



# The multiscale thermal-hydraulic simulation for nuclear reactors: A classification of the coupling approaches and a review of the coupled codes

Kanglong Zhang

Karlsruhe Institute of Technology (KIT),  
Hermann-von-Helmholtz-Platz 1,  
Eggenstein-Leopoldshafen, Germany

## Correspondence

Kanglong Zhang, Karlsruhe Institute of  
Technology (KIT), Hermann-von-  
Helmholtz-Platz 1, Eggenstein-  
Leopoldshafen, Germany.  
Email: kanglong.zhang@kit.edu

## Funding information

China Scholarship Council, Grant/Award  
Number: 201506340031; Helmholtz-  
Gemeinschaft, Grant/Award Number:  
FE533000840012; Helmholtz-  
Gemeinschaft NUSAFE Program, Grant/  
Award Number: FE533000840012; China  
Scholarship Council (CSC), Grant/Award  
Number: 201506340031

## Summary

Simulation is becoming increasingly important in the safety analysis of nuclear reactors nowadays. The physical phenomena in a nuclear power plant happen on three classified scales: system scale (phenomenon over the whole plant is concerned), component scale (phenomenon in specific component is concerned), and mesoscale (phenomenon in a small part of a component is concerned). Owing to the particular emphases, various codes are developed to simulate particular problems. System codes intend to predict the behavior of the whole power plant during normal or accidental phases (system scale). Sub-channel codes are for core behavior predictions (component scale). CFD codes can simulate the thermal-hydraulic in a fixed part of the plant (mesoscale). Those codes are coupled together to better predict the conditions in a nuclear reactor in last the two decades, which is the multiscale thermal-hydraulic simulation approach for nuclear power systems. Diverse coupling approaches are developed and various coupling codes are implemented. This paper first proposes a classification of those approaches. It tells that a multiscale coupling is composed of five items: coupling architecture, operation mode, domain coupling, field mapping, and temporal coupling. Numbers of options are available for each item. For coupling architecture, it can be internal coupling, via-IO coupling, server-client, or serverless coupling. For operation mode, it can be either parallel or serial. For domain coupling, it can be either domain-decomposition or domain-overlapping coupling. For field mapping, it can be manual-definition, processed by user-developing toolkit, or handled by third-party libraries. For temporal coupling, it can be explicit coupling, semi-implicit coupling, or implicit coupling. An evaluation of the approaches is performed based on new-proposed criterion. A general review of the multiscale thermal-hydraulic coupled codes is made based on the classification. Especially, a review of the domain-overlapping approach is present considering it is the most promising but challenging method for multiscale thermal-hydraulic simulation.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Author. *International Journal of Energy Research* published by John Wiley & Sons Ltd

**KEYWORDS**

classification of coupling approaches, multiscale thermal-hydraulic coupling, review of coupled codes, review of domain-overlapping

**1 | INTRODUCTION**

The commercial nuclear reactors have been in operation for electricity generation worldwide for many years and they were proved clean and safe. Nevertheless, continuous effort is still now made by the nuclear community to improve the power systems' safety and efficiency. In order to achieve this goal, the physical phenomenon inside the reactor has to be carefully and sufficiently identified and investigated as the base of new reactor design and methodologies. Additionally, various other aspects have to be carefully lucubrated as well, such as the economic risks and uncertainties,<sup>1</sup> the waste management and storage, and the spent fuel processing,<sup>2</sup> etc. Especially after the Fukushima accident, a review of the safety status for the nuclear power plants was necessary to identify areas that needs to be improved. In the meantime, safety analysis methodologies and the strategies for accident management are under continuous enhancement to adjust to the rapidly changing regulatory policies.<sup>3</sup>

Conducting experiment is a good way to investigate those problems. However, for a nuclear power plant, the experiment can hardly cover everything because of the expensive cost and measuring difficulties. Simulation poses perfect supplementary, thanks to its economic efficiency, super repeatability, and results' transparency. Its role in accident management was underscored and many severe accident studies were carried out.<sup>4</sup> However, because of the limit of the computation power and the lack of mathematical models, different simulations have different emphasis according to the problem concerned. Some are interested in the dynamic of the whole system while some focus on the physical phenomenon in a specified component or part of a component.

In a nuclear reactor, the thermal-hydraulic phenomena take place at diverse spatial scales whose characteristic lengths vary from meters down to nanometers. Hence, the simulations are typically classified into three main scales<sup>5,6</sup>:

1. System scale: the phenomenon which is tightly related to the dynamics of the overall nuclear power plant or facilities is concerned at this scale, eg, the large break loss of coolant accident, where the primary cooling system of the reactor fails and loss the coolant.<sup>7</sup>
2. Component scale: the phenomenon occurring in special reactor components such as the reactor core and the heat exchanger is concerned at this scale, eg, the departure from nucleate boiling which is very important concerning the reactor safety.
3. Mesoscale: the fine description of the reactor thermal-hydraulics is concerned at this scale, eg, the unsymmetrical coolant mixing in the downcomer and lower plenum (coolant of different temperatures entering the reactor vessel from different inlet nozzles will mix with each other in the vessel) in the reactor pressure vessel (RPV).<sup>8</sup>

The European NURESIM and NURISP projects make a similar classification. In addition, another scale—microscale—was taken into account, which focuses more on details of flow conditions.<sup>9</sup> Besides, in Niceno et al,<sup>10</sup> the thermal-hydraulic simulation expands to nanoscale referring to, eg, molecular dynamics modeling techniques. In order to describe the thermal-hydraulic processes undergoing at the various spatial scales, many thermal-hydraulic simulation codes were developed and applied worldwide, eg, 1D or 3D system thermal-hydraulic codes, porous-media codes (CFD-porous media, subchannel codes, and porous-media 3D codes), open-medium-CFD, large eddy simulation, detached eddy simulation, and direct numerical simulation.<sup>11</sup>

The system codes were to simulate almost all normal and accident scenarios of the whole nuclear power plant. It handles general tasks in the power plant, eg, the qualification of the safety margins (the threshold under which the system is assumed operating safely). It also defines and verifies the emergency operation procedure, etc.<sup>12</sup> The most widely spread system thermal-hydraulic codes developed for many decades is RELAP,<sup>13</sup> TRACE,<sup>14</sup> ATHLET,<sup>15</sup> CATHARE,<sup>16</sup> etc. The 1D or 3D coarse meshes favor a fast execution and robust numeric for the whole spectrum of design basis accidents. However, because of the coarse mesh applied, system codes are not intended to describe phenomena taking place at the meso or microscale, eg, turbulences.

Subchannel codes dedicate the description of thermal-hydraulics in the core region by dividing the core flow paths to groups of channels. Some of the famous codes are COBRA-TF,<sup>17</sup> COBRA-FLX,<sup>18</sup> VIPRE,<sup>19</sup> FLICA,<sup>20</sup> SubChanFlow (SCF).<sup>21,22</sup> They were

developed for an improved description of the core thermal-hydraulics using quasi-3D models at component scale (decimeter to centimeter scale) for the prediction of local safety parameters such as critical heat flux (CHF) ratio, critical power ratio (CPR), fuel centerline temperature, and fuel surface temperature. A very detailed review of subchannel analysis methods and codes can be found in Moorthi et al and Cheng and Rao.<sup>23,24</sup> In order to simulate the core thermal-hydraulics of full cores using subchannel codes and to take profit from the increasing computer power, some subchannel codes were parallelized, eg, SCF and CORBA-TF.<sup>25</sup> In addition, the codes using porous models to simulate the dedicated 3D porous media two-phase flow with a Cartesian or unstructured grid are being developed to overcome the usually 1D limitations of the system thermal-hydraulic codes. Instances are CUPID,<sup>26</sup> PORFLOW,<sup>27</sup> TWOPORFLOW,<sup>28</sup> and PORFLO.<sup>29</sup>

Furthermore, to improve the simulation of 3D-effect within nuclear power plant circuits, CFD codes such as ANSYS-CFX, STAR-CD, OpenFOAM, TrioCFD are increasingly applied to nuclear system analysis. The main motivation is the increasing and cheap computation resources, the parallel capability of the codes, and the improved physical models and numerics.<sup>30</sup> General guidelines of how to use CFD in reactor safety complementary to the system codes are given in Mahaffy et al.<sup>31</sup> Recent investigations have shown the potentials of CFD-codes for the simulation of complete nuclear power plants or part of it<sup>32-35</sup> using meshing at different spatial scales ranging from millimeter to some centimeters. CFD codes work well for single-phase problems that may be encountered in the primary and secondary circuits as well as in the containment of NPPs. However, their application to two-phase flow is not yet comparable with the ones for single-phase flow due to some essential difficulties summarized in Bestion.<sup>36</sup> Nevertheless, new methods known as the computational multifluid dynamics (CMFD), which dedicates to simulate the two-phase flow on mesoscale or microscale are already one of the most promising trends for reactor applications.<sup>37</sup> Recent research devoted to enhance and validate the CFD codes for two-phase flow problems of reactor safety has advanced.<sup>38-40</sup>

Considering the trends and the current capabilities of the different thermal-hydraulic codes for design and safety evaluations, the development of multiscale thermal-hydraulic simulations has been initiated in different teams worldwide, in order to enhance the nuclear reactor thermal-hydraulic simulation. Normally, the phenomena occurring on system scale, component scale, and mesoscale are simulated by system code, subchannel code, and CFD code, respectively. In the frame of

different European projects, eg, NURESIM, NURISP, and NURESAFE, multiscale coupling approaches were systematically elaborated and various safety-relevant phenomena<sup>9</sup> were investigated in detail from a multiscale perspective. Different publications<sup>41-43</sup> provide guidelines for potential coupling approaches.

During the last two decades, various multiscale thermal-hydraulic analysis has been carried out and diverse approaches were developed to couple various codes. An imperfection opposite to the prosperously developing of coupled codes and coupling approaches is that there is no acknowledged principles or standards on those approaches. The names of the coupling methods used by different developers usually differ from each other, although sometimes they refer to the same methodology. This situation causes misunderstanding or confusion very often, especially to researchers who have rare experience in this field. What is worse, the lack of well-organized standard of performing multiscale thermal-hydraulic coupling poses additional barriers during the planning of coupling tasks. Standards or guidelines for the multiscale coupling is imperative. This paper settles this issue by achieving two objectives:

1. Propose a clear, logical classification of the existing coupling approaches.
2. Evaluate the approaches and give a reference and guideline for developers who would like to develop a multiscale thermal-hydraulic coupled code from scratch.

