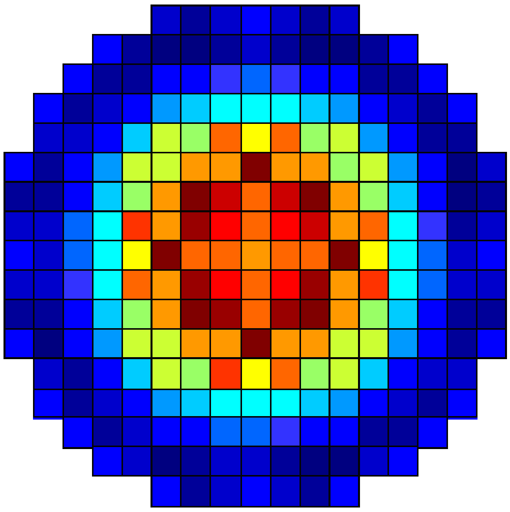

TRICOT 2008/SAFIR

Comparison of TRAB-3D / SMABRE versions for PWR in 2008

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Summary

The modeling of thermal hydraulics in the reactor dynamics computer code, TRAB-3D is being improved by coupling it internally to the SMABRE code. The present research is continuation of the work started already in a previous SAFIR project. Main advantages of internal type of coupling are possibilities to handle coolant flow reversals in core flow channels as well modeling cross flows in an open reactor core like EPR.

Due to unexpected passing away of the main developer of the code, the study was forced to new paths. The status check of the different code versions and identification of modifications leading to deviating results in traditional parallel coupling have been performed and reported. This report is more of a technical report describing new options and the modules undergoing the largest changes in the process.

In the test case for coupling, the plant model, consisting of the whole primary loop of a PWR and the secondary loop from the feedwater tank to the turbine valves has been used. As a test a pump seizure transient have been calculated with different coupling types and code versions. A stable and functioning steady state solution for a PWR core has been achieved with the new coupled code and the differences of core parameter distributions are very small. The capability of calculating the general flow system and circulation loops with SMABRE has been achieved with the new code version.

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Contents

1 Introduction

The objective of subtask TRAB-3D/SMABRE of SAFIR2010/TRICOT project is to improve the thermal hydraulics in the reactor dynamics computer code, TRAB-3D, by coupling it internally to the SMABRE code. TRAB-3D /1/ is a reactor dynamics code with three-dimensional neutronics and one-dimensional thermal hydraulics in a core and in a BWR circuit. The code can be used for transient and accident analyses of boiling (BWR) and pressurized water (PWR) reactors. The system code SMABRE /2/ models the thermal hydraulics of light water reactors. Both codes have been entirely developed at VTT.

Main advantages of internal type of coupling are possibilities to handle coolant flow reversals in core flow channels as well modeling cross flows in an open reactor core like EPR. Also the porous media model could be used for the thermal hydraulics to simulate 3-dimensional hydraulics. On the other hand, the possibility of describing flow 3-dimensionally in the core leads to renewal of hot channel calculations.

The basics for internal coupling were created for BWRs in the EMERALD project as a part of the SAFIR-Programme /3-6/. In TRICOT, the work has continued for the PWR /6/. The internal coupling of TRAB-3D and SMABRE needed large modifications and new modules especially into SMABRE, which should still have all the old calculation capabilities with parallel coupling left in it.

Up to now, the main features of coupling have been programmed mainly by the SMABRE developer who passed away recently. This unexpected and unfortunate accident has forced the studies to new paths. The status of the different code versions has been checked, and identification of modifications leading to deviating results in traditional parallel coupling have been performed, and comparison of the coupling types has been started. In spite of some plotted results from comparing coupling types, this report is a more technical report describing new options and the modules undergoing the largest changes in the process.

2 Internal coupling of TRAB-3D/SMABRE for PWR /6/

TRAB-3D /1/ is a reactor dynamics code with three-dimensional neutronics coupled to core and circuit thermal hydraulics. The code can be used for transient and accident analyses of boiling (BWR) and pressurized water (PWR) reactors. The system code SMABRE /2/ models the thermal hydraulics of light water reactors. Both codes have been entirely developed at VTT. The progress of coupling is described in /3-6/.

The internal coupling of TRAB-3D and SMABRE for BWR has required a lot of modifications to the original codes and also several new modules. Because the work done in the earlier project concentrated basically on the features needed for boiling water reactors, several features dealing with pressurized water reactors had to be done during the present project. The needed modifications were mainly dealing with parts outside the core.

Already at the 90’s, when at VTT the 3-D neutronics code HEXTRAN was coupled with the SMABRE code, division of the core and also the pressure vessel to parallel channels has been a typical procedure to describe the reactors for the coupled codes, even if it is not necessary for calculation of all transient types. Typically the number of parallel channels in the pressure vessel and in the core is at least equal to the number of the circulating loops.

Figure 1 illustrates the thermal hydraulics calculation system of SMABRE for the open core of PWR. The left figure is for the parallel coupling and the right one for the internal coupling. The selected boundaries between the two codes may be meaningful in some cases due to cross flows and hot channel calculations. For the open PWR core with parallel coupling, boundaries according to the left figure may be recommended. The stabilization of pressure due to the open core inside the lower and upper core support plates may be modeled with cross flows. Calculation of hot channels, marked with red boundaries in the figure, concentrates now only on the active fuel in the core. The yellow area represents the area where all the core channels are modeled. In the parallel coupling it consists of the active fuel part of the core. In the internal coupling all the flow channels also at the ends of the fuel assemblies are modeled. In that case the cross flow is modeled between the larger SMABRE channels.

