PASSPORT

Methodology for the analysis of safety system performance in relation to coupled plant system and containment processes

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ABSTRACT

The PASSPORT project aims at the development and validation of a novel computational methodology for the performance assessment of LWR safety systems during design-basis accidents and beyond-design-basis accidents. The primary objective of the novel methodology under development is in fact to provide more accurate predictions of a nuclear power plant by coupling 1-D simulations of the primary system components (handled by TRACE) with typical 3-D phenomena occurring in containment compartments (better captured by the dedicated code GOTHIC).

During 2012, a review of existing experimental facilities and programs on passive cooling systems suitable for the assessment of the TRACE and GOTHIC codes in stand-alone and coupled mode was completed. The PANDA large-scale facility, built and operated at PSI, was confirmed as the premiere source of data for the assessment of the tools and models developed in PASSPORT in view of the availability of integral test experiments challenging the interaction of containment phenomena with primary system behaviour. Thus, through a detailed and systematic comparison of GOTHIC and TRACE on the simulation of different PANDA experiments (integral test ISP-42 and B-tests), a good understanding of the capabilities and limitations of the codes GOTHIC and TRACE has been established and thus hinted at the potential complementarities of the two in a coupled configuration.

Finally, a large part of 2012 has been spent on implementing and testing the coupling between TRACE and GOTHIC. The coupling implements a mass and energy transfer at the interface of the respective simulation domains of the two codes. The coupling allows the two-phase mixture as well as non-condensable gases to flow from the domain of one code into the domain of the other at an arbitrary number of coupling points. Each code treats the coupling points essentially as boundary conditions that are continuously updated based on data provided by the other code. This principle minimizes the ingress that has to be made into the codes as the implementation is restricted to the boundary conditions without modifying the actual equation solvers of the codes.

Project goals

The PASSPORT project was launched as a joint research activity between ENSI and the Paul Scherrer Institut (PSI) and involves a technical collaboration between the STARS project at the Laboratory for Reactor Physics and System Behaviour (LRS) and the Laboratory for Thermal-Hydraulics (LTH). The PASSPORT activities aim at the development and validation of a novel computational methodology for the performance assessment of LWR safety systems during design-basis-accidents and beyond-design-basis accidents. One foreseen advantage of this methodology is to allow for a more advanced modelling and thereby more accurate simulations of accidents involving weak to strong interactions between the primary coolant circuit and the containment. As this might be relevant not only for safety analyses of current operating Gen-II reactor types but also in order to bring forward the state-of-the-art in this area for the analysis of Gen-III/III+ concepts, especially those relying on passive systems, the underlying principle is to achieve a comprehensive and generic methodology for a wide range of applications. Thus, one first objective is to develop a mass, momentum and energy coupling scheme between the best-estimate state-of-the-art codes TRACE for 1-D system analysis and GOTHIC for 3-D containment behaviour. The second and complementary objective is to validate this methodology on the basis of available integral and/or separate testeffects experiments with special emphasis on tests where interactions between primary coolant/containment systems are mainly driven by physical phenomena. These types of tests would indeed be the most challenging ones for the methodology and therefore, simulating these accurately would provide stronger confidence in the acquired capabilities and range of applicability. For 2012, the specific objectives of the project were as follows:

- Literature survey of available experimental data for validation of the coupled code.
- Develop an integral model of the PANDA facility with GOTHIC, for applications to the ISP-42 experiments.
- Develop and implement a coupling between the system code TRACE and containment code GOTHIC.
- Verification of the coupling for selected simplified test cases.

This report presents the status and progress achieved during 2012 in relation to the above objectives and outlines the perspectives for 2013.

Work carried out and results obtained

Survey of available experiments for validation of the coupled code

The planned literature survey of available experimental data has been conducted [1], providing a description of the relevant coupled phenomena between primary system and containment, and of the available experimental facilities as well as of related experimental programs performed.