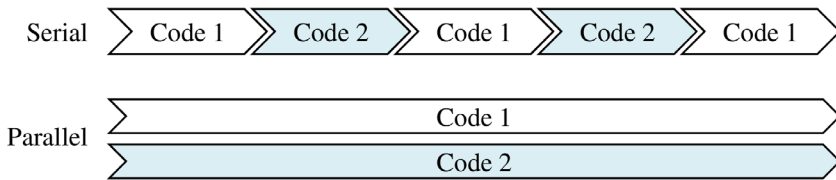
Apart from that, another objective of the paper is to propose a review of the multiscale-coupled codes so that the history and development sequence is more accessible.

The first chapter gives the background of multiscale thermal-hydraulic coupling and describes the motivations and objectives of this paper. The second chapter sorts out the approaches and gives an overview and evaluation of the multiscale coupling schemes. The third chapter reviews the multiscale coupled codes. Finally, the conclusion completes the paper.

## 2 | THE MULTISCALE THERMAL-HYDRAULIC COUPLING APPROACHES

### 2.1 | A classification of the approaches

From the informatics point of view, the coupling of multiscale thermal-hydraulic codes can be either parallel or serial, as illustrated in Figure 1. In this context, parallel mode especially refers to the interprocess



**FIGURE 1** Operational logics of the serial and parallel coupling [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

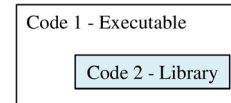
parallelization, eg, message passing interface (MPI)-based models. On the contrary, the architecture-based classification differentiates between the internal and external coupling. In an internal coupled system, one code compiles as a static or dynamic library fully integrated inside the other code resulting in one single executable, see Figure 2; while the external coupling option offers three possibilities, see Figure 3:

1. Data exchange via input and output (IO) files.
2. Use a supervisor to coordinate the coupling procedures.
3. The two codes directly communicate with each other forming a serverless system.

The internal coupling is the most applied method because of its relative simplicity. The server-client and serverless external coupling can achieve high performance and pose better expandability and maintainability compared with the internal coupling. However, intensive programming effort is necessary as well as in-deep knowledge of the coding structure of the involved solvers is required. Moreover, the condition could become more complex when the parallel mode is expected.

In a multiscale coupling system, the system code, the subchannel code, and the CFD code are coupled to achieve a more realistic simulation of a nuclear power plant using a code-specific spatial resolution of the computational domain. For instance, the coarse mesh of system code for the whole nuclear power plant, the relatively refined mesh of subchannel code for the core region, and the fine mesh for several specific parts, eg, the downcomer. So, one of the critical tasks for the multiscale coupling is how to specify which code is in charge of which computational domains within the entire problem. In this context, the way of coupling the different computational domains of the involved thermal-hydraulic solvers (system, subchannel, and CFD) is of great importance. Therefore, two methods are specified: domain decomposition and domain overlapping. Figure 4 demonstrates the two options with the simulation of a pipe using a system code and a CFD code.

For the domain overlapping case shown in Figure 4, the system code intends to model the entire pipe while the CFD code only simulates part of the pipe. The lower part of the figure illustrates the domain decomposition

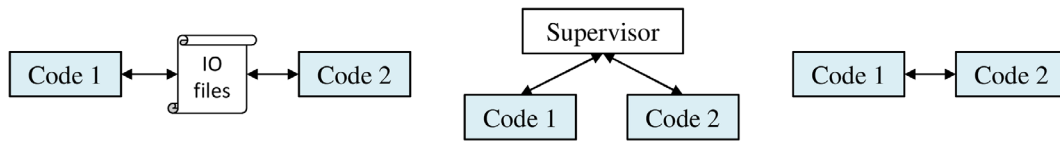


**FIGURE 2** Arrangement of codes for internal code coupling [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

method where the system code describes the pipe without the three central nodes, which are simulated by the CFD-code. The intercode data transfer occurs at the two boundaries between the CFD model and the system model, which is represented by the two double-sided arrows. The upper part of Figure 4 illustrates the domain overlapping method. There, the system code simulates the whole pipe and the CFD code simulates the three central cells only. These three cells represent the overlapping domain. The fields at the boundaries where the overlapping domain starts and ends are extracted from system code, and are then transferred to the CFD-code as its updated boundary conditions. The two 1-way arrows denote this data transfer. On the contrary, the data from CFD to the system code are body fields derived from the whole CFD computation domain. Those body data are used to correlate the system solution. A bunch of gray one-way arrows represents them.

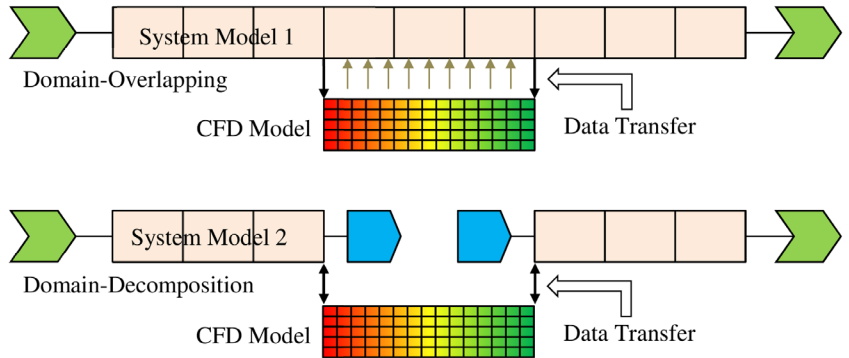
In general, the meshes of system code, subchannel code, and CFD code have different spatial resolutions, see Figure 4. There, the CFD mesh is much finer than the one of the system code. Consequently, the fields have to be translated from one mesh to the other in a proper way before the data transfer. For it, three options are available:

1. Manual definition of mesh spatial matching relations. It is a direct method free of programming effort but calls for massive work at any time when a newly coupled code is developed.
2. User-developed toolkit. In this method, the mesh matching finalizes in an automatic way and it is relatively efficient. It can focus on specific mapping problems for a special coupling scheme but it is not universal and powerful.
3. Use of a third-party mesh-processing toolkit, eg, the MEDCoupling library<sup>44</sup> of the SALOME platform. This toolkit is general and powerful. It can properly handle different mesh-mapping scenarios in an

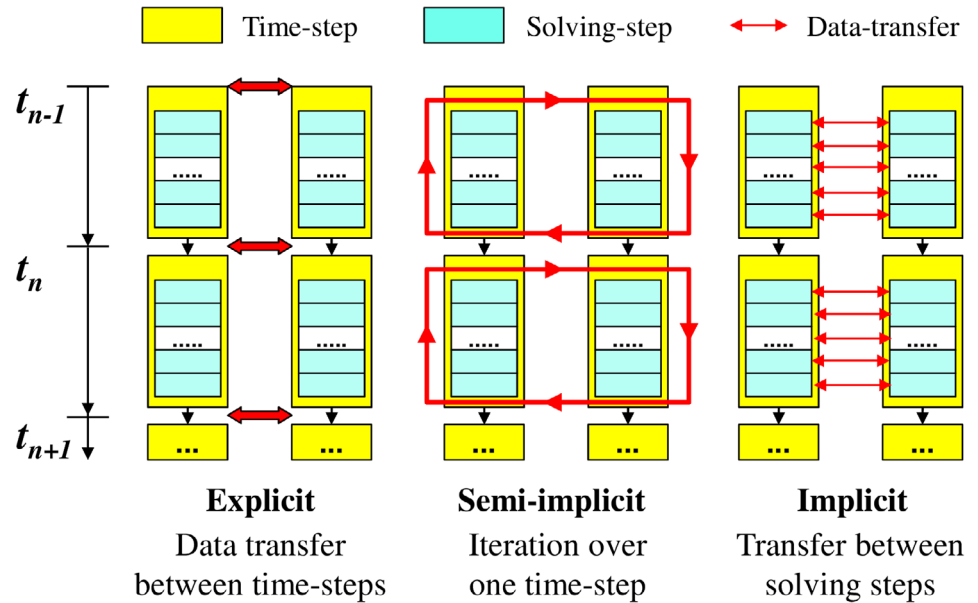


**FIGURE 3** Schematics of data flows for external code coupling [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 4** Demonstration of the domain overlapping and domain decomposition coupling approaches [Colour figure can be viewed at wileyonlinelibrary.com]



**FIGURE 5** Working principles and differences of the explicit, semi-implicit, and implicit temporal coupling [Colour figure can be viewed at wileyonlinelibrary.com]



automatic manner. However, those toolkits mostly require mesh definitions while most of the system and subchannel codes do not have meshes.

The mesh interpolation and physical field mapping methods together with the domain coupling compose the spatial coupling since they deal with the geometric objects. Beyond the spatial coupling, the other element for multiscale coupling in terms of mathematics and physics is the temporal coupling approach that is in charge of the synchronization of the data transfer among the involved solvers. The spatial coupling solves the problem of how to transfer the data properly, while

the temporal coupling solves the problem of how to use these data in order to establish a synchronous multiscale coupling code. The following three different temporal coupling approaches are implemented in different multiscale codes: (a) explicit coupling, (b) semi-implicit coupling, and (c) implicit coupling. Figure 5 illustrates the basic principles and the differences among these approaches.

The explicit coupling is the most straightforward temporal coupling method where the data transfer is carried out only once at the beginning or end of each time step. No check of the convergence of the codes' result within a time step is performed. Hence, the

results may be inconsistent with each other, which might result in a consequently unsteady situation during the solution.

In order to ensure the data consistency within one time step of the coupled codes, the semi-implicit coupling is implemented, where the data transfer is done many times until all the codes' result convergence within one time step. Hence, it is more robust than the explicit coupling, while on the other hand, it is more complicated to be implemented. Furthermore, the performance of the coupled codes can be improved by spreading the data transfer down to the solution procedures of the set of equations, which is the implicit coupling. This is the most efficient, robust coupling approach but needs significant modification of the source code, and hence it is challenging.

It is worth to note that Figure 5 only presents the general form of the three temporal coupling methods. The typical explicit coupling method is the operator splitting (OS) method, which is demonstrated in Chorin,<sup>45</sup> and now widely used in various coupling works. It is also called the operator splitting semi implicit (OSSI) method sometimes though it is actually an explicit method.<sup>46</sup> There are also diverse varieties for the semi-implicit<sup>47,48</sup> and implicit<sup>49</sup> coupling methods. Moreover, some other acceleration techniques are also massively developed and implemented to the codes temporal coupling.<sup>50-53</sup> They aimed at the optimization of the intercodes synchronization as well.<sup>54</sup> gives a review of the temporal coupling methods in detail. It is worth to note that those methods are not limited to multiscale coupling but they are universal methods for various coupling issues, eg, multiphysics coupling and for non-nuclear applications as well.

