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AN APPROACH TO VALIDATION OF COUPLED CFD AND SYSTEM THERMAL-HYDRAULICS CODES

M. Jeltsov, F. Cadinu, W. Villanueva, A. Karbojian, K. Kööp and P. Kudinov
Royal Institute of Technology, Stockholm, Sweden
marti@safety.sci.kth.se, francesco@safety.sci.kth.se, walter@safety.sci.kth.se, pavel@safety.sci.kth.se

Abstract

This paper discusses the development of approach and experimental facility for the validation of coupled Computational Fluid Dynamics (CFD) and System Thermal Hydraulics (STH) codes. The validation of a coupled code requires experiments which feature two way feedback between the component (CFD sub-domain) and the system (STH sub-domain). We present results of CFD analysis that are used in the development of a flexible design for the TALL-3D experimental facility. The facility consists of a lead-bismuth thermal-hydraulic loop operating in forced and natural circulation regimes with a heated pool-type 3D test section. The goal of the design is to achieve a feedback between mixing and stratification phenomena in the 3D tests section and forced / natural circulation flow conditions in the loop. Finally, we discuss the development of an experimental validation matrix for validation of coupled STH and CFD codes that considers the key physical phenomena of interest.

Keywords: Coupled Codes, V&V, CFD, System Thermal-Hydraulics, Liquid Metals

Introduction

Nuclear power plants are complex systems which behavior is driven by the interactions between many different physical processes at different scales. Quite naturally, then, the simulation of nuclear power plants requires coupling between different physical models (which can span different time and length scales). For ease of implementation, this often takes place in the form of *code coupling*.

In this paper we are concerned with *multi-scale* coupling – between STH and CFD, which can resolve feedbacks between system thermal hydraulic behavior and local, 3D effects in smaller scales. In the case of STH/CFD coupling, the macro-scale is the integral, coarse mesh, 1D description of the system while the micro scale is represented by the 3D, fine mesh domain of the CFD simulation.

In order to achieve high maturity [1] of any (single or coupled) code, verification, validation and uncertainty analysis must be performed. The validation process targets the accuracy of the code results compared to the experimental measurements. The validation of coupled codes consists of two steps. First, each code is verified and validated separately (the validation is obtained by performing separate physical effect tests). Second, validation of coupled codes against experimental data is performed. This requires experiments which feature mutual feedback between sub-components of the complete system. Each component is resolved then by a sub-code assigned to it. Important requirement for validation experiments is a measurement system that can provide adequate quality data for validation of both STH and CFD [1].

In this paper we discuss an approach for the validation of coupled codes that allows us to identify and separate potential deficiencies in the STH simulation, in the CFD modeling and in the coupling method. The approach is implemented in the design of the TALL-3D experimental facility, expressly constructed for the validation of coupled CFD/STH codes. We discuss results of steady state and transient calculations with the CFD code Star-CCM+ in support of the TALL-3D design development. Finally, we provide a tests matrix for the experimental program that aims at providing systematic data for validation of different coupling approaches and codes and captures important system (1D) and local (3D) phenomena in separate effect and coupled behavior.

1. TALL-3D experimental facility

Application of the coupled codes is justified when: i) a single code is not able to predict the system behavior with sufficient accuracy (i.e. 3D effects are important and not captured in 1D STH) or ii) it saves the computational costs (3D CFD modeling of the whole experiment is unpractical). However, full 3D modeling with CFD might still be useful to identify proper sub-divisions of the computational domain into virtual 1D and 3D sub-domains modeled later by coupled STH and CFD codes respectively.