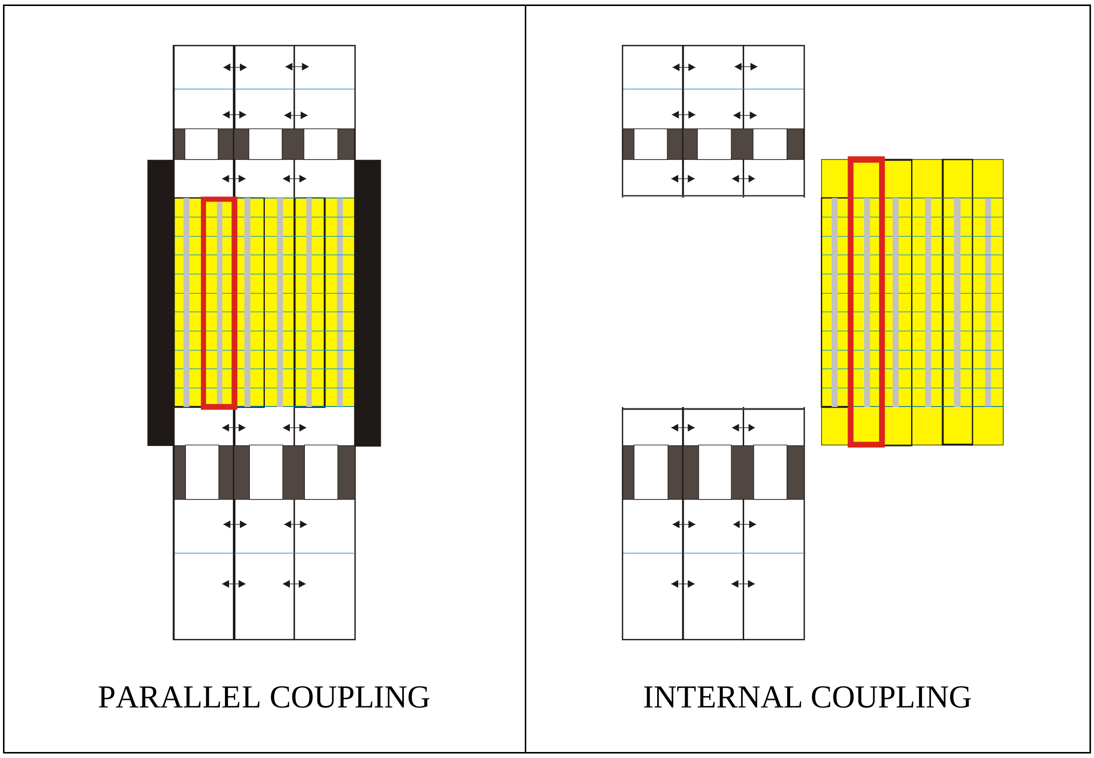

Figure 1. Typical arrangement in calculation of open core with TRAB-3D/SMABRE with parallel and internal coupling.

In the internal coupling the yellow area of the right side of figure 1 represents the core island in the SMABRE calculation. Modeling of cross flows between the SMABRE core channels at the upper and lower ends of the core may be still be used. In internal coupling TRAB-3D performs the neutronics calculation, SMABRE will take care of the hydraulics calculation of the whole cooling circuit including the reactor core, and the heat transfer calculation may be carried out by either code by the user's choice. Whereas in parallel coupling TRAB-3D performs the core hydraulics and heat transfer, and the coarse SMABRE core hydraulics with fewer channels are solved in parallel.

3 TRAB-3D/SMABRE versions

The latest large modifications to SMABRE have been realized about ten years ago to SMABRE4.6. The code manuals are focused to that validated code version. Later SMABRE-versions are modified according to needs in input/out or trip logic systems concerning typically automation and signals in plants. Last version of these is SMABRE5.0.

The internal coupling of TRAB-3D and SMABRE needed large modifications and new coding specially into SMABRE. These versions of the codes are TRAB-3D 3.0 and SMABRE 6.0, which should have also all the old calculation capabilities left in it.

Internal coupling of these codes makes it possible to use them for analyzing the supercritical pressure HPLWR reactor. Internal coupling is needed for special design of HPLWR core with up- and downward flow channels in the core. The development of HPLWR version has been performed simultaneously with internal coupling. Even if the modeling of features caused by supercritical pressure are performed in another project, this has created useful cross-checking possibility for both code versions. In figure 2 the main idea of internal coupling with the ability of reversed flow calculation is demonstrated, because in one third of HPLWR core flow is downwards. Another example of HPLWR is the modeled several axial power profiles of SMABRE-code, depicted in figure 3. This has meaning if several largely deviating axial power profiles exist in the core.

The main idea for HPLWR version is to increase the capability of the code to supercritical circumstances. In HPLWR project new material properties have been implemented to the code and they may be used also for the traditional TRAB-3D/SMABRE. Due to numbering, two versions of HPLWR-version is updated, one for small nodalizations like EPR and one for large like HPLWR with 1404 flow channels.

Furthermore, there are several code versions updated by Jaakko Miettinen. These versions have been saved permanently and could be compared also in the future studies.