In view of the development of the multiscale coupling methods for thermal-hydraulic codes to solve reactor safety problems, it is important to look at the solution procedure applied to solve the system of equations in the thermal-hydraulic codes. If the set of equations are solved separately in the thermal-hydraulic codes, it is a weakly coupled code. Otherwise, it is a strong coupling if the

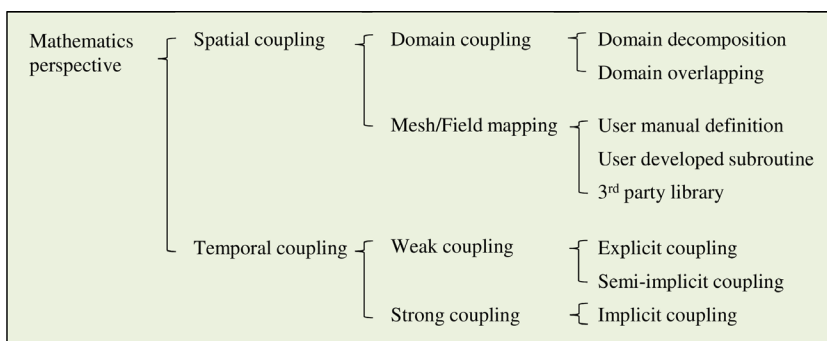
equation sets are solved simultaneously. Figure 6 presents a classification of the multiscale coupling approaches from the mathematical perspective.

Figure 7 summarizes all possible coupling approaches for the multiscale coupling of thermal-hydraulic codes (a summary from Figures 1 to 6). There are four possibilities—S1.1, S1.2, S1.3, and S1.4—for Strategy 1 (S1, coupling architecture). Two options—S2.1 and S2.2—for Strategy 2 (S2, operation mode) and two choices—S3.1 and S3.2—for Strategy 3 (S3, domain coupling). Three methods—S4.1, S4.2, and S4.3—for Strategy 4 (S4, physical field mapping). Three patterns—S5.1, S5.2, and S5.3—for Strategy 5 (S5, temporal coupling). Each of the five strategies has to be determined for a coupling strategy. In other words, a multiscale coupling approach is composed of the five pieces below.

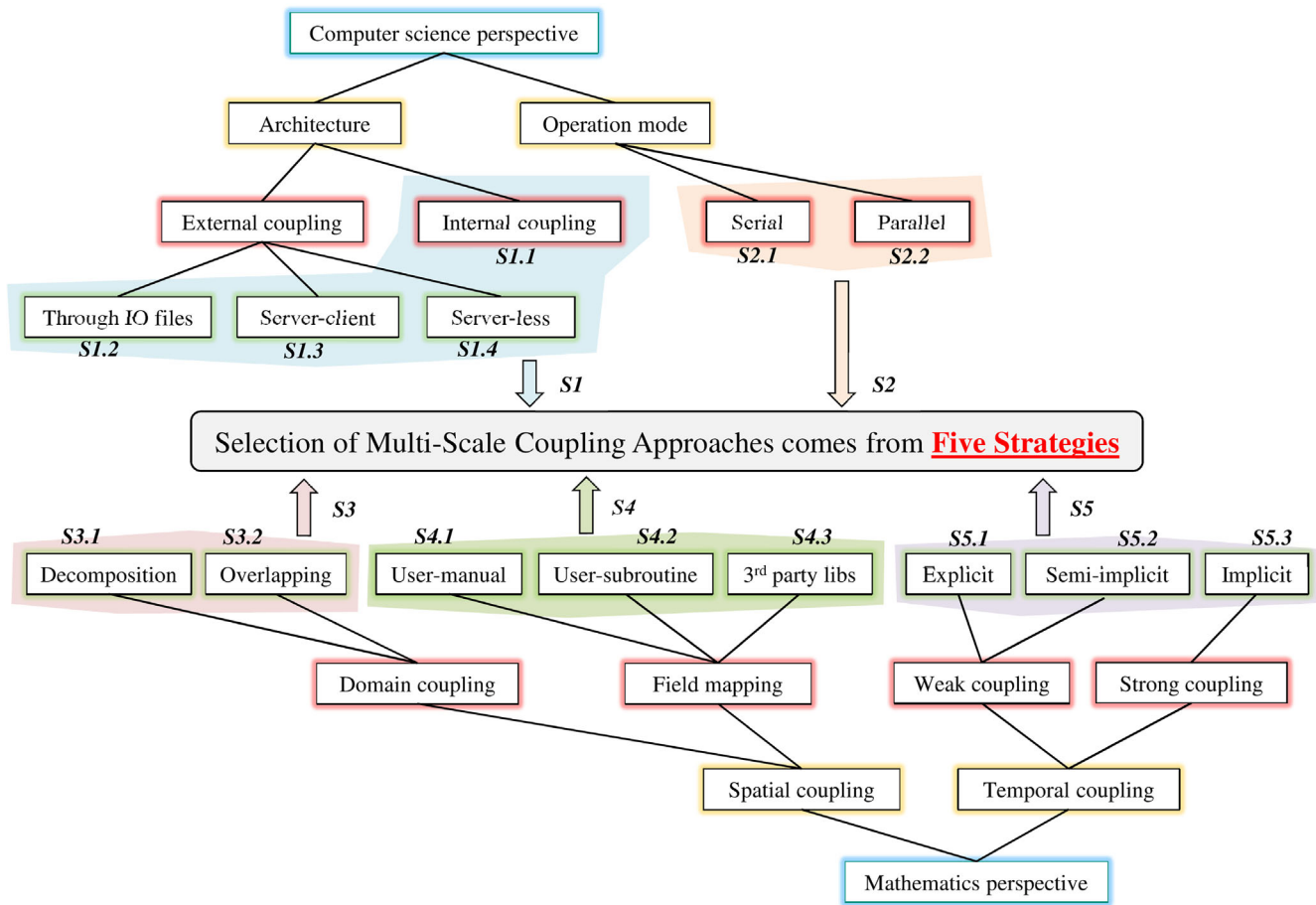
According to the universal standard of classification, there are mainly five challenges for a potential multiscale thermal-hydraulic codes coupling:

1. Selecting coupling architecture. Developers have to balance the complexity and efficiency according to their demands. From S1.1 to S1.4, the coupling architecture is getting more complex but more efficient and flexible.
2. Selecting the operating mode. Normally parallel is better than serial because it is more efficient and has good expandability. However, it is more complicated.
3. Geometry adaption. Developers must specify the relations between the different codes' thermal-hydraulic domains. Different strategies mean distinct developing work.
4. Handling field mapping. The data and field translation between different codes' meshes is always a crucial problem for code coupling. Plenty of work is necessary for this task.
5. Assuring data synchronization. This is the base of a correct coupled simulation. It is the temporal coupling between coupled codes.

If two or more codes are to be coupled, the above five challenges have to be solved and proper approaches have to be carefully selected.



**FIGURE 6** Classification cladogram of the multiscale coupling approaches from the mathematical perspective [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 7** Overall classification of the multiscale coupling approaches and there are five strategies to identify a multiscale coupling system [Colour figure can be viewed at wileyonlinelibrary.com]

**TABLE 1** The evaluation criteria with the weighting factors of the five main coupling strategies

Strategy Group	Evaluation Criteria-Weighting Factor				
<b>S1: Architecture</b>	<b>Efficiency-5</b>	<b>Flexibility-4</b>	<b>Scalability-3</b>	<b>Maintainability-2</b>	<b>Simplicity-1</b>
S2: Operation mode	Efficiency-4	Scalability-3	Maintainability-2	Simplicity-1	
S3: Domain coupling	Robustness-3	Realizability-2	Simplicity-1		
S4: Field mapping	Accuracy-5	Capability-4	Universality-3	Efficiency-2	Simplicity-1
S5: Temporal coupling	Accuracy-4	Robustness-3	Efficiency-2	Simplicity-1	

## 2.2 | Evaluation of the approaches

This section presents and discusses the criteria considered for the selection of the different coupling strategies. On that basis, an evaluation of the coupling approaches is performed. All substrategies shown in Figure 7 are evaluated by a standardized scoring mechanism. From the general perspective of the coupling approaches, the more efficient the better, the more accurate the better, the more stable the better, and the easier the better. The evaluation criteria along with their weighting factors are listed in Table 1.

Three scores are used to evaluate the approaches, where 0 represents poor, 1 for normal, and 2 is good. Regarding the coupling architecture, five criteria were proposed and the corresponding weighting factors were assigned according to their importance to the integral coupling system. The final evaluating scores are calculated in Table 2 and the explanation follows.

1. Efficiency: first of all, the data within an internal coupled system is exchanged via memory, which is the fastest way of data transfer. Nevertheless, the

**TABLE 2** The evaluation of the coupling architectures

S1: Architecture	Effic-5	Flexi-4	Scala-3	Maint-2	Simp-1	Final Score
S1.1 Internal coupling	1	0	0	1	1	$1 \times 5 + 0 \times 4 + 0 \times 3 + 1 \times 2 + 1 \times 1 = 8$
S1.2 IO files coupling	0	0	0	1	2	$0 \times 5 + 0 \times 4 + 0 \times 3 + 1 \times 2 + 2 \times 1 = 3$
S1.3 Server-client	2	1	2	2	0	$2 \times 5 + 1 \times 4 + 2 \times 3 + 2 \times 2 + 0 \times 1 = 24$
S1.4 Server-less	2	2	2	2	0	$2 \times 5 + 2 \times 4 + 2 \times 3 + 2 \times 2 + 0 \times 1 = 28$

interprocess parallel capability is impossible under this architecture. As to the server-client and serverless coupling, though the popular data transfer is through networks and the speed is slower than that via memory, the shared memory could achieve rather high data transfer rate. Moreover, the potential interprocess parallel capability of the two architectures makes it possible to handle big cases by dispersing the tasks to plenty of processors, which will increase the calculation efficiency. These are the reasons why the server-client and serverless coupling architectures make two scores while the internal coupling gets only one. As to the last option—the coupling through IO files—it is actually not a fully independent coupling architecture from the other three. Because the IO data communication must be realized by, at least one of the other three options. Nevertheless, the reason to include it in the lists is that the data transfer is not through neither memory nor networks but files, which is the most inefficient coupling method.