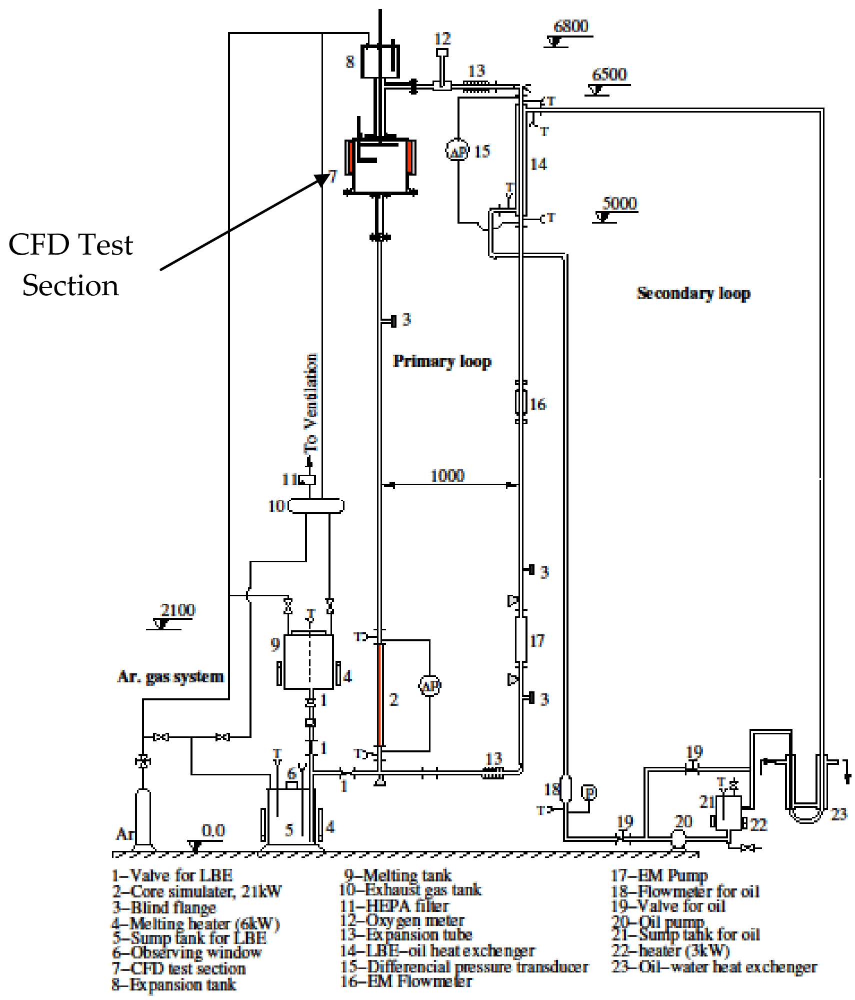


Figure 1: TALL loop configuration with the proposed CFD test section.

Any experimental facility that is going to be used for validation of coupled codes has to meet two basic criteria. The first and perhaps most important one is that feedbacks between local and integral phenomena in different sub-domains resolved by different codes are significant. Second, the facility should allow separate validation of every code used in the coupled system.

The TALL-3D facility is a modification of KTH's TALL, a Lead-Bismuth eutectic, 7 meters tall, thermal-hydraulic loop which has previously been used for the study of natural and forced circulation transients. The TALL facility consists of a primary and secondary loop. In the current configuration, the primary loop consists of a pump, an electrical heater, a heat exchanger and piping. The internal diameter of the main piping is 27.8 mm. The maximum LBE velocity in the heater section is 2 m/s. Experiments performed in the TALL facility, both, in the forced and natural circulation flow regimes, have already been used to validate STH codes [2].

In TALL-3D, a new test section (Figure 1) is introduced in the existing loop-type facility, representing the CFD sub-domain in the coupled code analysis (component 7 in Figure 1). The CFD test section provides different feedbacks to the system depending on the experimental conditions. The temperature at the CFD test section outlet defines the temperature of the fluid at the heat exchanger (component 14 in Figure 1) inlet.

1.1 Specific requirements and description of the TALL-3D design

In TALL-3D, the goal of the CFD test section design is to obtain a strong two-way feedback between the local thermal hydraulic phenomena inside the test section and the system dynamics of the loop. A STH code, then, is not expected to capture the behavior of the system alone.

