UPGRADING THE TWO-PHASE THERMOHYDRAULIC MODEL FOR THE FULL-SCOPE SIMULATOR OF PAKS NUCLEAR POWER PLANT

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ABSTRACT

The upgrade of the full-scope simulator of Paks Nuclear Power Plant (NPP) started in 2008. As a major part of this activity, the original two-phase thermohydraulic module (SMABRE) was replaced by our own development: the two-phase-flow module called RETINA. The validity of the new module was demonstrated by a number of transient calculations comparing the simulation results obtained by the new module with the ones produced by the original module. In the paper we briefly review the replacement procedure with a focus on the differences between old and new thermohydraulic modules. Some simulations results are shown to give some insight on the validation process.

INTRODUCTION

The full-scope training simulator of Paks Nuclear Power Plant has been in service since 1988. In the last two decades practically each element of the simulator has been upgraded, replaced because of the rapid development of the computer techniques making the solution of a great amount of earlier unsolvable problems possible. Moreover, the requirements against the simulator have also been changed. Originally the simulator was used only for training of the operating personnel of the Paks Nuclear Power Plant, but in the last decade it was also utilized as a "test bed" for new systems prior their installation on the real plant.
Changes, however, have not touched two fundamental modules of the simulator viz. the neutron-kinetics and the two-phase thermohydraulics models. Recently, the introduction of new fuel assemblies and consequently the intermediate cores with mixed fuel at the plant gave motivation to take another big step and replace both modules with our codes of own development - in order to simulate better the 3D processes in the core.
Since the simulator plays a crucial role in the life of the power plant such a change needs to be carefully planned, and what is more important, the results obtained by the new modules have to be generally accepted by the operating personnel and the authority.
In this paper we focus on the replacement procedure of the two-phase thermohydraulic module of the simulator. The features of the old and new thermohydraulic models are briefly introduced with a focus on differences between them and some simulations results obtained by both modules are presented, too, in order to demonstrate the validity of the new module.

THE REPLACEMENT PROCEDURE

Since the Paks full-scope simulator is a real-time system, each module of the simulator is managed by a scheduler program. It calls various models sequentially taking into account that all modules have to finish their calculation within 0.2 sec. The communication between modules (coupling between models) is clearly defined through the simulator database. Therefore, from computational point of view we just had to follow the basic concepts used for each module of the simulator during the replacement process.
The basic idea was to change the old and new thermohydraulic modules in two steps. In the first step, the nodalization (spatial discretization) of the plant remains the same and we have to demonstrate that utilizing the new module we can obtain practically the same results than we had before using the original module. In the paper we shall focus on this step. In the second step the nodalization of the system will be refined and we have to demonstrate that the simulation results are still reasonable for this new nodalization, too. In these steps, we are going to use the old neutron-kinetic module of the simulator, so in a third, final step we are going to replace the neuron-kinetic module of the system, too. Using this strategy, significant changes can happen only in a specific subsystem, which has the same environment than its predecessor. Therefore the identification of the source of a problem encountered during the test procedure is straightforward.
To test the vitality of the new thermohydraulic module a list of transient calculations have been performed and then compared with simulation results obtained by the old code. The list covers a wide variety of physics so it includes such as turbine load rejection, pump and

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turbine trip transients, small- and large-break loss of coolant accidents.

SMABRE AND RETINA: THE PAST AND THE FUTURE

The full-scope real-time simulator of Paks NPP originally had a two-phase flow module called SMABRE. This code was developed to simulate various two-phase flow transients up to the complexity of so-called **SMA**ll-**BRE**ak loss of coolant accidents (LOCA). Nevertheless, as the training simulator in Paks was getting involved more and more into the life of the plant, its scope had to be extended up to the complexity of severe accidents including for instance, the simulation of rapidly evolving large-break LOCAs (Végh et al., 1994; Végh et al., 1995). It turned out that the extension of the code in such directions is not straightforward at all. More and more specific models had to be implemented around the original module making finally the original code somewhat messy.
This fact has given us a strong motivation recently, when the refinement of the nodalization of the system became necessary, to replace the whole code to a new one called RETINA.
RETINA was developed in our institute in 2000. Since it differs very significantly from SMABRE in many respect, it was a quite challenging task to achieve practically the same simulation results with this code than we had before with the use of SMABRE.
Let us briefly summarize the major differences between SMABRE and RETINA. Details are given in (Házi et al., 2001; Miettinen, 1999)