2. Flexibility: the codes involved in a serverless architecture could communicate with each other through their private channels upon demand. It is easy to assign and change specified data at specified channels. While for that in a server-client system, all of the information has to be in the control of one code or a standalone supervisor. Each client code is isolated from the other client codes. Changes or assignments of the transferred data usually go to two channels and the server. So, two scores are for the serverless and one is for server-client. The internal coupling and the IO coupling are the least flexible architectures because everything is frozen once the coupling is established for the former method. Any changes to the data would lead to modifications to the entire coupling system. As to the latter method, the condition is even more complex since new logics have to be developed in order to change the writing or reading content in the files. Therefore, no score was given to these two architectures.
3. Scalability: for the server-client and serverless coupling, the new well-developed component can be conveniently plugged into the coupling system without

significant modifications to the existing codes. Thus, they both get two scores thanks to their good scalability. Because of the same drawback, as explained in the previous paragraph, if new code integration is necessary, the entire existing system of the internal coupling have to be reorganized as an integral and the IO writing and reading logics of the existing IO coupling system have to be updated to include the new components. This is a repeatable and error-prone work, which should be avoided. Thus, no score is assigned to both methods.

4. Maintainability: this character has positive correlations with the flexibility and scalability of the coupled systems. For the server-client and serverless system, the codes update or upgrade could focus on specified components while keeping others untouched. Therefore, they both make two scores. For the internal and IO coupling, as it is mentioned above, no matter where the maintenance takes place, the entire system is affected. This is not the ideal way to maintain the codes while neither the worst way. Therefore, they both get one score here.
5. Simplicity: normally, the IO coupling is the easiest method because there is no need to dig into the code's numerical source but just concerns the input and output logic. The internal coupling is a little bit complex because the codes numeric has to be carefully inspected in order to properly organize the computation sequence of the coupling system. The worst situation regarding simplicity is found in case of the server-client and serverless system because not only the codes numeric should be inspected but also the parallel mechanisms have to pay lots of effort in order to achieve successful synchronization of the codes.

The evaluation of the operation mode is closely relevant to that of the coupling architecture and hence it can be treated as its subset to some extent. The scores are calculated in Table 3. From the evaluation of the coupling architecture, the parallel operation has overwhelming superiority over the serial mode on efficiency and scalability. While conversely, that outstanding superiority results in the complexity of the maintenance and



**TABLE 3** The evaluation of the operation mode

S2: Operation Mode	Effic-4	Scala-3	Maint-2	Simp-1	Final score
S2.1 Serial	0	0	2	2	$0 \times 4 + 0 \times 3 + 2 \times 2 + 2 \times 1 = 5$
S2.2 Parallel	2	2	0	0	$2 \times 4 + 2 \times 3 + 0 \times 2 + 0 \times 1 = 14$

**TABLE 4** The evaluation of the domain coupling options

S3: Domain Coupling	Robust-3	Realize-2	Simp-1	Final score
S3.1 Decomposition	1	0	2	$1 \times 3 + 0 \times 2 + 2 \times 1 = 5$
S3.2 Overlapping	2	2	0	$2 \times 3 + 2 \times 2 + 0 \times 1 = 10$

development of such coupling approaches. It is worth to note that the “parallel” mode here not only refers to the interprocess but also the inprocess parallelization. So, for the internal coupling, though the interprocess parallel is not available, the process itself could be parallelized, eg, the CFD codes. As a consequence, the maintainability here focuses on the entire system while not specified components or functions, which is slightly different from that of the coupling architecture.

Regarding the domain coupling, Table 4 shows the scores assigned to the two options. As explained before, the domain overlapping method is more robust and hence superior compared with the domain decomposition method. The criteria realizability and simplicity are related to the evaluation of the workload for users and developers. Users have to split the integral system code model into several pieces in order to connect with the subchannel or CFD-pieces if the domain-decomposition method is adopted. This is a repeatable, error-prone work and not user-friendly. On the contrary, in the case of the domain overlapping method, the model of the system code can be directly used. The only challenging task is the identification of the proper location in the source code where to get and put data. Moreover, the use of modern mesh manipulation libraries, eg, the MEDCoupling library could simplify this identification work and high-level automation of the domain matching can be implemented. On the contrary, the easier for the user, the more difficult for the developer, so the domain overlapping is rather tough to implement.

Table 5 shows the results of the evaluation of the three field-mapping approaches using the criteria described above. It is worth to note that the scores for the criteria are conditional and assumed to be well-developed.

1. Accuracy: if the users define the mesh relationships, the overlapping and interpolation of the meshes can hardly be calculated correctly unless the meshes are all of the regular shapes and regularly arranged. Poor

mesh mapping may lead to errors. Alternatively, the user can develop special routines to handle this problem in a more convenient and accurate manner. However, this is an open problem depending heavily on the selected method and level of the toolkit. Finally, the third party library is characterized by high accuracy and interpolation functions.

2. Capability: generally speaking, the third party library is more powerful than other alternatives and it can handle more complicated cases than the private subroutines.
3. Universality: the third party library is able to handle various mesh or field mapping types and it is accessible for various coupled codes.
4. Efficiency and simplicity: the third party library has superior capability and can be adapted to various situations and cases. Consequently, the inter logics must be complex and special effort has to be made in order to properly use it. For all other options, the logic can be quite simple and just focus on specified problems. Therefore, they could reach high efficiency compared with the third party libraries.

The last evaluation is related to the temporal coupling. The scores are presented in Table 6. The difference between the three temporal coupling methods has already been well-discussed in Section 2.1. The data convergence between the coupled codes is not guaranteed under explicit coupling while for semi-implicit and implicit, the convergences can be both achieved through inner-iteration techniques and inherent matrix solutions, respectively. This is why both the accuracy and robustness of the last two methods get two scores while the explicit gets one. Moreover, for most cases, the system efficiency keeps growing from explicit, semi-implicit to implicit coupling, as a benefit from the better performance of the convergence. In the opposite direction, the coupling system becomes more complex because of the applied techniques accelerating the convergence rate.

**TABLE 5** The evaluation of the mapping approaches

S4: Field Mapping	Accur-5	Capab-4	Univ-3	Effic-2	Simp-1	Final score
S4.1 User manual	0	0	0	2	2	$0 \times 5 + 0 \times 4 + 0 \times 3 + 2 \times 2 + 2 \times 1 = 6$
S4.2 User subroutine	1	1	0	1	1	$1 \times 5 + 1 \times 4 + 0 \times 3 + 1 \times 2 + 1 \times 1 = 12$
S4.3 third party library	2	2	2	0	0	$2 \times 5 + 2 \times 4 + 2 \times 3 + 2 \times 2 + 0 \times 1 = 24$

**TABLE 6** The evaluation of the temporal coupling options

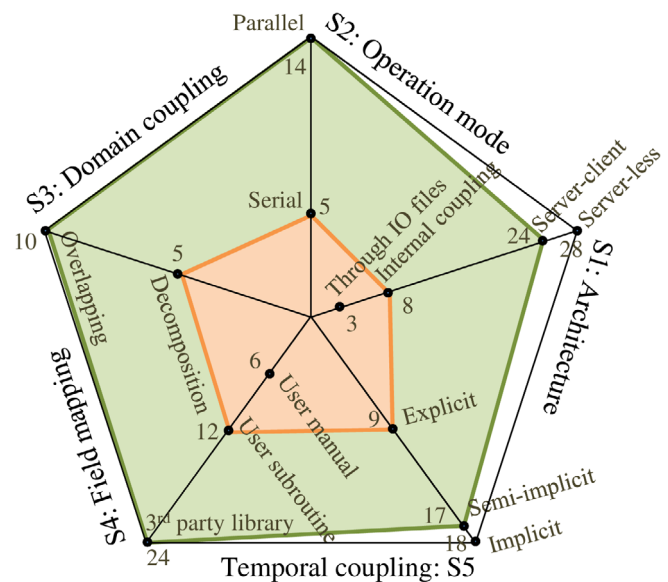
S5: Temporal Coupling	Accur-4	Robust-3	Effic-2	Simp-1	Final score
S5.1 Explicit	1	1	0	2	$1 \times 4 + 1 \times 3 + 0 \times 2 + 2 \times 1 = 9$
S5.2 Semi-implicit	2	2	1	1	$2 \times 4 + 2 \times 3 + 1 \times 2 + 1 \times 1 = 17$
S5.3 Implicit	2	2	2	0	$2 \times 4 + 2 \times 3 + 2 \times 2 + 0 \times 1 = 18$

Considering the above tables for reference, the higher the score is, the better is the performance of the coupling system; or in other words, the more advanced is the coupling system. Moreover, the scores supply a quantitative standard for the selection of the multi-scale coupling approach. Figure 8 shows the main strategies as well as their substrategies unified based on the scores calculated from Table 2 to Table 6. From this Figure, it can be inferred that the level of the coupling system can be represented by the area covered by the closed curves. Two instances are displays in the radar map, the orange pentagon denotes the internal-serial-domain-decomposition-user-subroutine-explicit coupling and the green pentagon denotes the server-client-parallel-domain-overlapping-third-party-library-semi-implicit coupling.

### 3 | A REVIEW OF THE MULTISCALE THERMAL-HYDRAULIC COUPLED CODES

#### 3.1 | Coupling of system code and subchannel code

The first multiscale thermal-hydraulic simulation of a nuclear power plant was done with the coupled code TRAC/COBRA-TF by the Pacific Northwest National Laboratory (PNNL).<sup>55</sup> It was a tight coupling at the level of the governing equations. Another multiscale coupled code of the system and subchannel codes is RELAP5/COBRA-TF developed by Korea Atomic Energy Research Institute (KAERI) where COBRA-TF was merged with RELAP5/MOD3<sup>56</sup> using parallel virtual machines (PVM).<sup>57</sup> This coupled code was verified<sup>58</sup> and finally, it forms the basis of the modern MARS code.<sup>59</sup> Several years later, RELAP5-3D and COBRA-TF were coupled using the PVM at the Bettis Atomic Power Laboratory



**FIGURE 8** Quantized standard for the multi-scale coupling approaches selection [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

(Betti Lab).<sup>60</sup> The new thermal-hydraulic code RELAP7 from the Idaho National Laboratory (INL) contains embedded subchannel capability that may be classified as an implicit coupling approach.<sup>61</sup> The most recent coupling of system and subchannel codes are ATHLET/CTF developed at the Shanghai Jiaotong University (SJTU),<sup>62</sup> Karlsruhe Institute of Technology (KIT)<sup>63</sup> (based on SALOME's<sup>64</sup> MEDCoupling library<sup>44</sup>), and Technical University of Munich (TUM).<sup>65</sup> The system and subchannel thermal-hydraulic coupled codes are summarized in Table 7. In the table, the corresponding coupling approaches according to the classifications in Section 2.1 of those coupled codes are also given.