Pre-design CFD calculations (presented in the next section) are performed to select the main test section parameters (geometry, loop mass flow rate, heater power) in such a way that the pool is completely mixed in forced circulation regime and thermal stratification develops in natural circulation regime.

There are other desirable requirements for the test section design. First, the design has to be as simple as possible, ideally 2D axisymmetric. Second, the design should be inherently flexible with respect to the parameters (dimensions etc.) in order to allow validating the widest range of code coupling strategies. Third, the boundary between pure 1D and 3D flows has to be defined as clearly as possible. Finally, the quantity of interest for the loop dynamics, which is the temperature profile inside the component, should be accurately measured, providing data suitable for the separate effect validation of the CFD code. The instrumentation must allow also measuring velocity profiles inside the 3D component and the integral pressure difference over the section. Mass flow and temperature measurement instruments for the rest of the loop are already implemented in the existing facility.

The design that meets all above mentioned criteria is presented in Figure 2. Changeable test section inlet nozzle (with different inlet diameters), vertically movable disk and band heater with adjustable power are considered in the design for flexibility in providing different configurations of the test section. The length of the inlet and outlet pipes is sufficient to provide fully developed flow, which enables to define realistic inlet and outlet boundary conditions for 3D test section. The disk is introduced in the upper part of the test section to provide an obstacle for the buoyant jet, thus enhancing the mixing in the test section. The inlet diameter is chosen to ensure that in forced flow conditions the jet reaches the disk and creates a large scale recirculation flow that mixes the pool even if the heater is switched on. In natural circulation flow conditions, the momentum of the jet is not enough to penetrate the developing thermally stratified layer.

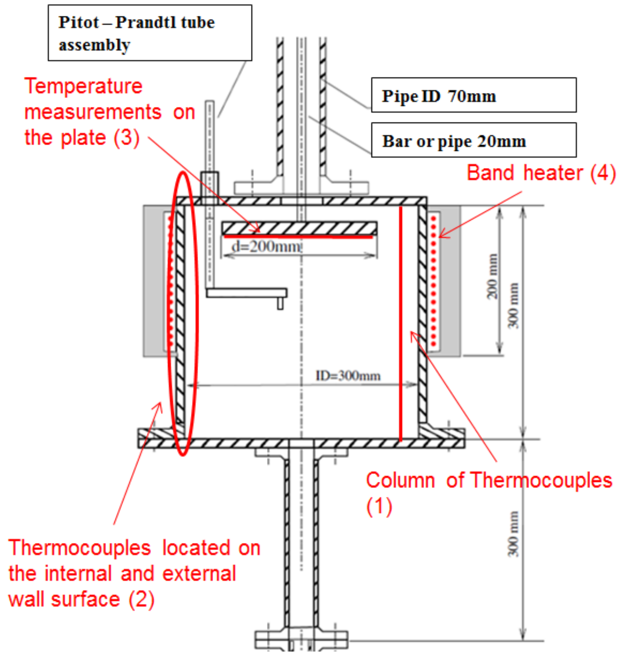


Figure 2: 3D-test section geometry. (1) Thermocouples in the bulk. (2) Thermocouples on the wall surface.(3) Thermocouples on the disc surface. (4) Test section band heater. For the velocity measurements, vertically and rotationally adjustable Pitot-Prandtl tube assembly is used.

The mutual feedback between the loop and the 3D section is obtained by leveraging the dynamic interplay between the following key physical phenomena: (i) development of stratification at small flow rate (natural circulation flow in the loop) inside a heated pool-like CFD test section; (ii) mixing in the test section at high flow rate (at forced loop convection); (iii) transient natural circulation in the loop under conditions of changing 3D tests section outlet temperature (which is in turn affected by the loop flow velocity and mixing/stratification phenomena). It is important to note that in the fully mixed regime or in steady state loop circulation a 1D modeling (heat balance and total pressure drop) can be applied to resolve the effect of the 3D tests section on the loop. The local 3D phenomena (mixing/stratification) are important for the integral system behavior only in transients where the 3D test section pool is not completely mixed and the instantaneous outlet temperature T_{out} can significantly deviate from what is predicted by a simple heat balance. T_{out} is important because it affects the natural circulation flow rate in the loop. This ensures the presence of multi-scale interactions between the component and the system dynamics.