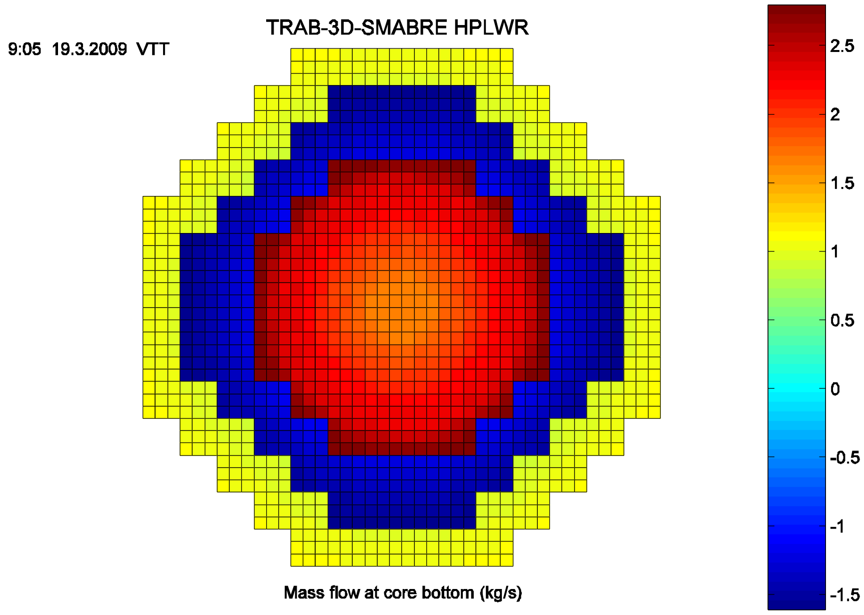

Figure 2. Mass flow at core bottom in the HPLWR- three way core.

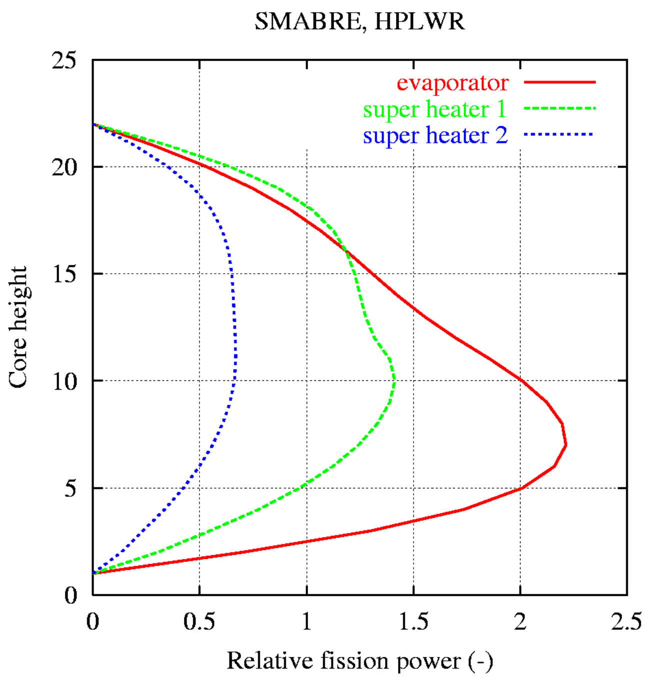

Figure 3. Three axial power profiles in the HPLWR- three way core.

4 Steps to single TRAB-3D/SMABRE

The several code versions explained in previous chapter has been tested against another and step by step the differences have been identified and marked into the source code. Many essential modifications deal with the pressure solution routines concerning inertial and friction terms. Few mistakes have been found and some features of the old version, SMABRE 5.0, have been returned. In these cases, validation of the coupled code and recalculation of BWR plant may give a final judgment of modifications. In the following part of the modifications are listed.

- At first the calls of all subroutines have been modified by removing junction dimensioning in order to able to debug the runs.

- Modification of time derivate of pressure. Originally this has been one value for each pressure system. This has been used for comparing new and old calculation results. The new derivate is for each node. The idea here is to include better the pressure change to enthalpy and needs some more attention in the future.

- Handling of loss coefficients in internal valves have been revised to SMABRE5.0 in source routines for comparing old and new parallel coupling. The new modifications need more studies when BWR model is used.

- Also inertia term (BTERM) calculation in pressure solution has been revised according to original SMABRE. Here the very important DTIX term, which originally depends on time steps, is now always defined by the maximum value given to DTIX because of small time steps used in coupled codes.

- Initialization of vapor and liquid temperature takes now better into account superheated steam. Also possibilities of giving steam enthalpies in input deck have been improved for same reason.

- Initialization of vapor and liquid mass flow has been updated according to code subroutine FLOMAN routines, where mass flows are solved. At the beginning of initialization flow rates are essential in order to have comparable Reynolds numbers to old solution.

- New definition of pressure used in valve control logic (IVAPRE /IVALVV).

- Definition of junction density in the pressure calculation routines for large nodes has returned to the old one. A new definition of density based on the flow rates was not able to apply for steam generators. The old definition is based on void fractions and node densities. This could be noticed in the future when BWRs are calculated. Correspondingly another parameter for mixture density has been created based on phase masses, not on void fractions, for internal coupling.

- The routines to handle loss coefficient for single and two phase flow have been modified. The final version of the code should be judged in the validation process.

- Single and two-phase friction coefficients are taken into account differently in friction term (FTERM) in pressure solution routines in the new and old code versions. These have essential affect especially in steam generators. The old version is used here for comparison of results, but the final form of routines should be defined through validation process and after recalculation of BWR cases.

- Effect of wall conductivity on heat transfer and its limitations are counted in parameter HWALL in heat transfer routines. Conduction heat transfer limitation for the wall heat transfer is needed, because no radial heat structure elements have been introduced when simple heat structures outside the core are used. The limitations have been modified according to SMABRE5.0 while comparing new and old parallel coupling, but more detailed comparison of simple and more sophisticated new models should be performed.

- Initialization of two-sided heat structures have been returned to the one of SMABRE5.0. For BWR cases this kind of structures have not been used. Models for fuel rod type of heat structures have improved largely in internal coupling, but the simple features should be able to be used also.

- Bernouilly kinetic energy conservation term is calculated in SMABRE for gravity term in pressure solution routines. Traditionally only small part of it could be taken account without difficulties in long pipes or large cross flow systems. In EPR, the pressurizer small and long pipe lines or large cross flows in downcomer are critical ones. For the comparison of results this has been equalized.

- Outputs, initialization routines and plotting systems have been updated to the new internal code system. The main reason for modifications has been needs to describe the node, junction and heat structure numbers with eight digits in the internal code version.