Moreover, the statics of the classified approaches are given in Figure 9, from which, it could be observed that developers intend to use relatively easier approaches to

**TABLE 7** Review of the multiscale thermal-hydraulic coupling of system and sub-channel codes

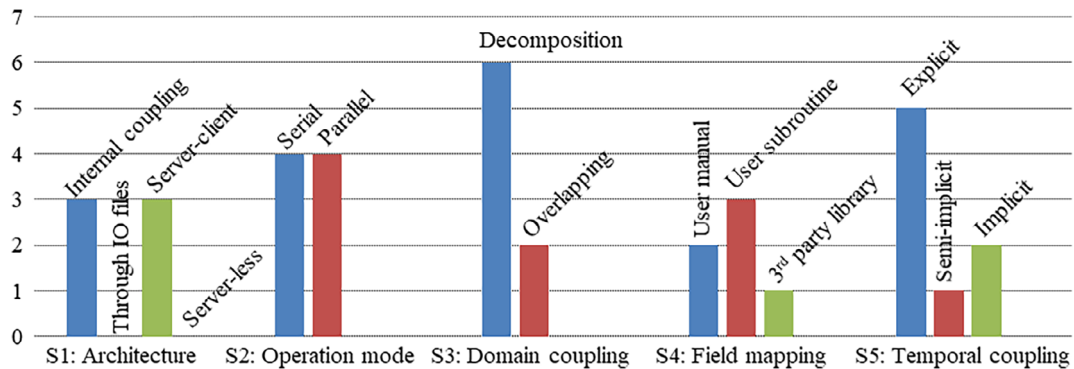
Year	System	Sub or CFD	Developer	S1.1	S1.2	S1.3	S1.4	S2.1	S2.2	S3.1	S3.2	S4.1	S4.2	S4.3	S5.1	S5.2	S5.3	Ref
1983	TRAC	COBRA-TF	PNNL	x				x		x			x				x	Thurgood and George <sup>55</sup>
1992	RELAP5	COBRA-TF	KAERI		x				x	x			x					Lee et al <sup>56</sup>
1999	MARS		KAERI	x				x		x			x					Jeong et al <sup>59</sup>
2002	RELAP5-3D	COBRA-TF	Bettis Lab			x			x	x						x		Aumiller et al <sup>60</sup>
2014	RELAP7			x				x		x							x	Zhang et al <sup>61</sup>
2015	ATHLET	COBRA	SJTU		x						x							Liu and Cheng <sup>62</sup>
2016	ATHLET	COBRA	KIT			x					x			x				Escalante et al <sup>63</sup>
2016	ATHLET	COBRA-TF	TUM						x									Périn <sup>65</sup>

Note: S1.1, internal coupling; S1.2, through IO files; S1.3, server-client; S1.4, serverless; S2.1, serial; S2.2, parallel; S3.1, decomposition; S3.2, overlapping; S4.1, user manual; S4.2, user subroutine; S4.3, third party libs; S5.1, explicit; S5.2, semi-implicit; S5.3, implicit.

implement the coupling system, eg, internal over serverless coupling, serial over parallel coupling, domain-decomposition over overlapping coupling, user-manual definition of field mapping over third party universal libraries, and explicit over implicit coupling. As Section 2.2 stated, complex approaches usually indicate better performance of the coupled codes. The performance here could be the calculation efficiency and accuracy, the system's robustness, and the reliability and extensibility of the coupled codes.

### 3.2 | Coupling of system code and CFD code

It is worth to note that the coupling of system thermal-hydraulic and CFD codes is a major trend in the context of multiscale coupling projects. Different versions of the RELAP5 code were first coupled with CFD code, eg, FLUENT. At INL, an in-deep review of the coupling methodologies and the treatment of the RELAP5-3D mass and energy conservation formulations,<sup>66</sup> the PVMEXEC tools<sup>67</sup> was carried out and base on it the coupling of RELAP-3D and FLUENT was realized.<sup>68</sup> The new capabilities of the RELAP-3D/FLUENT were demonstrated by the analysis of a very high-temperature reactor (VHTR).<sup>69,70</sup> Later on, the Royal Institute of Technology (KTH) investigated the coupling of FLUENT with RELAP5 using novel methods<sup>71,72</sup> where the FLUENT data is used to correlate the closure coefficient, eg, friction coefficients of RELAP5.<sup>73</sup> Another attempt to couple RELAP5 and FLUENT is performed at the University of Illinois at Urbana-Champaign (UIUC).<sup>74</sup> This coupling approach was applied for the analysis of the gas turbine-modular helium reactor (GT-MHR).<sup>75,76</sup> In addition, RELAP5 with FLUENT was also coupled at the Xian Jiaotong University (XJTU), where RELAP5 was compiled as a library (refer to Figure 2) and called by the FLUENT user-defined functions (UDF). It was verified with several cases<sup>77</sup> and went to practical applications.<sup>78</sup> At the University of Fukui (Uni Fukui), RELAP5 was coupled to FLUENT by means of IO-files, UDF, and a RELAP5 restart file.<sup>79</sup> This is a problem-oriented coupled system aiming to simulate the flow instability in steam generator U-tubes. At the University of Pisa (UniPi), RELAP5 was coupled with FLUENT UDF including parallel capability, where a MATLAB-script was written to wrap RELAP5.<sup>80</sup> It was applied for the simulation of natural and forced circulation tests<sup>81</sup> and a heavy liquid metal system—TALL/3D (with a new semi-implicit method).<sup>82</sup> At SCK-CEN, RELAP5-3D is coupled with FLUENT and tested using the data from the lead-bismuth eutectic (LBE)—cooled test loop and facility.<sup>83,84</sup>



**FIGURE 9** Statistical histogram of the system/sub-channel coupling approaches usage [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

It was also applied to the analysis of a protected loss flow transient in an LBE-cooled experimental reactor.<sup>85</sup>

Despite FLUENT, some other CFD or subchannel codes were also coupled to RELAP5 or RELAP5-3D. At Betti Lab, RELAP5-3D was coupled with CFX<sup>86</sup> using PVM and it was the first time where a semi-implicit coupling methodology<sup>87</sup> was implemented into the multiscale thermal-hydraulic analysis.<sup>88,89</sup> At the University of Pisa (UniPi), RELAP5-3D was coupled to CFX with a supervisor.<sup>90</sup>

The system thermal-hydraulic code ATHLET was also coupled with CFX<sup>91</sup> and was tested against the experimental data.<sup>92,93</sup> The coupled code was then applied to some experimental facilities.<sup>94,95</sup> In addition, UJV-Rez coupled ATHLET to FLUENT using IO-files for the data transfer and a supervisor script.<sup>96,97</sup> Additionally, ATHLET was coupled to the open-source code OpenFOAM at KIT<sup>98</sup> and it was applied to simulate the natural convection test of sodium-cooled fast reactor (SFR)—Phénix.

The system code TRACE was first coupled to CFX at Paul the Scherrer Institute (PSI) using the PVM and both explicit and semi-implicit temporal coupling approach.<sup>99</sup> The work was verified using data from the double T-junction experiment and the FLORIS experiment.<sup>100</sup> At the National Tsing Hua University, TRACE was coupled to FLUENT and both the ROCOM test facility and Maanshan Nuclear Power Plant (NPP) were investigated.<sup>101</sup> In addition, TRACE was coupled with the STAR-CCM+ at the University of Michigan. In this peculiar work, the CFD-code provides precise pressure drop to correlate the TRACE friction factors. Moreover, a new technique was developed to force TRACE to reproduce CFD-like velocity profiles. This new approach paved the way for new universal multiscale analysis tool for the nuclear reactor applications. It is able to handle both 1D<sup>102</sup> and 3D<sup>103</sup> cases.<sup>104</sup> In connection with this work, the domain decomposition and overlapping methods<sup>105</sup> are discussed in detail.

Another multiscale coupling approach was implemented at CEA to couple CATHARE with TRIO\_U in 2008. It was applied to the analysis of a gas fast reactor (GFR)<sup>106</sup> and later

on to SFR,<sup>107</sup> ie, for the simulation of the Phenix reactor natural circulation test.<sup>108,109</sup> At KAERI and Seoul National University (SNU), MARS was coupled to the CFD code CUPID<sup>110,111</sup>. These codes were applied to the simulation of tests such as PASCAL, VAPER,<sup>112</sup> and FRIGG and to assess the PWR steam generator (SG).<sup>113</sup> Some other code pairs, eg, SAS4A-SASSYS-1/STAR-CD,<sup>114</sup> CATHERA/STAR-CCM+,<sup>115</sup> and FLOW1D/NPHASE.<sup>116</sup> In different papers,<sup>117-119</sup> the different multiscale coupling approaches are also compared with the coupling methods and the performance.

The coupling of system thermal-hydraulic codes and CFD codes as well as the applied coupling approaches are listed in Table 8 in chronological order.

Figure 10 plots the statistics of the various applied system/CFD coupling approaches. Similar to that of the system/subchannel coupling approach, developers intend to use relatively easier approaches to implement the coupling system.