CFD modeling has to resolve a number of physical phenomena to capture the outlet temperature transient behavior. Specifically important are: (i) the buoyant plumes and forced jets, (ii) the jet/plume impingement and interactions with the obstacles and walls inside the test section, (iii) erosion of thermally stratified layer by buoyant plumes and forced jets, (iv) development of buoyant boundary layer on the 3D test section heater surface, and finally (v) interactions between the jet/plume and flows created in buoyant boundary layers that define the recirculation dynamics in the test section.

Consistently with the theory of buoyant jets in pool-like geometries, a full mixing in the test section can then be achieved for inlet velocities above a certain critical level V_{crit} [3].

It is instructive to note that in the first version of the test section design an immersed heater along the central vertical axis, was considered. After preliminary CFD analysis it became obvious that this scheme is not capable to provide both stratification development in the natural circulation regime and mixing in forced circulation. This was related to the complicated interactions between the buoyant jet at the inlet and buoyant boundary layer on the heater wall. Both flows had the same direction promoting mixing and inhibiting development of stratification in case of natural circulation regime in the loop. By decreasing the inlet jet velocity to the value at which stratification can be developed in natural circulation regime, it was found that sufficient mixing was not achievable in the forced circulation regime. Furthermore, the immersed heater represents an obstacle for the free jet which might introduce additional undesirable complications in the 3D phenomena of tests section behavior. Therefore, the version of the design with the band heater was chosen.

2. Calculations in support of the design

The goal of the calculations in support of the design is to confirm that, for the test section geometry shown in Figure 2, full mixing is obtained in steady state forced circulation in the loop and thermal stratification develops in steady state natural circulation conditions.

The steady state simulations have been performed with the CFD code STAR-CCM+, version 5.06 [4], by solving the steady state RANS equations using the coupled implicit solver and treating the gravity term using the Boussinesq approximation. The local time-step is defined by Courant number which has a value of 5. The model is two-dimensional axisymmetric and the mesh consists of about 60 000 polyhedral cells. Regions with higher gradients and/or with flow separation possible have denser mesh. Turbulence is modeled with the realizable $k-\varepsilon$ model, using a two layer all y+ wall treatment formulation developed for buoyancy driven flows (Xu model [5]). There are 12 prism layers modeled on the solid walls.

Table 1: Inlet boundary conditions corresponding to the two cases simulated for the design of the CFD test section. In both cases, $d_{inlet} = 50$ mm and is $\dot{Q}_{heater} = 5$ kW.

Cases	Inlet Conditions		Description
	Velocity (m/s)	Temperature (K)	
Case I	0.239	609	Inlet conditions corresponding to a steady state forced circulation in the unmodified TALL loop with mass flow rate $\dot{m} = 4.77$ kg/s.
Case II	0.042	695	Inlet conditions corresponding to a steady state natural circulation in the unmodified TALL loop with mass flow rate $\dot{m} = 0.83$ kg/s.

It can be expected that, from the quantitative point of view, some of these modeling hypotheses might have an adverse effect on the accuracy of the simulation results (in particular the hypothesis of the flow being 2D axisymmetric). On the other hand, the scope of these calculations is mainly to obtain a *qualitative* confirmation that stratification develops for a given set of inlet conditions with sufficient margin. Therefore, the modeling hypotheses above were deemed to be reasonable defaults. The calculation matrix with the corresponding inlet conditions is summarized in Table 1. In Case I, is forced flow regime provided by the EM pump. In Case II, the EM pump is switched off and flow is driven only by the temperature (density) difference between the hot and the cold leg. The characteristic values of mass flow rates in forced (4.77 kg/s) and natural (0.83 kg/s) circulation conditions are taken from previous tests in the original configuration of the TALL facility. Performed assessments suggest that additional pressure drop in the 3D test section is minor and characteristic values of the flow rates in the modified TALL-3D facility are not going to change significantly.