Differences in models and governing equations

Although the same governing equations were implemented in both codes, there are significant differences in the models used to describe interfacial mass, heat and momentum transfer. To be more specific, both models use a five-equation approach (Ishii, 1974; Wallis, 1969), that is two mass and two energy conservation equations are solved for the individual phases (water and steam). The momentum conservation equation is solved for the mixture and it is supplemented by a drift-flux model in order to be able to simulate mechanical non-equilibrium between phases (different gas and liquid velocities) (Zuber and Findlay, 1969).
The original drift-flux model of RETINA was quite different from the one implemented in the code SMABRE. However, our first experiences have shown that the use of the original model leads to very significant differences between the solutions obtained by both codes. This fact forced us to change the drift-flux model of RETINA to a simpler one, close to a model used in SMABRE.
The governing equations need to be supplemented by closure relations, which calculate the interfacial mass and energy transfers in order to close the equation system. There are significantly different closure relations in these codes.
Closure relations are needed for interfacial mass transfer (evaporation and condensation) and interfacial energy transfer (heat transfer between phases). The equation system is also need to be supplemented with models, which take into account heat and momentum transfer between the individual phases and heat structures (walls).
Practically, the same models were implemented in both codes for modeling wall friction (Blasius correlation), but all other models differ somewhat in the codes.
Originally some standard evaporation and condensation models were implemented in SMABRE, but as the times passed by and the simulation scope of SMABRE was extended, more and more specific models had to be introduced into the old code in order to satisfy the new simulation requirements. Furthermore, models used in a certain part of the NPP (e.g. in the pressurizer) were quite different from the ones used in another part (e.g. in the steam generators). This fact made difficult to make any changes to the nodalization of the system, which has became necessary recently.
In RETINA the modeling of evaporation and condensation is in strong relation with interfacial heat transfer models. Basically, correlation for mass transfer between phases were derived rigorously from interfacial heat transfer models making consistent the interfacial mass and energy transfers. In case of SMABRE such relation is not transparent in some of the evaporation and condensation models. In RETINA the interfacial heat transfer models use a simple concept driving back any meta-stable liquid or gas to equilibrium (saturation) with a calculated relaxation time. Using such model, large volumes like the pressurizer or the steam generators of the NPP did not require special treatment. On the other hand, the calculation of the relaxation time proved to be inadequate in some nodes of the nodalization (e.g. at the sprinkler of the pressurizer) and the model had to be tuned somewhat with an additional relaxation parameter.
The implementation of the heat transfer modeling between heat structures and individual phases differs significantly in the codes, although some models used in specific flow regimes have the same origin. As an example we mention Chen's model (Chen, 1966) used to calculate heat transfer in sub-cooled boiling region. Although this model appears in both codes, it is utilized in a quite different manner resulting in some differences in the heat transfer characteristics of the two codes.
The calculation of critical two-phase flow is another example where differences are relevant. This model leads to different break flow characteristics and as a consequence, one might expect that simulation results obtained by the two codes can be significantly different when a loss of coolant accident is simulated.

Differences in the numerical approach

RETINA and SMABRE use significantly different numerical approaches.
Although both codes use similar spatial discretization procedure and staggered grid arrangement for pressure and velocities, their time marching schemes are different. While SMABRE applies a kind of sequential solver, RETINA uses fully implicit time discretization, calculating the Jacobian problem by automatic derivative functions.
The application of a fully implicit solver has some drawbacks. In general, an implicit solver needs some iterations to find the solution of the problem in question; and using large time steps for a very fast transient, one might encounter convergence problems, because of the overestimation of the elements of Jacobian matrix.
Originally, RETINA used automatic step size control to avoid divergence of the solution and the number of iterations used in each time step was controlled by the norm of the corrections used in each iteration. This strategy proved to be inappropriate for a real-time application. Therefore the time step was finally set to 0.2 sec and the number of iteration in each time step was limited to one. As it will be demonstrated, the code is still able to calculate any relevant problem with reasonable accuracy - even using such a strict limitation.

SIMULATION RESULTS

The new thermohydraulic model has been tested by performing 10 reference calculations with SMABRE (Bürger et al., 2008) and repeating these calculations by RETINA. The environment of the codes was the same, namely the full-scope simulator of Paks NPP.
Practically, we had performed a run with SMABRE and than changing the thermohydraulic module, we repeated the calculations using the same initial condition with RETINA. Results obtained by the code were monitored by the Instructors' system of the simulator.
At the beginning of this procedure we had to obtain a steady state with RETINA with a prescribed accuracy (differences had to be less than 2% for each relevant physical variable) using SMABRE results as reference.
In Fig. 1 the results obtained by initiating 1st turbine trip of the NPP are shown. On the left (from 0 to roughly 25 minutes) and on the right (from 25-50minutes) the results of RETINA and SMABRE can be seen, respectively. The plot shows the pressure of the pressurizer, the position of the turbine control valve, the pressure of the steam collectors on the lost and working side, the water level and pressure of the 2nd steam generator.
In this scenario the failure of the turbine control valve causes an immediate turbine trip. Since the steam collectors are connected, therefore the pressure is rapidly increases in both sides, until it reaches the activation pressure of the collector blow-down valve (48 bar). The blow-down suddenly decreases the pressure of the steam generators, which leads to intensive boiling and the swelling of the water level.