The coupling of CFD codes and system codes are now the main trend in the nuclear community. Nevertheless, the coupling of subchannel code and system code is also under consistent investigation. As a supplementation, the coupling of a subchannel code and CFD code is also drawing attention nowadays though there are limited cases published, eg, the coupling of TrioCFD with the subchannel code Subchanflow in the University of Science and Technology of China where the domain-decomposition, explicit, and MEDCoupling methods are used. Another such coupled code was in CEA where TrioCFD couples with a subchannel code—Trio MC. Moreover, they are coupled with the system code—CATHARE. This work is under the framework of the ASTRID project for a generation-IV sodium fast reactor.<sup>123</sup>

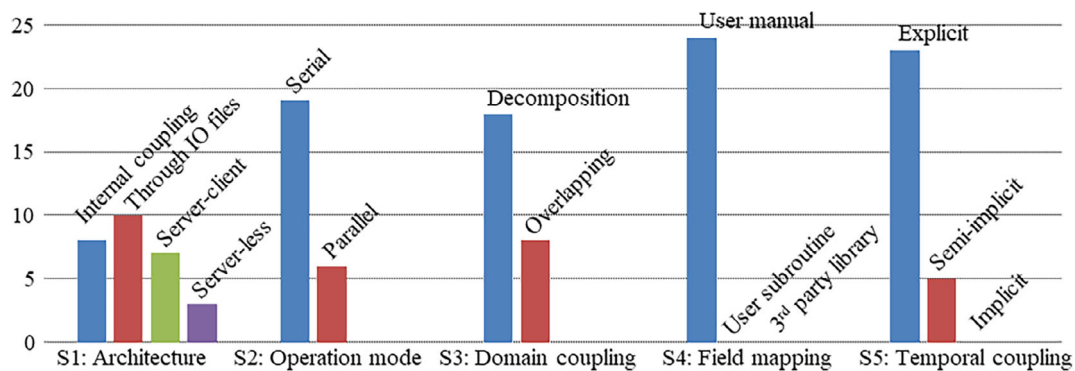
### 3.3 | A special review of the domain overlapping approach

Domain decomposition and domain overlapping are the two options for domain coupling. Since domain overlapping is a new, efficient, promising, but complicated

**TABLE 8** Review of the multi-scale thermal-hydraulic coupling of system and CFD codes

Year	System	Sub or CFD	Developer	S1.1	S1.2	S1.3	S1.4	S2.1	S2.2	S3.1	S3.2	S4.1	S4.2	S4.3	S5.1	S5.2	S5.3	Ref
1999	ATHLET	CFX	FZR					x		x		x						Kliem et al <sup>120</sup>
2001	RELAP5-3D	CFX	Bettis Lab		x			x		x		x			x			Aumiller et al <sup>86</sup>
2002	RELAP5-3D	CFX	Bettis Lab		x			x		x		x			x			Aumiller et al <sup>89</sup>
2002	RELAP5-3D	COBRA-TF	Bettis Lab		x			x		x		x			x			Aumiller et al <sup>60</sup>
2002	RELAP5-3D	FLUENT	INL		x			x		x		x			x			Schultz and Weaver <sup>68</sup>
2008	CATHARE	TRIO_U	CEA			x				x	x				x			Perdu and Vandroux <sup>106</sup>
2009	ATHLET	CFX	GRS							x		x			x			Papakchiev and Lerchl <sup>91</sup>
2009	RELAP5	FLUENT	KTH	x							x	x			x			Cadinu and Kudinov <sup>72</sup>
2010	SAS4A-SASSYS-1	STAR-CD	ANL		x					x	x	x			x			Fanning and Thomas <sup>114</sup>
2011	RELAP5-3D	FLUENT	UIUC		x		x			x		x			x			Yan <sup>76</sup>
2011	TRACE	CFX	PSI				x			x		x			x			Bertolotto <sup>100</sup>
2012	RELAP5	CFX	UniPi		x					x		x			x			Mengali et al <sup>90</sup>
2013	ATHLET	FLUENT	UJV Rez		x					x		x			x			Macek and Vyskoci <sup>96</sup>
2013	ATHLET	OpenFOAM	KIT		x					x		x			x			Huber et al <sup>98</sup>
2013	CATHENA	STAR-CCM+	McMacter		x					x		x			x			Szymanski <sup>115</sup>
2013	MARS	CUPID	KAERI	x						x		x			x			Park et al <sup>110</sup>
2013	RELAP5-3D	STAR-CCM+	ICL		x					x		x			x			Palazzi et al <sup>121</sup>
2013	RELAP5	STAR-CCM+	KTH	x						x		x			x			Cheng and Hassan <sup>122</sup>
2014	ATHLET	CFX	GRS		x					x		x			x			Theodoridis et al <sup>93</sup>
2014	CATHARE2	TRIO_U	CEA			x				x		x			x			Bavière et al <sup>109</sup>
2014	MARS	CUPID	SNU	x						x		x			x			Cho et al <sup>111</sup>
2014	RELAP5	FLUENT	XJTU	x						x		x			x			Li et al <sup>77</sup>
2014	RELAP5	FLUENT	U-fukui		x					x		x			x			Watanabe et al <sup>79</sup>
2014	RELAP5	FLUENT	UniPi		x					x		x			x			Martelli et al <sup>80</sup>
2015	TRACE	FLUENT	NTHU							x		x			x			Ku et al <sup>101</sup>
2016	TRACE	STAR-CCM+	UMICH	x						x		x			x			Grunloh and Manera <sup>102</sup>
2017	RELAP5-3D	FLUENT	SCK-CEN		x		x			x		x			x			Toti et al <sup>83</sup>
2017	TRACE	STAR-CCM+	UMICH	x						x		x			x			Grunloh and Manera <sup>103</sup>

Note. S1.1, internal coupling; S1.2, through IO files; S1.3, server-client; S1.4, serverless; S2.1, serial; S2.2, parallel; S3.1, decomposition; S3.2, overlapping; S4.1, user manual; S4.2, user subroutine; S4.3, third party libs; S5.1, explicit; S5.2, semi-implicit; S5.3, implicit.



**FIGURE 10** Statistical histogram of the system/CFD coupling approaches usage [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

approach in a code coupling picture, it is essential to make a deep investigation of it. Here, a special review of this approach is presented.

In a multiscale domain overlapping simulation, system codes simulate the whole model and subchannel or CFD codes simulate specific components or parts resulting in several obvious overlapped domains. The revealed superiority of the domain overlapping approach over the domain decomposition approach is that the former method is more robust and efficient than the latter one. Meanwhile, another latent advantage of the domain overlapping approach is that the models for coupled and standalone system codes are identical. Thus, no additional modifications are required to transfer models from system code standalone to a coupled version, which is always a compulsory task for a domain-decomposition approach where some additional interfaces have to be defined and added to the original standalone models.

Despite the two superiorities, drawbacks of the domain-overlapping approach are also apparent:

1. intensive alterations to the system code source could go deep down to the governing equation set in order to properly use the data from subchannel or CFD codes since there are no predefined interfaces in the system code receiving the incoming data as updated boundary conditions;
2. as a consequence of the first drawback, in-depth understanding of the source code and heavy programming work are necessary.

Because of the above difficulties, the domain overlapping approach is only applied to limited multiscale coupling cases, despite its seductive superiorities.

### 3.3.1 | CATHARE/TRIO\_U

The first domain overlapping effort for multiscale coupling reported in literature is the development of the

coupling system of a system code—CATHARE and a CFD code TRIO\_U. CATHARE was developed in collaboration between CEA, EDF, IRSN, and AREVA-NP for more than 30 years. It could simulate various types of nuclear reactors including pressurized water reactors, gas-cooled reactors, and heavy metal reactors, etc. TRIO\_U was developed in CEA and is specially designed for industrial CFD calculations on structured and non-structured grids. It was split into the TRUST platform and an open-source CFD code—TrioCFD in 2015.

Their coupled pair was first presented and used for transient analysis in a GFR, in which the two involved codes were equipped with a generic API and were coordinated by a third supervisor.<sup>106</sup> The simulated transient was a blackout scenario where the whole reactor is modeled with CATHARE while only the 3D upper plenum is modeled with TRIO\_U. During the coupling calculation, CATHARE provides coolant mass flow rate and temperature at the core outlet as the inlet boundary conditions of TRIO\_U, while the outflow coolant mass flow rate from CATHARE was used as the TRIO\_U outlet boundary condition instead of the classical imposed pressure outlet. After completing a step forward, TRIO\_U gives feedback on the coolant temperature exiting the plenum and no further hydraulic feedbacks is available for CATHARE correlations.

An advanced application of the coupled codes to the Phénix SFR to better simulate the significant 3D TH phenomena due to nonsymmetrical situations or local buoyancy effects was mentioned in Tenchine et al<sup>107</sup> and was then minutely described by Bavière.<sup>109</sup> Moreover, it was further compared with a domain-decomposition coupled pairs—ATHLET/OpenFOAM in Piale.<sup>118</sup> This application also adopts a domain overlapping approach where the CFD domain is restricted to the core whereas the system code domains include both the core and the loops with their components. During the coupling calculation, CATHARE supplies coolant mass flow rate and enthalpy both as the inlet and outlet boundary conditions for

TRIO\_U from the experience gained from the last application to GFR. TRIO\_U then gives feedback of enthalpy and pressure difference at the codes' joint boundaries to CATHARE forcing, which reproduces the CFD-like TH results.

Compared with the application to GFR, the SFR application includes the pressure correlation. However, for both of them, only the physical fields locating downstream after the overlapped domains were correlated in the system codes, while the fields in the overlapped domains of the system code were never touched or correlated.

### 3.3.2 | SAS4A/SASSYS-1/STAR-CD

SAS4A/SASSYS-1 was a nuclear system code developed by the US Argonne National Laboratory, which was originally developed for SFR while now extended to other liquid metal reactors. STAR-CD is the legacy CFD package of CD-adapco which is a commercial CFD code with a wide range of applications including buoyancy-driven flows and heat transfer. The first coupling attempt was performed with a 4S facility model whose main bodies are a core and an outlet plenum. Kind of a domain overlapping method was applied here since SAS4A/SASSYS-1 models the whole facility while STAR-CD simulates the outlet plenum. However, this case can be hardly classified as classical coupling because the new thermal-hydraulic boundary data of STAR-CD was simply exported from SAS4A/SASSYS-1 while no feedback was available in the reverse direction. In other words, it is a so-called “one-way” coupling.

Later on, with the same facility, the capability of the coupled pair was improved by implementing feedbacks from STAR-CD to SAS4A/SASSYS-1 and the correlations now are on the fly.<sup>114</sup> During the coupling calculation, the thermal-hydraulic parameters, eg, coolant mass flow rate, temperature, and pressure are transferred from SAS4A/SASSYS-1 as updated inlet and outlet boundary conditions to STAR-CD. Once the CFD code finishes the current step calculation, the pressure difference was added to the plenum inlet in the system code to correlate its total pressure drop and mass flow rate. The system temperature is correlated in a little bit complicated but similar way. Apparently, all of the fine feedback from STAR-CD to SAS4A/SASSYS-1 performs only in the boundary nodes. Though the pressure field in the overlapped domain of the system model was quasi-correlated due to the additional pressure source at the plenum inlet, the field distribution does not reflect the CFD results. This is a similar spatial coupling approach as that of CATHARE/TRIO\_U.