5 New options in TRAB-3D/SMABRE

SMABRE5.0 as well as the earlier and validated versions of SMABRE4 include several options reported in the code manual /7/. For the internal coupling and the supercritical features of the code some of the old options have been modified and several new have been created. At present, reporting of these new features has not been done, and partly also coding behind the options is incomplete. In the list below the main new options are listed and very shortly described. The checked descriptions will be included in the code input manual.

TRAB and SMABRE running modes defined by ICIL and ISMA:

ICIL	= 0	no beginning part of circuit in TRAB-calculation
	= 1	TRAB-3D, normal BWR
	= 2	no upper plenum
	= 3	only core model with SMABRE (external coupling)
	= 4	only core mode
	= 5	only neutronics, update for SMABRE, no reading
	= 6	only neutronics, update for SMABRE, read from SMABRE
ISMA	= 1	SMABRE alone
	= 2	SMABRE alone
	= 3	SMABRE coupled externally with the TRAB core model
	= 4	SMABRE frozen alone, no update for TRAB
	= 5	internal thermal hydraulics, update for TRAB, no reading

= 6 only neutronics, update for TRAB, read from TRAB

Table for model switches in TRAB by ITMODE:
ITMODE(1) =1 HTR by derivate,
=2 HTR by flux,
=3 HTR by flux and derivate
ITMODE(2) dial flow:
=0 no dial,
=1 dial steady state by pump head,
=2 by core friction,
=3 by both
ITMODE(3) calculating Doppler temperature with SMABRE
= 1 HTR no meaning,
= 2 Doppler temperature with SMABRE,
<> 2 Doppler temperature with TRAB
ITMODE(4) = SMABRE repetitions in steady state
ITMODE(5) = 8 for isolated island initiation of SMABRE PID control
ITMODE(6) pump flow adjust:
= 3 update pump speed from TRAB
< 7 normal,
= 7 SMABRE PID in trip cards,
= 8 TRAB,
= 9 ramp,
ITMODE(7) = steam line valve external rmap if =8
ITMODE(8) = PID control

Junction and valve flow by IWFLOW:
IWFLOW = 1, 2 noncritical valve and system flow defined by friction
= 3 Moody valve flow and system flow defined by friction
= 4 Moody valve flow and sound velocity limited system flow
= 5 sound velocity limited system flow

In new version parameters IHEACO+IHEAST are used instead of IWHEAT, which was on the other hand totally modified during the development of internal coupling. The correspondences between new and old options need some more studies.

Core fuel heat structure integration by IHEACO:
IHEACO = 0 subroutine SLABHO for the core is used and as result one wall temperature (TWAL) is calculated, PAR-table date, giving in SMABRE input deck is used for material properties
= 1 SLABHT for core with two temperatures (TWAL/TWAL2), PAR-table material data
= 2 average fuel model TFUEA, PAR-table material data
= 3 average fuel model TFUEA, MATFUN material data
= 4 average fuel model TFUEA, TRAB material data
= 5 average fuel model TFUEA, reserved for new curves
= 6 radial temperature profile for fuel in model TFUEP, PAR-table date, giving in SMABRE input deck is used for material properties
= 7 radial prof. model TFUEP, MATFUN material data
= 8 radial prof. model TFUEP, TRAB material data

= 9 radial prof. model TFUEP, reserved for new curves

Structure heat structure integration by IHEAST:

IHEAST = 0 older subroutine SLABHO is used and one wall temperature (TWAL) is calculated as result
= 1 SLABHT new mode with two wall temperatures (TWAL/TWAL2)
= 2 TSTRUS with several radial points (TSTRU(NSPOI,NHEA))
= 3 TSTRUS reserved for additional features

Core heat generation by IWSLAB:

IWSLAB = 0, 1, 2 typically
= 4 for a simple control rod model affecting core power only control rod effects
= 5 for a simple point model during ATWS and CRW, scram not possible, single-group neutron kinetics
= 6 multi-group neutron kinetics
= 7 requires special reactivity table
= 9 for an external power setting like parallel or internal coupling

Core simulate by ICOMOD:

ICOMOD = 0 normal
= 1 shift external
= 2 split into core island

Material functions by IMATFU:

IMATFU = 0 old SMABRE5.0, Prandtl number, Pr = 1.0 for heat transfer
= 1 new material properties
= 2 supercritical material properties
= 3 supercritical + modified material properties for supercritical and calculation of Prandtl number from material properties

Evaporation model used for nodes by IENTR,

IENTR = 0, 1 SMABRE model in the standalone calculations and in comparison with parallel coupled calculations
= 3 TRAB evaporation model in internal coupling

Junction friction by IJOPT: given (1), calculated (2) or both (3/4)

IJOPT =1 use only singular dp (= pressure difference)
=2 add effects of area contraction and wall shear
=3 add effects of area contract, wall shear and singular dp, SMABRE form
=4 add effects of wall shear and singular dp, SMABRE form
=5 calculate friction with TRAB formalism singular and shear

Friction mode in junction by IFRMOD: (If IJOPT is less than 5, SMABRE Blasius model is always used, used for old standalone and parallel coupling.

IFRMOD = -1, 0 SMABRE model,
= 1 TRAB frictions
= 2 (BWR, EPR) TRAB frictions

Two-phase multiplier in junction by ITWMOD: (If IJOPT is less than 5 SMABRE homogeneous model is always used.

