such as the single phase heat transfer coefficient, the nucleation site density and the waiting time. This is done very carefully and the selection is comprehensible. A particularly innovative part of this work is section 7.6 where the interaction between the different nucleation sites as well as the bubbles is considered. As a result, correlations for static coalescence and sliding coalescence are established from which corresponding heat fluxes are defined. Thus, the new heat flux partitioning model is finally composed of five terms: liquid convective heat flux, static coalescence evaporation heat flux, sliding coalescence evaporation heat flux, quenching heat flux and vapor convective heat flux. At the end of the chapter, the new model is summarized in a clear form.

Chapter 8 then validates the overall model. Here, however, I lack the information on how exactly this was done. I understand the new heat flux partitioning model, whose equations are listed at the end of chapter 7, as models that are suitable to be incorporated into a CFD code. While the abstract of the thesis says that it was implemented in NEPTUNE_CFD, no statements are made here about which modelling framework the new model was used in. This makes it difficult to understand the validations shown here. Apart from that, it is shown that the new model can reproduce the main trends well. Particularly interesting are the illustrations of the dependence of the individual contributions of the heat flux on the wall superheat.

The last chapter of this part, chapter 9, is dedicated to the critical heat flux. Here, existing models are mentioned and the importance of heat flux partitioning models for the prediction of the departure from nucleate boiling is emphasized. The only reference to the new heat flux partitioning model is the test of Zhang's criterion.

The third part of the thesis considers flows with mixing vanes in order to build a bridge to real flows in the core of PWR. For this purpose, corresponding experiments DEBORA-Promoteur and AGATE-Promoteur (single phase) are presented in chapter 10 and simulated with NEPTUNE_CFD in chapter 11. Since there is obviously no reference to the newly developed heat flux partitioning model and the chapters do not contain new innovative approaches or findings. In my view they are rather unnecessary for this doctoral thesis.

Chapter 12 finally summarizes the results of the thesis and lists some perspectives.

Style

The thesis is very well written and very good readable. The use of the colored boxes with notes or highlighting important results is very pleasant. The work follows a clear logical structure. All decisions, e.g. to use a certain sub-model, as well as conclusions drawn are clear and comprehensible. The graphics are good, although sometimes the colors and symbols are difficult to distinguish. Especially the summarizing tables, e.g. for the comparison of different models, are very helpful to keep the overview in this complex modeling.

In my opinion, it is somewhat unusual to use the "we" form in a dissertation, since it is supposed to be the candidate's independent work. In this respect, it is sometimes difficult to distinguish between the candidate's own work and existing work. The numbering of the references is not clear, as it does not follow the order of the first mention, the author's name or the chronology. The use of °C for temperature differences is not in accordance with the international standard and should be replaced by K.

Overall Evaluation

This thesis presents a very good scientific work on a relevant topic. In my opinion, it is correct and original in terms of scientific content. The work shows that the candidate has a very deep physical understanding of the many phenomena involved in wall boiling. Wall boiling processes are very complex and when the modelling is improved by a more accurate physical representation of the phenomena (as was done here), one encounters new parameters that are difficult to determine. In this respect, the new heat flux partitioning model will not bring a fundamental breakthrough in modelling, but it is a significant step towards improved modelling. Despite the complexity of the phenomena, the candidate succeeds in describing the problems in a way that is easy to understand, so that the work reads well. The only weakness, in my opinion, is that there is no comparison of the NEPTUNE_CFD simulations for the DEBORA cases with the new model. A direct comparison with the results from chapter 4 would have been desirable. However, this does not detract from the overall very high quality of the work and I can definitely recommend it for defense.

En conclusion, je donne un avis très favorable pour la soutenance de la thèse de Luc Favre.

Dirk Lucas