### 3.3.3 | RELAP5/STAR-CCM+

RELAP5 is the outstanding system code by the US NRC, and STAR-CCM+ is the commercial CFD software which is one of the featured products of CD-adapco since 2004. This coupling work was carried out under the European project THINS which devoted to the development and validation of advanced multiscale simulation tools for Gen IV reactors.<sup>124,125</sup> The LBE thermal-hydraulic loop TALL-3D which has three vertical “legs” and a pool-type 3D test section was used to test the coupled pair, in which, RELAP5 models the entire facility while only the 3D test section was simulated by STAR-CCM+. From the perspective of modeling, this is a domain overlapping coupling, but the limitation is that the feedback from CFD codes only takes place at the boundaries of the overlapped domains in the system codes. Especially, the feedback in this case only contains coolant temperature by adding a so-called “virtual heater,” which is assumed having extremely high thermal conductivity and extremely low heat capacity to the outlet of the overlapped domain in the system model. Similar to CATHARE/TRIO\_U, only the downstream after the 3D test section could be influenced.

### 3.3.4 | RELAP5/FLUENT

A refreshing method was invented for the coupling of RELAP5 and FLUENT, which is significantly different from the previous three attempts and points out the most promising direction for the domain overlapping approach. In this coupled pair, the feedback from CFD codes no longer only takes place at the codes' joint boundaries but to the entire overlapped domains of the system codes. Benefit from this feature, the system codes now could produce CFD-like fields in the entire overlapped domains. Different from the typical additional source term method (ASTM), the fine-resolution fields from CFD codes are now used to update the energy loss coefficients caused by form and friction in the system code. It behaves differently from directly appending fixed sources or sinks to the governing equations, thus force system code produces CFD-like pressure drop and distribution in a more logical and robust manner.

This method uses data from FLUENT to close the RELAP5 equation set, thus was named to “closure-on-demand”<sup>71</sup> or “coupling-by-closure”<sup>72</sup> method. It inspected the motion equation of RELAP5 in detail and drops the calculation units of the convective pressure drop as well as the form-friction pressure drop from the equation and use the total pressure drop from FLUENT

to represent the two drop items by imposing the two effects all into the form-friction loss coefficient. It is worth to note here that the correlation is only for the pressure field since only the motion equation was modified. Moreover, this work is a “one-way” coupling since only data from FLUENT was passed to RELAP5 while nothing was done to update FLUENT boundary conditions. Another clue indicating this is a not well-developed coupling work is that the synchronization between RELAP5 and FLUENT is not guaranteed because the correlations performed with pretty large time intervals compared with the real transient time step size. At the very beginning of the development work, the results of FLUENT were first processed forming a reference data table. Then the correlations to RELAP5 were evaluated on the fly by linear interpolation from the table values. Even for the follow-up strengthened method where the correlations from CFD were written in the RELAP5 restart file for potential usage, it is still not that a convenient and automatic way for efficient coupling.

Despite the insufficient development of the coupled code—RELAP5/STAR-CCM+, the idea using CFD data to calculate closure coefficients for the whole overlapped domain in the system code is the most precious highlight and figuring out the most effective direction to implement domain-overlapping coupling.

### 3.3.5 | TRACE/STAR-CCM+

Following the basic idea from the previous coupling work of RELAP5/FLUENT, a new coupled pair of the US NRC system code TRACE and the CFD code STAR-CCM+ was developed. The updated boundary conditions of STAR-CCM+ first come from a complete step of TRACE and then its fine fields are used to calculate the new closure coefficients for TRACE, forcing which produce CFD-like TH distributions in the entire overlapped domain. This coupled pair works well for both 1D<sup>102</sup> and 3D<sup>104</sup> system models. And as a supplement to the correlation for convective and form-friction pressure drops in RELAP5/FLUENT, the initial effect was also well-examined and eliminated from the total pressure drop from STAR-CCM+ to counteract the non-erasable initial pressure drop in TRACE motion equation. What's more, the velocity fields in the system overlapped domain could be correlated by applying a newly developed “velocity matching faces (VMF)” method to reconstruct the disrupted inner-relationship between the pressure and velocity fields. Another highlight of this work is the in-depth exploration and optimization of the performance of this domain overlapping coupling approach, and as a consequence of which the inertial domain overlapping

(IDO) and stabilized IDO (SIDO) methods were put forward.

This is the first well-developed coupled code using the closure-updated method for domain overlapping coupling where the feedback is bidirectional and the data synchronization is strictly ensured by adopting an operator splitting (OP) temporal coupling method.<sup>54</sup> For the test phase, various academic cases were applied and the results were quite encouraging.

## 4 | CONCLUSION

Multiscale thermal-hydraulic analysis and code coupling for nuclear power system simulations are increasingly becoming a promising area nowadays. Within the scope, the particular capabilities of nuclear system codes, sub-channel codes, and CFD codes are combined together to better describe and predict physical phenomena inside a nuclear power system. This paper classifies the multiscale coupling approaches to five main strategies: coupling architecture, operation mode, domain coupling, field mapping, and temporal coupling. Each of the five main strategies is further classified into several subcategories in order to cover all possible coupling approaches. Consequently, the paper puts forward a standard summarizing and classifying the multiscale thermal-hydraulic coupling approaches. On the basis of the standard, the paper evaluates those classified approaches based on a new-proposed criterion. Quantized scores are graded to the approaches, thus researchers now have a clear and logical guideline when planning the coupling project and selecting appropriate coupling methods. Furthermore, a general review of the multiscale thermal-hydraulic coupled codes including the coupling of system code and subchannel code and the coupling if system code and CFD code is made based on the standard. The review helps researchers have clear picture of the history and development sequence of the coupled codes. Especially, a review of the domain overlapping approach is made considering it is the most promising but challenging method for multiscale thermal-hydraulic simulation. In short, this work supplies a reference for future multiscale simulation tools' development. It is an effort to standardize the nomenclature and selection of the multiscale thermal-hydraulic coupling procedures.

## ACKNOWLEDGEMENT

The authors wish to acknowledge the support of the China Scholarship Council (CSC) (201506340031) as well as of the Helmholtz-Gemeinschaft NUSAFE Program (FE533000840012) of Karlsruhe Institute of Technology (KIT).



**ORCID**Kanglong Zhang  <https://orcid.org/0000-0002-8883-9788>**REFERENCES**

- Kessides IN. Nuclear power: understanding the economic risks and uncertainties. *Energy Policy*. 2010;38:3849-3864.
- M. M. Abu-Khader, "Recent advances in nuclear power: a review," *Progress in Nuclear Energy*, vol. 51, no. 2, pp. 225-235. <https://doi.org/10.1016/j.pnucene.2008.05.001>, 2009.
- Zeng M, Liu Y, Ouyang S, Shi H, Li C. Nuclear energy in the post-Fukushima era: research on the developments of the Chinese and worldwide nuclear power industries. *Renew Sustain Energy Rev*. 2016;58:147-156.
- Saghafi M, Ghofrani MB. Accident management support tools in nuclear power plants: a post-Fukushima review. *Progress in Nuclear Energy*. 2016;92:1-14.
- Guelfi A, Bestion D, Boucker M, et al. NEPTUNE: a new software platform for advanced nuclear thermal hydraulics. *Nuclear Science and Engineering*. 2007;156(3):281-324.
- D'Auria F, Galassi G. Scaling in nuclear reactor system thermal-hydraulics. *Nuclear Engineering and Design*. 2010;240(10):3267-3293.
- Petruzzi A, D'Auria F. Thermal-hydraulic system codes in nuclear reactor safety and qualification procedures. *Science and Technology of Nuclear Installations*. 2008;2008(3):1-16, 2007.
- Höhne T, Krepper E, Rohde U. Application of CFD codes in nuclear reactor safety analysis. *Science and Technology of Nuclear Installations*. 2010;2010(3):1-8, 2009.
- Bestion D, Lucas D, Anglart H, Niceno B, Vyskocil L. Multi-scale thermal hydraulic analyses performed in NURESIM and NURISP projects. *20th International Conference on Nuclear Engineering and the ASME 2012 Power Conference*. California, U.S.: Anaheim; 2012.
- Niceno B, Sato Y, Badillo A, Andreani M. Multi-scale modeling and analysis of convective boiling towards the prediction of CHF in rod bundles. *Nuclear Engineering and Technology*. 2010;42(6):620-635.
- Bestion D. From the direct numerical simulation to system codes—perspective for the multi-scale analysis of LWR thermal hydraulics. *Nuclear Engineering and Technology*. 2010;42:608-619.
- Bestion D. "System Code Models and Capabilities," *THICKT-2008, INIS-IT--008*. Italy: Vitanza; 2018.
- RELAP5-3D, "RELAP-3D home," 2019. [Online]. Available: <https://relap53d.inl.gov/SitePages/Home.aspx>. [Accessed September 25, 2019].
- TRACE. *TRACE V5.1051 Theory Manual*. Washington DC: Division of Safety Analysis Office of Nuclear Regulatory Research U. S. Nuclear Regulatory Commission; 2016.
- G. Lerchl, H. Austregesilo, G. H., H. M. and L. W., "ATHLET mod 3.0 cycle A," Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, GRS-P-1, Cologne, 2012.
- Emonot P, Souyri A, Gandrille J, Barre F. CATHARE-3: a new system code for thermal-hydraulics in the context of the NEPTUNE project. *Nuclear Engineering and Design*. 2011;241(11):4476-4481.
- R. K. Salko and M. N. Avramova, "COBRA-TF subchannel thermal-hydraulic code (CTF) theory manual," Pennsylvania State University, CASL-U-2015-0054-000, State College, 2015.
- CORBA-FLX-Team, "COBRA-FLX: a core thermal-hydraulic analysis code: technical report," AREVA NP inc, ANP-100311NP, Washington D.C. U.S., 2010.
- Y. Sung, P. Schueren and A. Meliksetian, "VIPRE-01 modeling and qualification for pressurized water reactor non-LOCA thermal-hydraulic safety analysis," Westinghouse Electric Company, WCAP-15306-NP-A, Pittsburgh, U.S., 1999.
- Toumi I, Bergeron A, Gallo D, Royer E, Caruge D. FLICA-4: a three-dimensional two-phase flow computer code with advanced numerical methods for nuclear applications. *Nuclear Engineering and Design*. 2000;200(1-2):139-155.
- Sanchez V, Imke U, Ivanov A. SUBCHANFLOW: a thermal-hydraulic sub-channel program to analyse fuel rod bundles and reactor cores. *17th Pacific Basin Nuclear Conference, ISBN: 978-607-95174-1-0*. Cancun, Mexico: Sociedad Nuclear Mexicana; 2010.
- Imke U, Sanchez V, Gomez R. SUBCHANFLOW: a new empirical knowledge based subchannel code. *Jahrestagung Kerntechnik*. Berlin: Germany; 2010.
- Moorthi A, Sharma AK, Velusamy K. A review of sub-channel thermal hydraulic codes for nuclear reactor core and future directions. *Nuclear Engineering and Design*. 2018;332:329-344.
- Cheng Z, Rao Y. Strategies for developing subchannel capability in an advanced system thermal hydraulic code: a literature review. *AECL Nuclear Review*. 2015;4(1):23-41.
- Kucukboyaci V, Sung Y. COBRA-TF parallelization and application to PWR reactor core subchannel DNB analysis. *ANS MC2015 – joint International Conference on Mathematics and Computation(M&C), Supercomputing Nuclear Applications (SNA) and the Monte Carlo (MC) Method, ISBN: 978-0-89448-720-0, CASL-U-2015-0167-000*. Nashville: American Nuclear Society; 2015.
- Jeong J, Yoon H, Park I, Cho H. The CUPID code development and assessment strategy. *Nuclear Engineering and Technology*. 2010;42(6):636-655.
- Runchal A, Sagar B. "PORFLOW: A Multifluid Multiphase Model for Simulating Flow, Heat Transfer, and Mass Transport in Fractured Porous Media," *Nuclear Regulatory Commission, NUREG/CR--5991; CNWRA--92--003 ON: TI93008514*. Washington, DC, U.S.: U.S. Department of Energy, Office of Scientific and Technical Information; 1993.
- Chavez VJ, Imke U, Sanchez-Espinoza V. TWOPORFLOW: a two-phase flow porous media code, main features and validation with BWR-relevant bundle experiments. *Nuclear Engineering and Design*. 2018;338:181-188.
- M. Ilvonen, V. Hovi and P. Inkinen, "PORFLO development, applications and plans in 2008-2009," VTT Technical Research Centre of Finland, VTT-R-01414-10, Finland, 2010.
- C. Calvin and D. Nowak, *Handbook of Nuclear Engineering: 12 High-Performance Computing in Nuclear Engineering*, Boston, MA, U.S.: Springer, DOI: <https://doi.org/10.1007/978-0-387-98149-9>, ISBN: 978-0-387-98130-7, 2010.
- Mahaffy J, Chung B, Dubois F, et al. *Best Practice Guidelines for the Use of CFD in Nuclear Reactor Safety Applications*. Paris: Nuclear Energy Agency, Committee on Safety of Nuclear Installations, NEA/CSNI/R(2014)11; 2007.
- Böttcher M. Detailed CFX-5 study of the coolant mixing within the reactor pressure vessel of a VVER-1000 reactor