The report identifies the PANDA facility at PSI [5] as the primary and most adequate source of assessment. In this respect, the ISP-42 integral test series – investigating typical passive safety system operating modes of a general interest for Light Water Reactor (LWR) and Advanced Light Water Reactor (ALWR) containments – is considered a suitable validation option. Interactions between primary reactor system and containment have been found

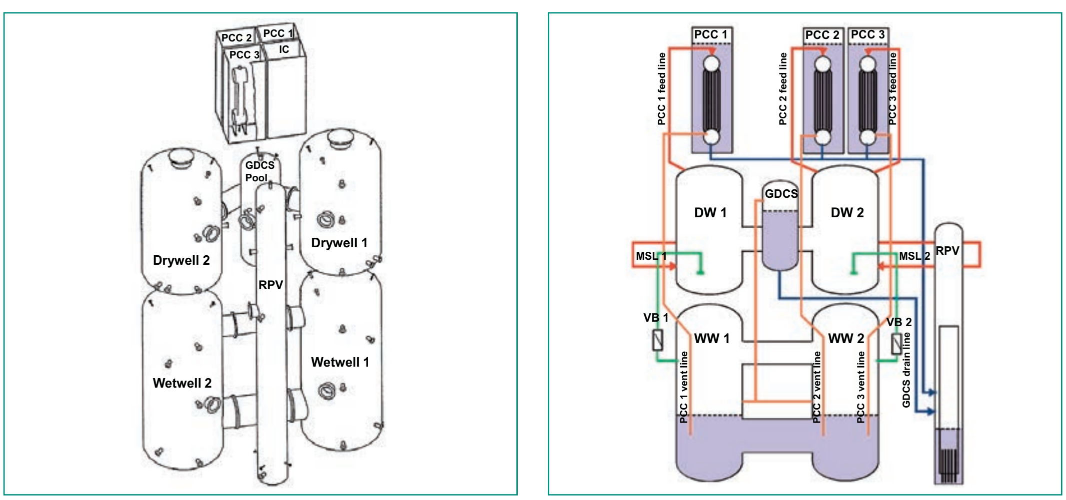

Figure 1: *Panda facility: Vessel layout (a) and configuration for phase b of ISP-42 (b)*

in the ISP-42 Phase B, including the activation of the passive emergency core cooling system GDCS (Gravity Driven Cooling System), and the effects of the discharge of subcooled water into the RPV (Reactor Pressure Vessel). Figure 1 shows a 3-D sketch of the PANDA facility and the configuration used for Phase B of ISP-42. Phenomena like the suppression of boiling following GDCS water injection, the interaction of the interruption in steam production with the PCCS (Passive Containment Cooling System) operation and the final resumption of boiling in the RPV have been highlighted as suitable figures of merit for the assessment of the coupled code.

One typical situation for a passive cooling system where the need of a coupled code is clearly identified is in the transition phase between the late primary pressure blowdown and the GDCS injection during a LOCA (Loss Of Coolant Accident) accidental sequence, when GDCS injection is passively triggered due to hydrostatic head. It has however been noticed that «the PANDA facility is not designed for assessing GDCS injection into the vessel» [6]. For that reason, attention has been focused on other experimental programs available worldwide, selecting the PUMA facility (US NRC, Purdue University, West Lafayette, IN, USA) [7] as an interesting counterpart of PANDA. Moreover, with respect to the recent studies on the SMR (Small Modular Reactor) concepts – as they typically feature a small high-pressure containment which, coupled to the RPV, directly intervenes in the accident mitigation – a good validation target has been identified in the International Collaborative Standard Problem (ICSP) currently on-going in the OSU-MASLWR experimental facility (Oregon State University, Corvallis, OR, USA) [8].

Finally, possible applications of a containment/system coupled code to operating Gen-II LWRs have been identified. Interactions between the primary system and the containment can be pointed out especially during the late stage of the LOCA, where the pressure difference is sufficiently small and the influence of the pressure in the containment is affecting the mass loss through the break [9][10]. Another potential benefit from the GOTHIC solution in the coupled code could be a more accurate estimate of the local temperature of the condensate accumulating in the recirculation sumps. This could help better investigating sump clogging safety issue during the long term cooling phase following a LOCA, by more accurately determining the evolution of the temperature in the sumps, which is known to be an influential factor in the formation of precipitates contributing to sump screen clogging [11]. One should however acknowledge that this is not a standard application of GOTHIC, and appropriate preliminary assessment of the code would be needed.