2.1 Case I: Forced Circulation

In the forced circulation case the inlet velocity and temperature are, respectively, 0.239 m/s and 609 K (the inlet is located 35 cm below the test section). The calculated temperature distribution and the streamlines pattern in the pool are shown in Figure 3.

The interaction of the high momentum jet with the disk produces a recirculation pattern characterized by the presence of two, large scale counter-rotating vortexes (Figure 3.b). The vortex at the top of the test section mixes the cold jet fluid with the hot fluid adjacent to the heater. The vortex at the bottom of the test section drives the hot fluid adjacent to the heater towards the bottom of the test section. Therefore, the action of both vortexes tends to homogenize the temperature field inside the test section. Predictably, a hot spot is present in the stagnation point between the vortexes and the wall.

The resulting temperature field (Figure 3.a) shows that the recirculation induced by the jet-disk interaction and buoyant boundary layer on the heater mixes effectively the fluid in the test section. Figure 3.c presents a plot of temperatures in each single cell in the simulation domain. It illustrates that temperature in most of the cells in the domain is uniformly around 625 K except the jet region where it is determined by the inlet jet temperature (609 K) and thin layer in the vicinity of the heated wall where it has peak value of 642 K.

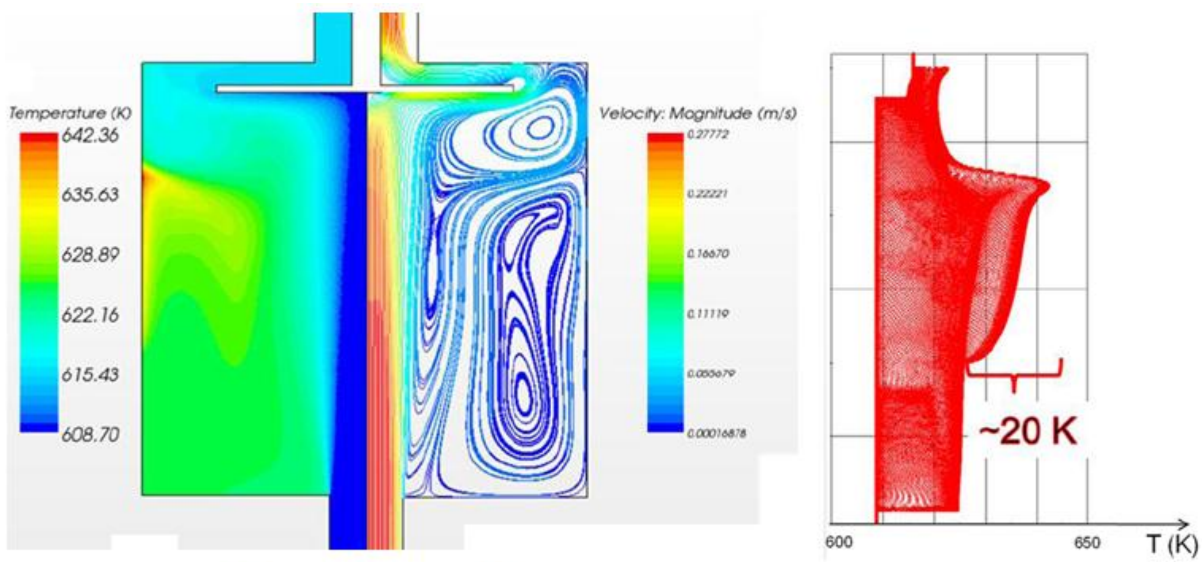
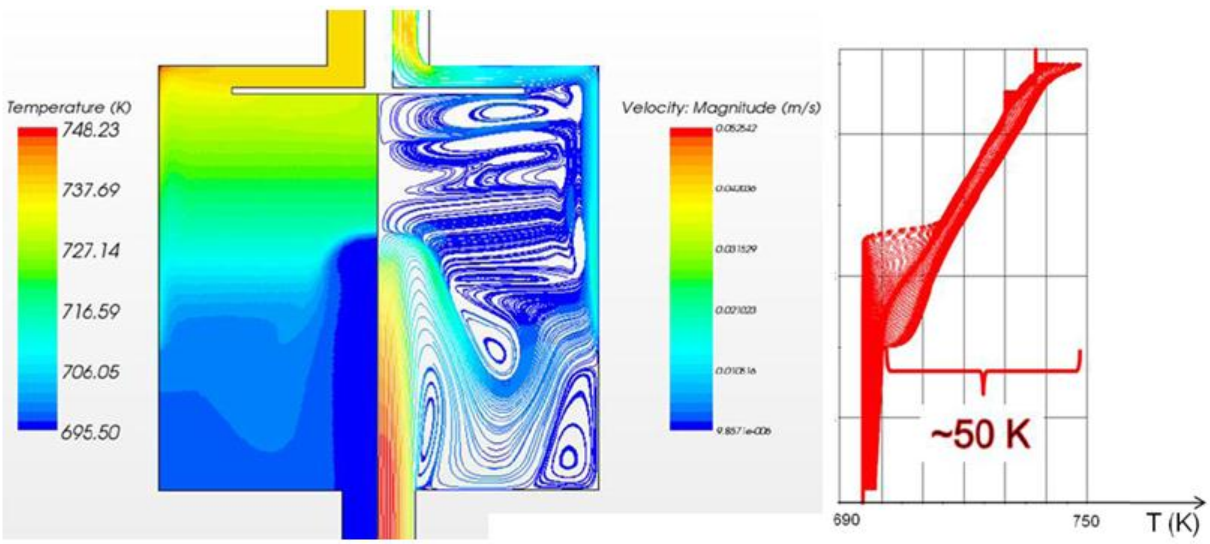