ITWMOD = 1
= 2 EPR, TRAB friction
= 9 BWR, TRAB friction

Phase separation in junction is defined by IDRMOD:
= -1 SMABRE model
= 0 SMABRE model
> 0 TRAB slip as drift
= 3 EPR
= 5 BWR

Fuel type heat structure options by IHTYP:

IHTYP = 3 with SMABRE wall boiling in separate run and parallel coupled
= 4 with TRAB wall boiling, needed in internal coupling

6 Comparison of coupling types

The PWR test case for coupling is in a geometry resembling the EPR reactor core with 241 hydraulic channels and 20 axial core nodes. The used fuel is a typical PWR fuel. In this application the number of loops is 4, the number of pressure vessel sectors and their respective SMABRE channels is 8 and the number of core channels in SMABRE is 17. The whole primary loop and secondary loop from the feedwater tank to the turbine valves have been modeled in SMABRE. The model is quite similar to, but not exactly identical to the model of the EPR plant.

For these comparisons nominal primary pressure of the steady state has been increased slightly. First test with lower pressure level have been performed and the results are promising. As a dynamic test case a pump seizure transient has been performed with different coupling types, code versions and with SMABRE or TRAB-3D heat transfer options. Some results of comparison are depicted in figures.

Already in /6/ it was reported about good results in comparing the core distributions. Presently they are even better. Figure 3 shows the ratio of the radial power distribution calculated by the parallel coupling with the new TRAB-3D/SMABRE version to the old version. Figure 4 presents the mass flow after 25 second of transient. These indicate that results with parallel couplings with old and new versions are good ones.

Secondly, the core distributions are compared with internal coupling to parallel coupling. Figure 5 show the ratio of core inlet mass flow distribution in the core channels and the radial power distribution between the internal and parallel coupling. The differences are very small as it was earlier anticipated that in a PWR (EPR) application similar difficulties would not be encountered as in a BWR calculation due to heavy boiling in the steady state of BWR.

During the transient, also the main parameters in the primary and secondary circuit are equal in comparing parallel coupling between old and new code versions. This is shown in figure 7 and 8, where total core mass flow and maximum of channel outlet equal quality is predicted (note that outlet equal quality is calculated in internal coupling at nodes with SMABRE and in parallel coupling at mesh points by TRAB, thus half a node further up in a channel). In figure 9 core peaking factor and in figure 10 primary pressure behavior during transient are shown.

The results from internal and parallel coupling deviate during the transient. For the core the result is fine. The differences are not large and may be result from used options, as an example the effect of SMABRE and TRAB heat transfer options to result, or from the internal coupling itself. Research continues with testing the new options and validation, which is necessary after large code modifications. The first studies in lowered pressure indicate same kind than the results above.

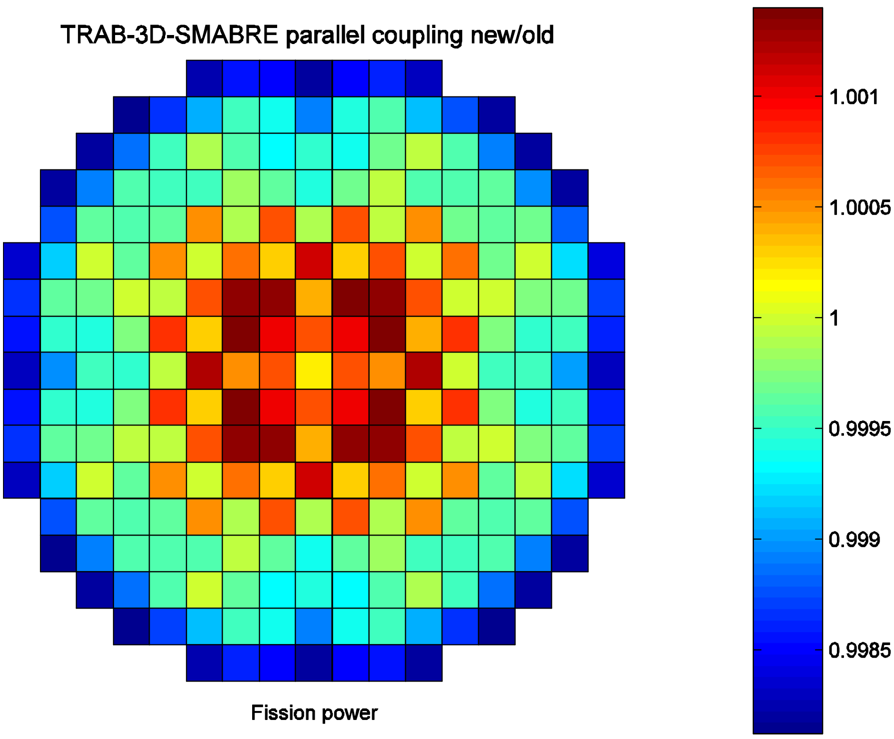

Figure 3. Steady state relative fission power distribution calculated by old TRAB-3D/SMABRE version using parallel coupling relative to distribution calculated with new code version.