Pre-studies on the PANDA facility

Pre-studies on the PANDA facility were carried out with stand-alone calculational models developed with TRACE and GOTHIC, with the objective of comparing the capabilities of the two codes in simulating one typical cooling system. A study regarding the modelling of heat transfer in the Isolation Condenser (IC) and in the Passive Containment Condenser (PCC) was conducted [2]. The simulations were assessed using experimental data from the PANDA B-tests (IPSS «Innovative Passive Safety Systems» project) [12].

IC systems are typically designed to provide cooling to a Boiling Water Reactor (BWR) core following isolation from the primary heat sink. Steam rises from the RPV to the IC heat exchanger submerged in an elevated pool; gravity drives the condensate back to the RPV, preventing core uncovering. PCC systems are instead fed by a steam-air (steam-nitrogen) mixture from the drywell, following an accident where the RPV is depressurized. Performance of the PCCS in presence of light gas (hydrogen, simulated by helium) must be considered to account for postulated accidents with core heat-up and fuel cladding oxidation. The study showed that both codes were generally able to achieve good agreement with experiments but certain weaknesses and possible improvements were identified.

- Stand-alone simulation with GOTHIC of experiments investigating the IC system performance confirmed the capability of the code to capture specific primary system phenomena (natural circulation in a closed two-phase loop and condensation of pure steam in vertical tubes). Slight underprediction of the condenser performance has been observed (Table 1).
- The GOTHIC model generally predicts the overall performance of the PCC better than the TRACE code (Table 2) even though the general trends are well predicted by both codes (see the heat transfer efficiency as function of non-condensibles content and pressure in Figure 3).
- The pool-boiling model of TRACE (based on the Gorenflo correlation [13]) performs better than the model of GOTHIC (based on the Chen correlation [14]) (Figure 2).

Test	Experiment			GOTHIC code		RELAP5 code [12]	
	P [bar]	*Q_{el} [kW]*	*Flow [kg/s]*	*P [bar]*	*error*	*P [bar]*	*error*
B1	3.04	480.4	0.222	3.22	6.1%	3.20	5.3%
B2	6.16	1036.8	0.497	6.94	12.7%	6.98	13.3%
B3	8.98	1371.0	0.675	10.38	15.6%	11.0	22.5%

Table 1:

Gothic predictions on pure steam tests (b1, b2 and b3), compared with experiments and previous analyses using relap5 code [12].

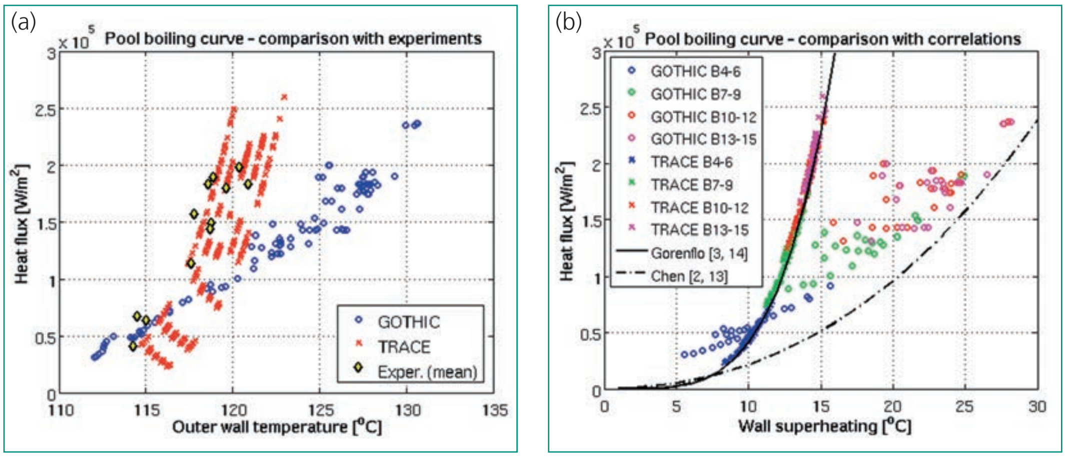

Figure 2:
Trace and gothic results on the boiling curve, compared with experiments (a) and respective pool boiling models (b).