Figure 3: 2D temperature field (a), streamlines (b) and axial temperature distribution (c) for the steady state forced circulation.

2.2 Case II: Natural Circulation

In the natural circulation case the inlet velocity and temperature are, respectively, 0.042 m/s and 695 K. The calculated streamlines and temperature profiles are shown in Figure 4.

In this case, the low momentum jet is not able to penetrate thermally stratified layer and it dissipates not reaching the disk at the top. The top bulk part of the pool is mostly stagnant. A buoyant boundary layer flow develops along the heater surface and pushing hot liquid through the gap between the disc and the top wall of the test section to the outlet. Figure 4.c (temperature in each computational cells is plotted) shows an almost constant temperature gradient in the top part of the test section. The difference between temperatures at the bottom and at the top in steady state conditions is about 50 K. Although the volume of the test section is stratified and the temperature distribution is not uniform, the outlet temperature in steady state is defined by the heat balance and can be predicted by a STH 1D code. However, the transient development of stratification and mixing in the tests section is a complex 3D process that is generally not resolved by a 1D code.



a) b) c)

Figure 4: Temperature field (a), streamlines (b) and axial temperature distribution (c) for the steady state natural circulation.

3. Development of validation test matrix

3.1 Key physical phenomena and validation test matrix

Any attempt towards validation of coupled codes must be preceded by a separate validation of the STH and CFD components. The validation tasks can, then, be broken down into three sub-tasks:

- Separate effect validation of STH
- Separate effect validation of CFD
- Validation of Coupled Codes.

Successful validation of separate STH, CFD and coupled codes implies that all important physical phenomena can be resolved with sufficient accuracy by the respective codes. Important physical phenomena that define the behavior of TALL-3D facility are presented in Table 2. The list of physical phenomena is divided in three parts that correspond to validation of STH, SFD and coupled codes respectively. To provide data for code validation against key physical phenomena we propose the validation test matrix presented in Table 3.

Table 2: Physical phenomena, which STH, CFD or STH-CFD coupled codes can be validated against. The check marks in the table indicate which transient allows a particular validation.