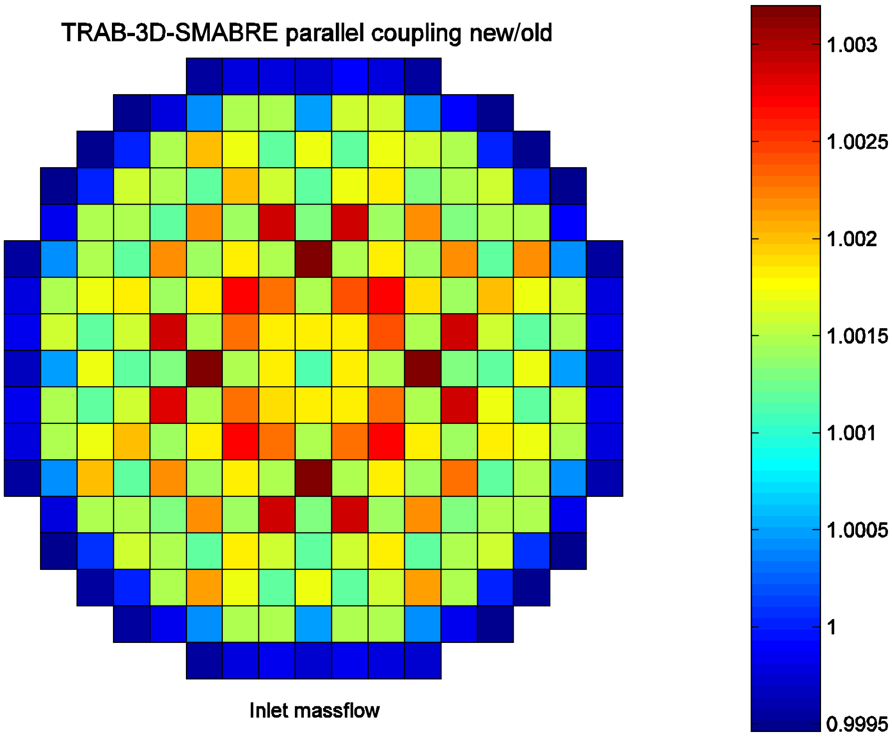

Figure 4. Steady state bundle flow at core inlet at end of the 25 sec transient calculated by old TRAB-3D/SMABRE version using parallel coupling relative to distribution calculated with new code version.

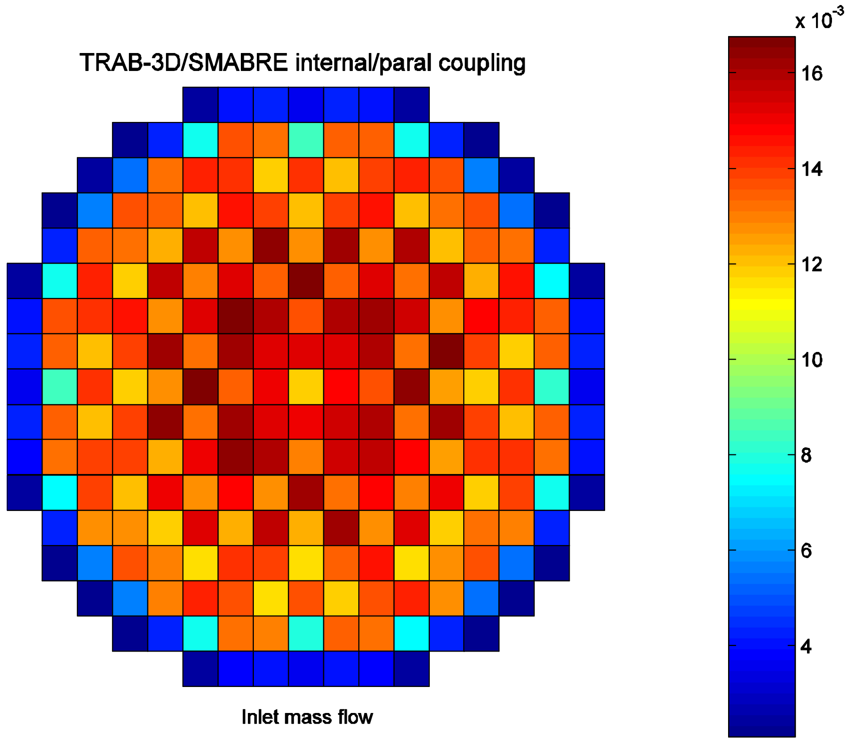

Figure 5. Steady state bundle flow at core inlet calculated by TRAB-3D/SMABRE with internal coupling relative to distribution with parallel coupling.

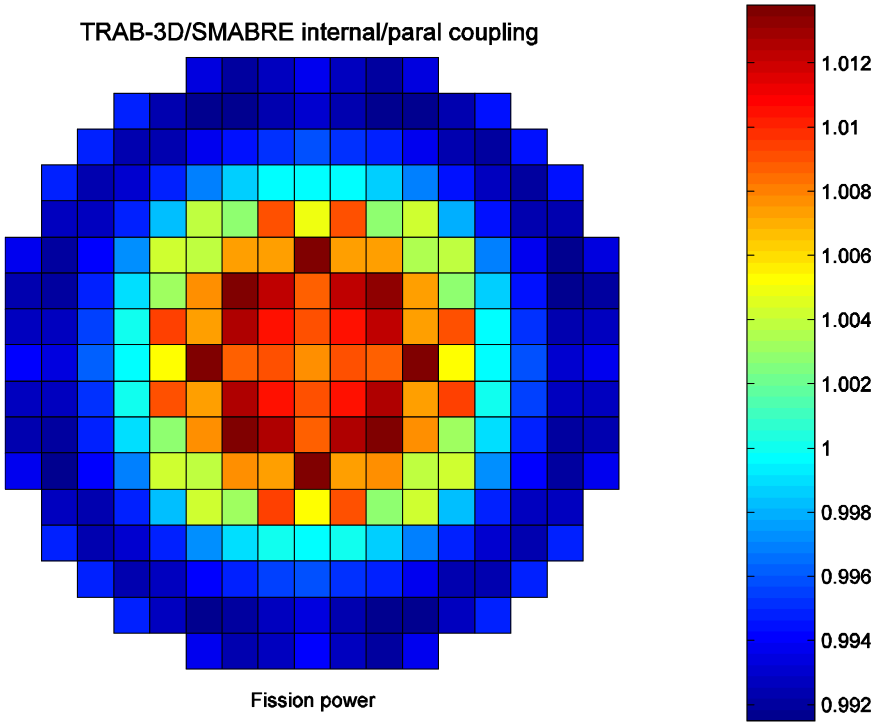

Figure 6. Fission power distribution calculated by TRAB-3D/SMABRE with internal coupling relative to distribution with parallel coupling.