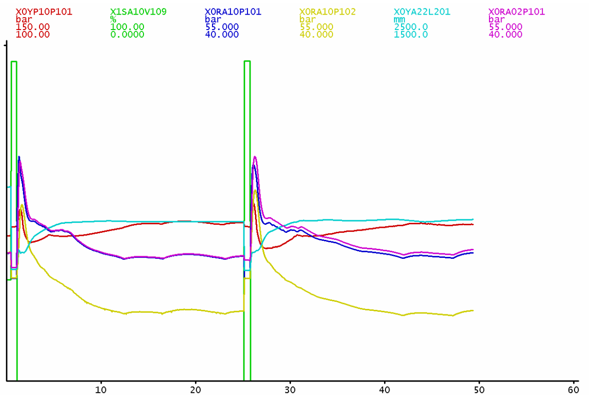

Fig. 1 Simulation results obtained by RETINA (left) and SMABRE (right) for turbine trip.

In Fig. 2 the simulation results of tripping three pumps are shown - plotting some relevant quantities, i.e. the reactor power, the water level and pressure of the pressurizer, pressure of the steam collector, and the water levels of the 1st and 2nd steam generator.
The test scenario is as follows: Due to power failure, the primary circulating pumps stop in the 2nd, 4th, and 6th loops. The flow rate decreases in the core and the coolant adsorbes more heat from the fuel increasing the pressure in the primary circuit. Accordingly, the reactor control system reduces the power level by ~40% and as a consequence the pressure falls down again to the nominal value.

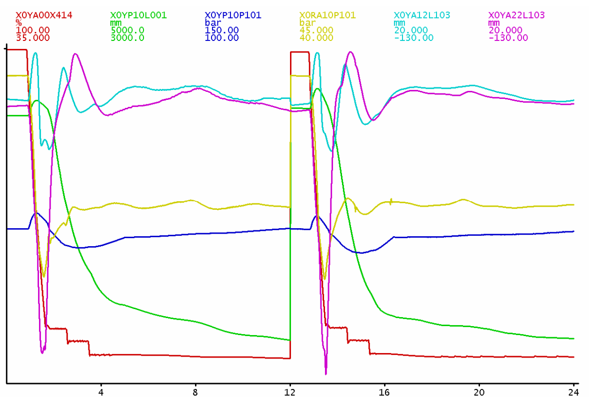

Fig. 2 Simulation results obtained by RETINA (left) and SMABRE (right) for the trip of three main pumps.

Finally, in Fig. 3 the results of the calculations obtained by both codes for the opening of the pressurizer's safety valve can be seen. The relevant quantities shown in the figure are the following: pressurizer pressure, flow through the safety valve, level of the pressurizer, pressure above the zone, pressure of the relief tank and the water level in the containment.
In this test the pressurizer safety valve opens and the pressurizer starts to blow-down into the relief tank. The pressure rapidly increases in the relief tank until its

rupture plate breaks and the coolant blows-down to the containment.

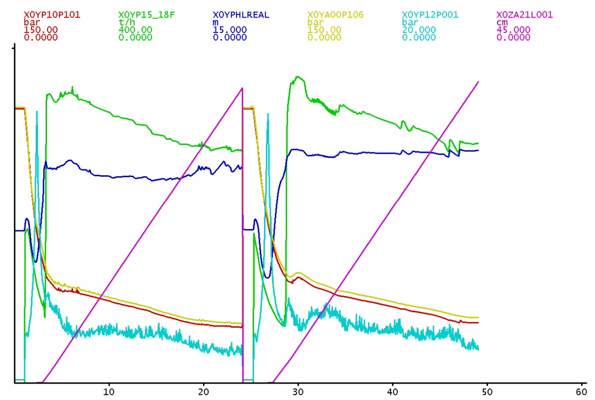

Fig. 3 Simulation results obtained by RETINA (left) and SMABRE (right) for opening of the pressurizer's safety valve.

As it can be seen, the results of RETINA are practically the same than that of SMABRE for each of these transients. No relevant differences can be observed in the physical parameters, although the codes are quite different considering their models and numerical approaches.

CONCLUSION

Although the change of a physical model in a simulator may seem to be a straightforward task, our experiences show that such a work can bring serious challenges depending on the complexity of the modeling problem. The replacement of the two-phase thermohydraulic module of the real-time full-scope simulator of Paks NPP has been briefly reviewed in this paper.

In spite of the fact that there are significant differences between the implementation of the new and old modules considering their models and numerical methods, the results obtained by the new module are in good agreement with the ones obtained by the old one.

However, it should not be so surprising, since the underlying physics addressed by both codes are the same. Therefore the good agreement is partially due to the facts that the numerical approaches together with the models used in the codes are describing reasonable well the real physics. From another point of view, it is also a result of the control system, which drives both models in the same way as far as their output remains accurate enough.

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