Test	Description	Condenser efficiency			
		Experimental	GOTHIC	TRACE	RELAP5 [12]
B4	*3 bar – 1 g/s air*	94.9%	85.0%	67.3%	85.0%
B5	*3 bar – 3 g/s air*	89.6%	78.3%	64.0%	84.0%
B6	*3 bar – 28 g/s air*	56.7%	54.7%	52.6%	74.0%
B7	*6 bar – 1 g/s air*	97.5%	85.9%	75.9%	84.0%
B8	*6 bar – 3 g/s air*	93.2%	81.4%	72.7%	81.0%
B9	*6 bar – 28 g/s air*	74.0%	65.3%	57.3%	78.0%
B10	*9 bar – 1 g/s air*	97.0%	87.4%	83.1%	78.0%
B11	*9 bar – 3 g/s air*	93.4%	84.7%	79.1%	77.0%
B12	*9 bar – 28 g/s air*	88.1%	70.5%	66.9%	70.0%
B13	*9 bar – 0.137 g/s helium*	94.3%	90.2%	90.5%	80.0%
B14	*9 bar – 0.41 g/s helium*	89.8%	88.3%	88.3%	79.0%
B15	*9 bar – 3.87 g/s helium*	76.4%	77.7%	78.2%	75.0%

Table 2:

Comparison between predictions on steam-air (and steam-helium) mixture tests (b4 through b15).

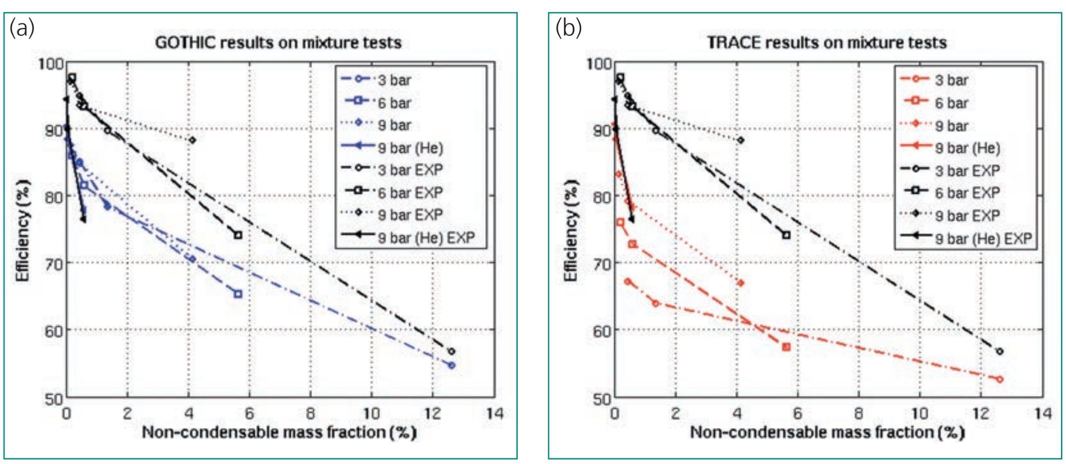

Figure 3:
Experimental efficiency degradation curves compared to gothic (a) and trace (b) predictions.