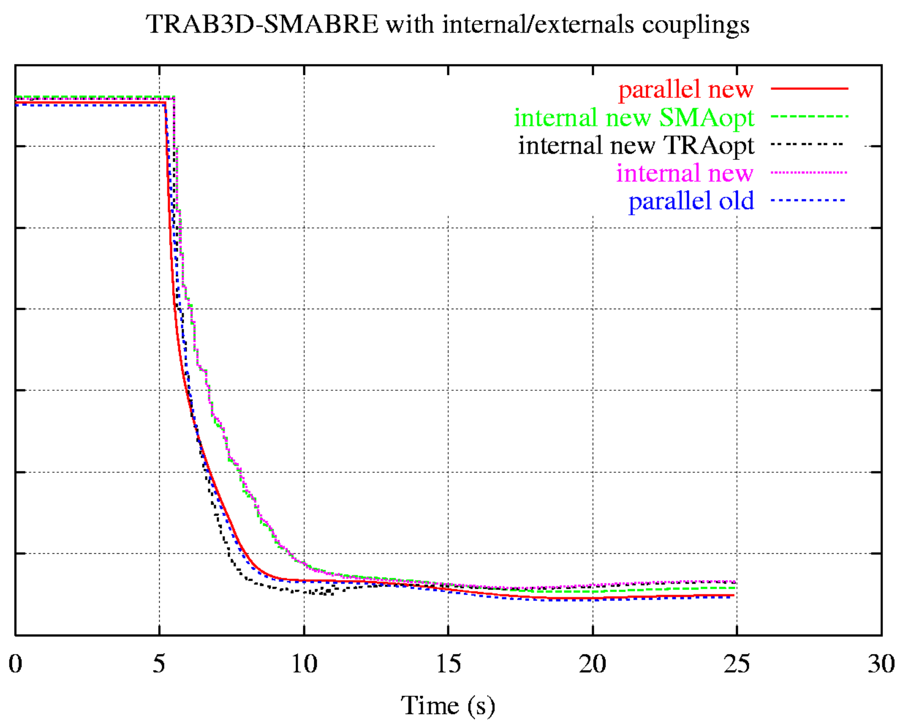

Figure 7. Total core mass flow in pump seizure transient with two coupling types, old and new code versions and with SMABRE and TRAB set of heat transfer options.

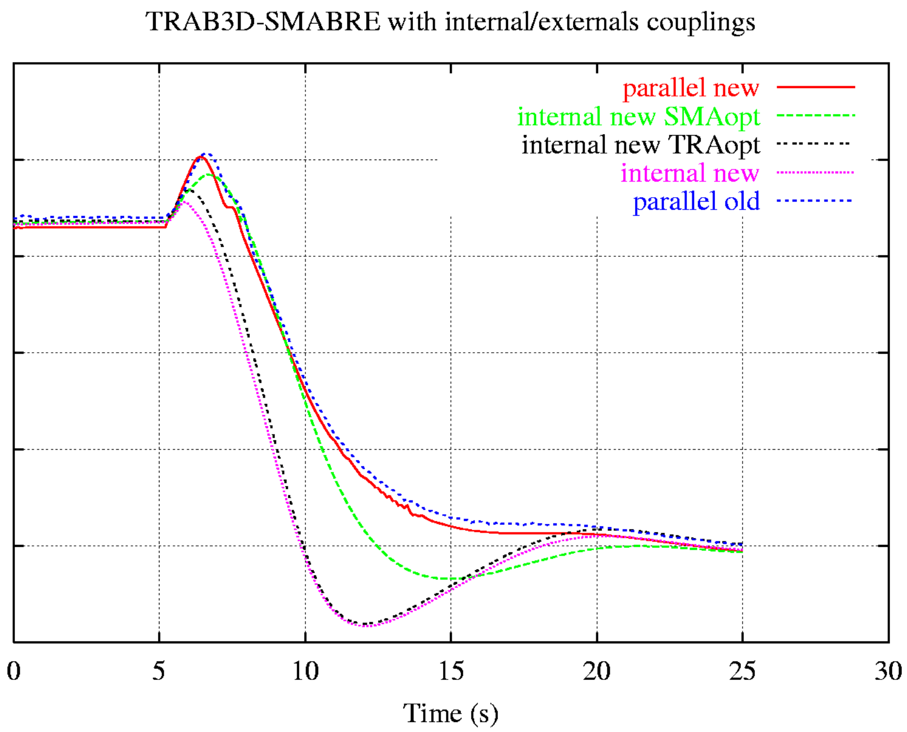

Figure8. Maximum of channel outlet equal quality in pump seizure transient with two coupling types, old and new code versions and with SMABRE and TRAB set of heat transfer options.