	Physical Phenomena	Steady circulation Heater power				Transients (see Table 3)											
		Forced		Natural													
		Off	On	Off	On	1	2	3	4	5	6	7	8	9	10	11	12
STH validation	1. Drag in forced circulation	✓	✓														
	2. Drag in natural circulation			✓	✓												
	3. Transient drag					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	4. Heat transfer in forced circulation	✓	✓														
	5. Heat transfer in natural circulation			✓	✓												
	6. Stability of natural circulation			✓	✓												
	7. Thermal inertia of the loop sections – transient					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	8. Heat losses as a function of the system temperature – steady state	✓	✓	✓	✓												
	9. Heat losses as a function of the system temperature – transients					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CFD validation	1. Free jet flow	✓	✓	✓	✓												
	2. Jet impingement on a surface	✓	✓														
	3.Jet-induced recirculation	✓	✓														
	4.Stratification development						✓		✓		✓						
	5. Mixing					✓		✓		✓		✓	✓	✓	✓	✓	
	6. Buoyant jet flow						✓	✓	✓		✓		✓				✓
CFD+STH validation	1. Transient response of the CFD test section					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2. Transient response of the loop					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	3. Nonlinear feedbacks and instabilities					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Three classes of experiments are envisioned: forced circulation steady states (SSF), natural circulation steady states (SSN) and transients (T). The nomenclature “On” and “Off” in Table 2 and Table 3 refers to the state of the 3D test section heater. It is instructive to note that total number of steady states (4) is defined by 2 circulation regimes (natural or forced) in the loop and two states of the heater (On or Off). We use following notations for defining the steady states (see also Figure 6):

- **Forced** circulation in the loop, 3D test section pool heater **Off** – **SSF-Off**
- **Forced** circulation in the loop, 3D test section pool heater **On** – **SSF-On**
- **Natural** circulation in the loop, 3D test section pool heater **Off** – **SSN-Off**
- **Natural** circulation in the loop, 3D test section pool heater **On** – **SSN-On**

The total number of considered transient (12) is limited by condition that each transient is a transition (depicted by arrows in Figure 5) between two steady states. Thus each transient test also produces data for validation in the initial and final steady states.

Table 3: Validation tests matrix.

	Transient Number	"From" steady state	"To" steady state	Actions at time "zero"
High priority	#1	SSN-Off	SSF-Off	Activate the pump
	#2	SSF-Off	SSN-On	Deactivate the pump, Activate the pool heater
	#3	SSN-On	SSN-Off	Deactivate the pool heater
	#4	SSN-Off	SSN-On	Activate the pool heater
	#5	SSN-On	SSF-On	Activate the pump
	#6	SSF-On	SSN-On	Deactivate the pump
Low priority	#7	SSN-On	SSF-Off	Activate the pump, Deactivate the heater
	#8	SSF-Off	SSN-Off	Deactivate the pump
	#9	SSN-Off	SSF-On	Activate the pump, Activate the heater
	#10	SSF-On	SSF-Off	Deactivate the heater
	#11	SSF-Off	SSF-On	Activate the heater
	#12	SSF-On	SSN-Off	Deactivate the pump, Deactivate the heater