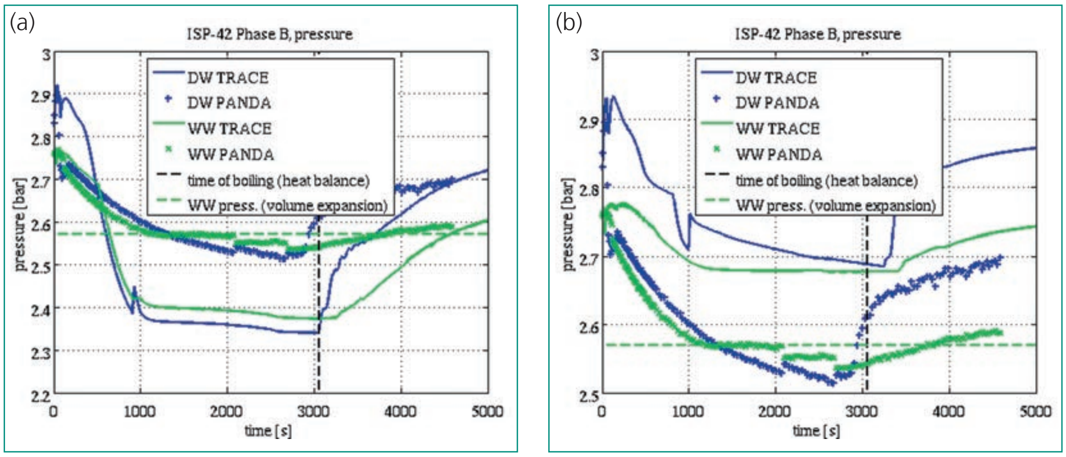

Figure 4:
Experimental and simulated pressure evolution during phase b of the ISP-42 experiment with 1 kpa (a) and 10 kpa (b) of initial air partial pressure in the dw.

A more detailed study of the TRACE model was published as well and investigated certain complex flow patterns in the PCCS [3]. In particular, it has been demonstrated that light non-condensable gases, such as helium and hydrogen, tend to cause a circulating flow pattern in the heat exchanger with reversed flow in some pipes (this flow pattern was also indicated by past experiments in PANDA).

Another prestudy evaluated the possibility of modelling the PANDA facility with the TRACE code alone [4]. Phases A (PCCS start-up) and Phase B (GDCS discharge) of the ISP-42 experiment were simulated. The results were generally satisfactory, showing that the TRACE code is able to reproduce experimental data about as well as other system codes. It was shown, however, that the simulation results of the ISP-42 Phase B experiment are highly sensitive to small variations in the initial air concentration in the Drywell (DW) (Figure 4) and that this effect is probably physical rather than an artefact of the TRACE code.

Development of an integral model of PANDA with GOTHIC

In 2012 a stand-alone integral model of PANDA (RPV included) was developed for GOTHIC. The nodalization scheme is shown in Figure 5. A detailed 3-D nodalization was prepared for the two drywells and relative Interconnecting Pipe (IP) (Figure 6-A). The mesh for each DW (Vol. 4s and 6s) consists of 1584 cells respectively, obtained with 72 crosssectional subdivisions (8 x 9) and 22 axial levels. The actual geometry of the two DWs and the IP was simulated, reproducing the curvilinear profile of the surfaces.