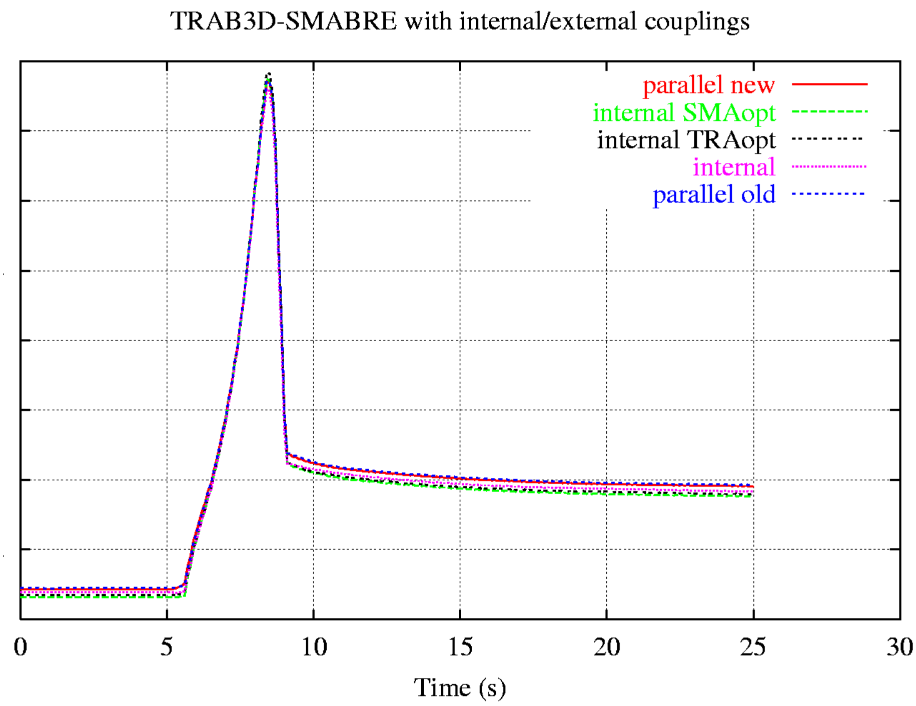

Figure 9. Core peaking factor in pump seizure transient in pump seizure transient with two coupling types, old and new code versions and with SMABRE and TRAB set of heat transfer options.

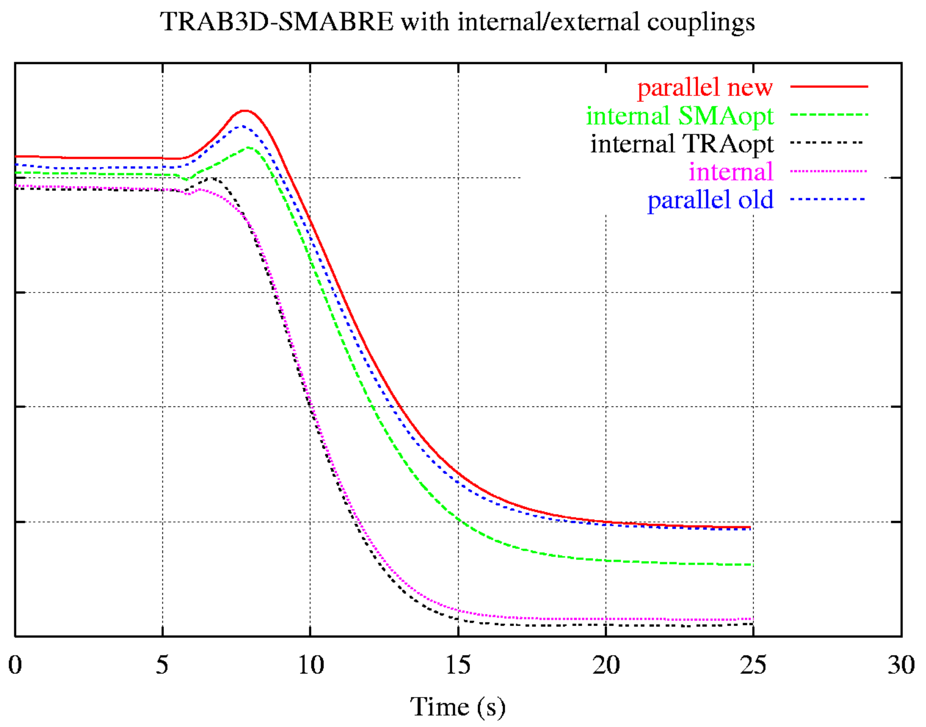

Figure 10. Primary pressure behavior in pump seizure transient with two coupling types, old and new code versions and with SMABRE and TRAB set of heat transfer options.

7 Further plans /6/

The new coupling method has been developed and tested for BWR and PWR cores. This work continues in the present project for the PWR core. Modeling of the heavy reflector around the core between the downcomer and the core, shown in figures 1 and 2, needs some modifications. On the other hand, the heavy reflector may be attached to the core bypass, too. The option to connect several fluid channels with one fuel assembly, needed for modern BWR fuels, needs programming and vice versa, the option to couple several fuel assemblies with one fluid channel is needed as well. For BWR dynamics applications the circuit model of SMABRE will be checked against existing TRAB-models and supplemented where necessary.

Internal coupling of the codes enables the calculation of reversed flows in core, which has been realized in HPLWR application, but also cross flows in the core. For this an iterative matrix inversion has been programmed in another project and could be utilized here. Also the porous media model, developed in other projects, could be coupled for the thermal hydraulics. The advantage in comparison with the iterative matrix inversion for the open core is that the porous media model includes the continuation equation solved for the momentum equations in all flow directions. The possibility of describing flow 3-dimensionally in the core leads to renewal of hot channel calculations.

8 Summary

The modeling of thermal hydraulics in the reactor dynamics computer code TRAB-3D is being improved by coupling it internally to the SMABRE code. The present research is continuation of the work started already in a previous SAFIR project. Main advantages of internal type of coupling are possibilities to handle coolant flow reversals in core flow channels as well modeling cross flows in a open reactor core like EPR.

TRAB-3D performs the neutronics calculation, SMABRE will take care of the hydraulics calculation of the whole cooling circuit including the reactor core, and the heat transfer calculation may be carried out by either code by the user's choice. In the test case for coupling, the plant model, consisting of the whole primary loop of a PWR and the secondary loop from the feedwater tank to the turbine valves has been used. As a test, steady state comparisons for core parameters and a pump seizure transient have been performed with different coupling types and code versions. The simultaneous development with the high pressure light water reactor, HPLWR, generates useful cross-checking possibility and application for internal coupling.

A stable and functioning steady state solution for a PWR core has been achieved with the coupled code. The differences of core parameter distributions are very small. The capability of calculating the general flow system and circulation loops with SMABRE has been achieved with new code version. The features leaded to deviating results between new and old version in parallel coupling has been found and reported.

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