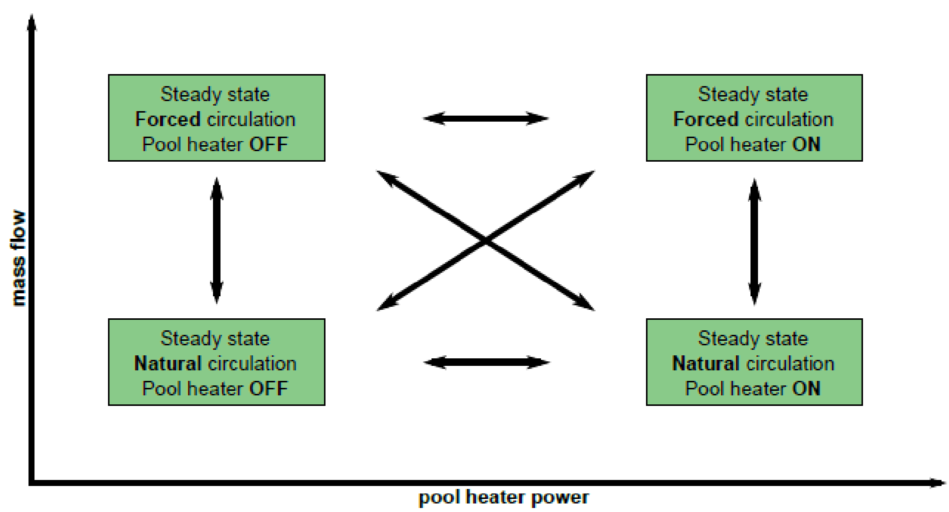


Figure 5: Different steady states and possible transients between them.

Table 2 lists the physical phenomena relevant to each test. It is important to note that steady state data only enable separate effect validation against fewer basic phenomena. That helps to implement step by step validation with gradually increasing complexity of the task. Given the final goal, which is validation of coupled STH to CFD codes, we prioritize tests according to the expected significance of the feedbacks between 3D test section and system (loop). Tests #1 to #6 belong to the high priority group and #7 to #12 belong to the low priority group. Both groups of transients can be executed as a continuous sequence in a single experiment.

The validation tests matrix presented in Table 3: Validation tests matrix.can be executed for each fixed configuration of the TALL-3D facility. The configuration of the CFD test section is defined by (values in bold are used as base case configuration):

- The inlet diameter d (40 mm; **50 mm**).
- The disc axial position z_D (**15 mm (upper)**; 150 mm (middle); 285 mm (lower)).
- The test section heater power Q_{heater} (2.5 kW; **5 kW; 10** kW).

In addition to the above, the test section heater timing can be also considered as variable parameter, however number of possible transients in this case is beyond reachable in practical sense.

3.2 Requirements to instrumentation

In order to provide sufficient amount of data for validation purposes, the instrumentation should allow proper resolution of a) velocity and temperature profiles in the CFD component, and b) 1D flow characteristics in the STH domain. For the STH code validation, existing integral measurements in the current loop include the LBE mass flow rate which is measured with an Electromagnetic (EM) flow meter (see item 16 in Figure 1) and temperatures which are measured with thermocouples (TC) at different locations. The proposed set of additional instrumentation can be seen in Figure 2. The local temperature measurements inside and along the surfaces of the CFD test section are performed with a set of thermocouples (see Figure 2 for details of their placements). The velocity field is measured using a Pitot-Prandtl assembly (see also Figure 2) that consists of a support and control system and a Pitot-Prandtl tube measurement probe with an attached thermocouple for density correction in the velocity calculation and for additional temperature data (see [6] for its successful implementation in the KALLA facility). An alternative non-intrusive way to measure velocities is the Ultrasound Doppler Velocimetry (UDV) and has been implemented in the KALLA facility [6] and also by Eckert, et al. [7]. It has the advantage of providing complete velocity profiles including boundary layers instantaneously but commercially available devices set a limit to the LBE's operating temperature.

4. Summary

In this paper we have presented an approach to design an experimental facility for validation of STH, CFD and coupled STH-CFD codes. General requirements for a code validation experiments together with specific requirements for the proposed TALL-3D facility are described. In order to meet those criteria, we have performed computational analyses, which have shown qualitatively that the necessary significant two-way feedback between the implemented 3D-test section and the system is achievable. Expected full mixing in steady state forced flow conditions and thermal stratification in steady state natural circulation flow conditions are both confirmed. A preliminary design of the 3D test section with certain degree of flexibility and adequate instrumentation has been selected. The list of key physical phenomena has been discussed and used for development of validation matrix and procedures that cover both separate effect test measurements and complex transient tests which feature the two-way feedback. Series of transient pre-tests simulations is necessary to finalize selection of the test parameters for the transient tests.

5. Acknowledgment

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