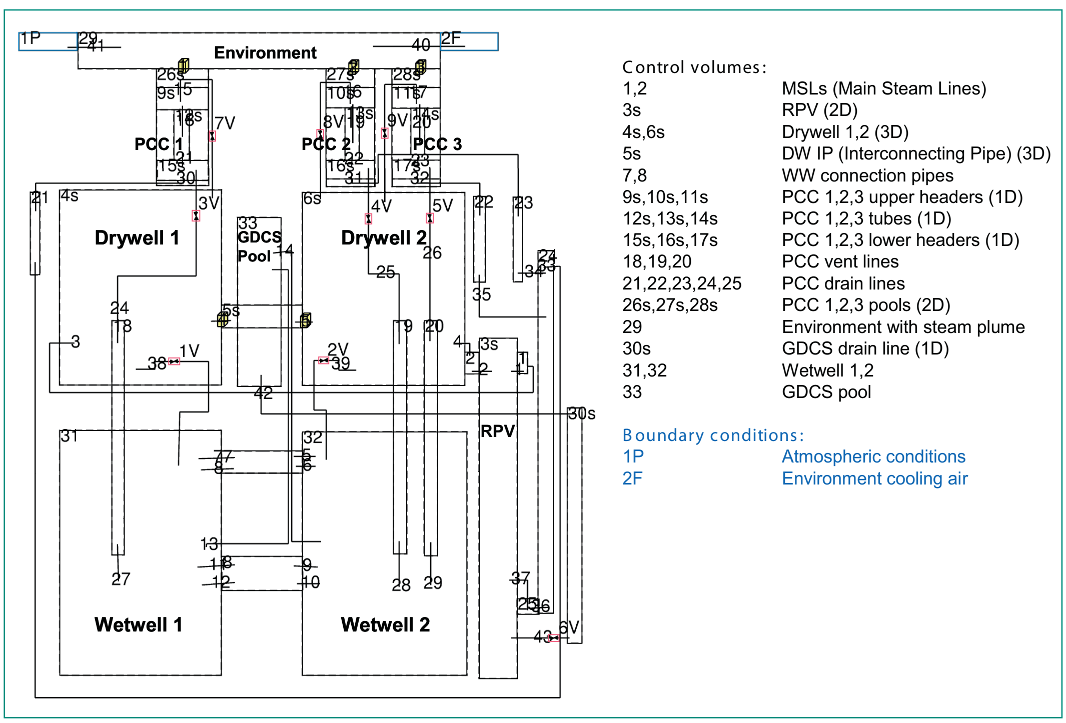

Figure 5:
GOTHIC nodalization scheme of the PANDA facility.

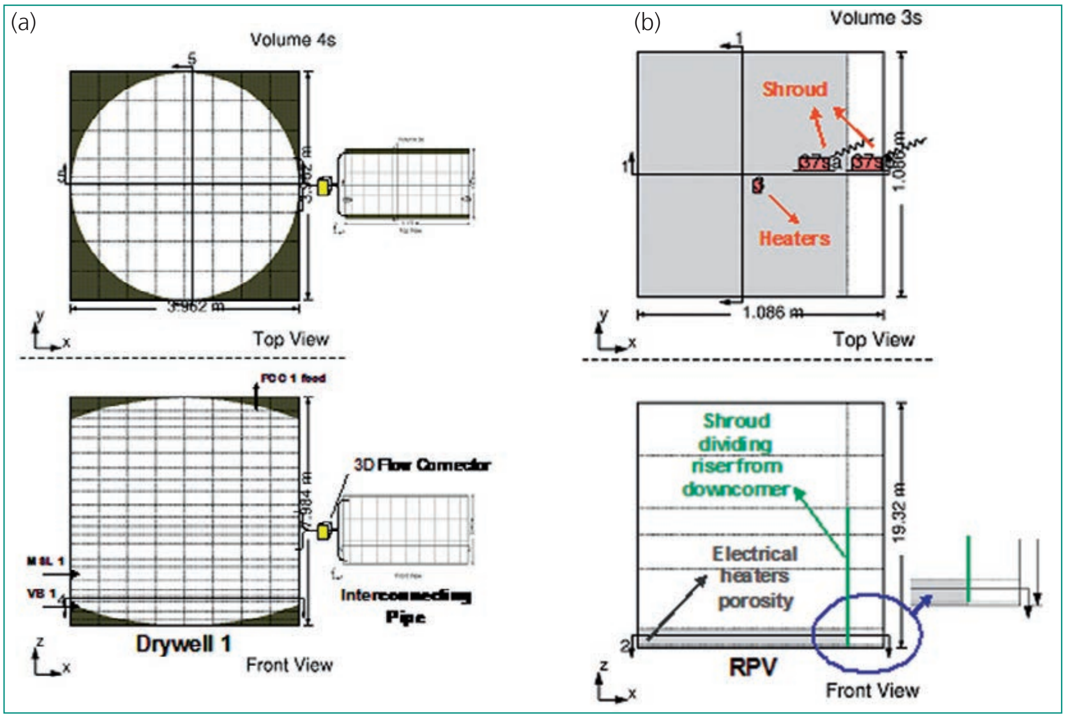

Figure 6:
GOTHIC nodalization developed for DW (a) and RPV (b).

A 2-D approximation was chosen instead to represent the volumes containing pools of water with natural circulation flows, i.e. the RPV (Vol. 3s) and the PCC pools (Vol. 26s, 27s and 28s). The utilization of a low number of cells (few tens, details of the RPV nodalization in Figure 6-B) is enough to simulate boiling phenomena and obtain a reasonable circulation pattern, as proved in [2]. Finally, the model of the three PCCS is one-dimensional [2].
The model has been validated with Phase B of the ISP-42 experiment, confirming the physical basis of the sensitivity to initial air concentration in the DW highlighted in [4]. The results are planned for publication in 2013.

Development of a numerical coupling between TRACE and GOTHIC

The main part of 2012 has been spent on implementing the coupling between TRACE and GOTHIC based on the pre-studies. The coupling allows the two-phase mixture as well as non-condensable gases to flow from the domain of one code into the domain of the other at an arbitrary number of coupling points. Each code treats the coupling points essentially as boundary conditions that are continuously updated based on data provided by the other code. This principle minimizes the ingress that has to be made into the codes as the implementation is restricted to the boundary conditions without modifying the actual equation solvers of the codes.
A first version of the coupling scheme has been completed and was verified in several steps, starting from small GOTHIC models involving various lumped and subdivided volumes and connected by one or more junctions. Liquid, vapour and non-condensable gases were made to pass through these junctions by means of gravity, initial pressure differences or forced by connecting a flow boundary condition to one or more of the volumes. The results were satisfactory, as also by partially repeating the study published in [2].
The whole validation results are planned for publication in 2013.

National Cooperation

The project is carried out in a close collaboration between the Laboratory of Reactor Physics and Systems Behaviour (LRS), the Laboratory for Thermal-Hydraulics (LTH) and ENSI. Synergies with the Swiss federal polytechnic institutes ETHZ/EPFL are expected with the preparation and supervision of relevant MSc and PhD theses.

International Cooperation

The lessons from the study [2] have led to a research proposal submitted to the IAEA. The topic proposed to investigate by means of Computational Fluid Dynamics (STAR-CCM+) the complex boiling and recirculation pattern taking place on the pool side of the PCCS. The proposal has been accepted in late 2012 and a fellow researcher from the Nuclear Power Institute of China (NPIC) will conduct in 2013 a 6-month long internship at PSI.

Assessment 2012 and Perspectives for 2013

The goals for 2012 have been achieved. The detailed literature survey [1] could confirm the PANDA facility as the premiere source of data for the assessment of the tools and models developed in PASSPORT. In this respect, through the benchmark of GOTHIC and TRACE on the simulation of different PANDA experiments (integral test ISP-42 and B-tests), a good understanding of the capabilities and limitations of the codes GOTHIC and TRACE has been established and thus hinted at the potential complementarities of the two in a coupled configuration. Moreover, a large part of the work in 2012 consisted in designing and developing a novel dynamic coupling between GOTHIC and TRACE. A first version has been developed and was verified on simple problems. For 2013, the following work is planned.

- The verification and validation of the coupling scheme will be completed using data from the PANDA ISP-42 experiments. For an objective evaluation of the added-value of the coupling, the same experiments will be simulated using stand-alone versions of the two codes and models, and compared with the coupled code solution.
- The versatility of the coupling might be extended by adding a supplementary capability where each side of a heat exchanger (e.g. the PCC) can be separately modelled by one of the two codes.
- The analysis of additional experimental tests to enlarge the validation basis of the above coupling schemes will be considered if suitable tests are identified as well as if sufficient experimental data and specifications are to that aim made available through e.g. international collaborations.
- As last step, an attempt to apply the coupled code for the simulation of a postulated accident in a Swiss nuclear power plant will be aimed at. The accident as well as the plant to consider will need to be evaluated, noting that a plant specific GOTHIC containment model will be required for coupling to the available TRACE models of the Swiss reactors.

Publications

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