- during a non-symmetrical heat-up test. *Nuclear Engineering and Design*. 2008;238:445-452.
33. Böttcher M, Krüßmann R. Primary loop study of a VVER-1000 reactor with special focus on coolant mixing. *Nuclear Engineering and Design*. 2010;240:2244-2253.
  34. Cheng JP, Yan LM, Li FC. CFD simulation of a four-loop PWR at asymmetric operation conditions. *Nuclear Engineering and Design*. 2016;300:591-600.
  35. Cheng W, Ferng Y, Chen S, Chieng C. Development of CFD methodology for investigating thermal-hydraulic characteristics in a PWR dome. *Nuclear Engineering and Design*. 2015; 284:284-292.
  36. Bestion D. The difficult challenge of a two-phase CFD modeling for all flow regimes. *Nuclear Engineering and Design*. 2014;279:116-125.
  37. Yadigaroglu G. Computational fluid dynamics for nuclear applications: from CFD to multi-scale CMFD. *Nuclear Engineering and Design*. 2005;235(2-4):153-164.
  38. Mañes JP, Espinoza VHS, Vicent SC, Böttcher M, Stieglitz R. Validation of NEPTUNE-CFD two-phase flow models using experimental data. *Science and Technology of Nuclear Installations*. 2014;2014:1-19.
  39. Krepper E, Lucas D, Frank T, Prasser H-M, Zwart P. The inhomogeneous MUSIG model for the simulation of polydispersed flows. *Nuclear Engineering and Design*. 2008; 238:1690-1702.
  40. Antal S, Ettorre S, Kunz R, Podowski M. *Development of a Next Generation Computer Code for the Prediction of Multicomponent Multiphase Flows*. State College: Pennsylvania State University; 2000 pp. 1-10.
  41. IAEA. "Use and Development of Coupled Computer Codes for the Analysis of Accidents at Nuclear Power Plants," IAEA-TECDOC-1539. Vienna, Austria: IAEA; 2007.
  42. F. D'Auria, A. B. Salah, G. Galassi, J. Vedovi, F. Reventós, A. Cuadra, J. Gago, A. Sjöberg, M. Yitbarek, O. Sandervåg, N. Garis, C. Anher, J. Aragonés, G. Verdù, R. Mirò, D. Ginestar, A. Sánchez, F. Maggini, J. Hadek, J. Macek and K. Ivanov, "Neutronics/thermal-hydraulics coupling in LWR technology, state-of-the-art report," Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, ISBN: 92-64-02084-5, NEA No. 5436, CRISSUE-S - WP2, Paris, 2004.
  43. Bousbia-Salah A, D'Auria F. Use of coupled code technique for best estimate safety analysis of nuclear power plants. *Progress in Nuclear Energy*. 2007;49(1):1-13.
  44. MED, "MEDCoupling developer's guide," SALOME-platform, 2019. [Online]. Available: <http://docs.salome-platform.org/latest/dev/MEDCoupling/developer/index.html>. [Accessed April 2, 2019].
  45. Chorin A. Numerical solution of the Navier-stokes equations. *Mathematics of Computation*. 1968;22(104):745-762.
  46. Zhang H, Guo J, Lu J, Li F, Xu Y, Downar TJ. An assessment of coupling algorithms in HTR simulator TINTE. *Nuclear Science and Engineering*. 2018;190:287-309.
  47. Hamilton S, Berrill M, Clarno K, et al. An assessment of coupling algorithms for nuclear reactor core physics simulations. *J Comput Phys*. 2016;311:241-257.
  48. Zhang H, Guo J, Li F, Xu Y, Downar T. The improvement of coupling method in TINTE by fully implicit scheme. *Nuclear Science and Engineering*. 2018;190:156-175.
  49. Knoll D, Keyes D. Jacobian-free Newton-Krylov methods: a survey of approaches and applications. *J Comput Phys*. 2004; 193:357-397.
  50. Aragonés JM, Ahnert C, Cabellos O, García-Herranz N, Aragonés-Ahnert V. Methods and results for the MSLB NEA benchmark using SIMTRAN and RELAP-5. *Nuclear Technology*. 2004;146:29-40.
  51. Walker H, Ni P. Anderson acceleration for fixed-point iterations. *SIAM Journal on Numerical Analysis*. 2011;49:1715-1735.
  52. Yeckel A, Lun L, Derby JJ. An approximate block Newton method for coupled iterations of nonlinear solvers: theory and conjugate heat transfer applications. *J Comput Phys*. 2009;228: 8566-8588.
  53. Zhang H, Guo J, Li F, Xu Y, Downar T. Efficient simultaneous solution of multi-physics multi-scale nonlinear coupled system in HTR reactor based on nonlinear elimination method. *Annals of Nuclear Energy*. 2018;114:301-310.
  54. Zerkak O, Kozłowski T, Gajev I. Review of multi-physics temporal coupling methods for analysis of nuclear reactors. *Annals of Nuclear Energy*. 2015;84:225-233.
  55. M. J. Thurgood and T. L. George, "COBRA/TRAC—a thermal-hydraulics code for transient analysis of nuclear reactor vessels and primary coolant systems," Pacific Northwest Laboratory, NUREG/CR-3046 PNL- 4385, Richland, 1983.
  56. Lee SY, Jeong JJ, Kim S-H, Chang SH. COBRA/RELAP5: a merged version of the COBRA-TF and RELAP5/MOD3 codes. *Nuclear Technology*. 1992;99:177-186.
  57. A. Geist, "PVM3 User's guide and reference manual," Oak Ridge National Laboratory, ORNL:TM-12187, Oak Ridge, 1995.
  58. Jeong J-J, Sim SK, Ban CH, Park CE. Assessment of the COBRA/RELAP5 code using the LOFT L2-3 large-break loss-of-coolant experiment. *Annual of Nuclear Energy*. 1997;24(14): 1171-1182.
  59. Jeong J-J, Ha K, Chung B, Lee W. Development of a multi-dimensional thermal-hydraulic system code, MARS 1.3.1. *Annals of Nuclear Energy*. 1999;26:1611-1642.
  60. Aumiller DL, Tomlinson ET, Bauer RC. Incorporation of COBRA-TF in an integrated code system with RELAP5-3D using semi-implicit coupling. *RELAP5 International Users Seminar*. Utah: Park City; 2002.
  61. H. Zhang, L. Zou, H. Zhao and R. Martineau, "Developing fully coupled subchannel model in RELAP-7," Idaho National Laboratory Originating Organization, INL/EXT-14-33102, Idaho, 2014.
  62. Liu X, Cheng X. Sub-channel/system coupled code development and its application to SCWR-FQT loop. *Nuclear Engineering and Design*. 2015;285:39-47.
  63. Escalante J, Marcello V, Espinoza V, Perin Y. Application of the ATHLET/COBRA-TF thermal-hydraulics coupled code to the analysis of BWR ATWS. *Nuclear Engineering and Design*. 2017;321:318-327.
  64. SALOME, "SALOME-the open source integration platform for numerical simulation," CEA, EDF, Open Cascade, 2019. [Online]. Available: <https://www.salome-platform.org/>. [Accessed July 8, 2019].
  65. Y. Périn *Thesis: Development of a Multi-Physics Multi-Scale Simulation Tool for LWR Safety Analysis* München: Technischen Universität München <https://mediatum.ub.tum.de/doc/1311657/1311657.pdf> 2016

66. Weaver WL. A mass and energy conserving form of explicit coupling for use with RELAP5-3D. *RELAP5 International Users Seminar*. Park City, Utah; 2002.
67. Weaver WL. *The Application Programming Interface for the PVMEXEC Program and Associated Code Coupling System*. Idaho: Idaho National Laboratory, INL/EXT-05-00107; 2005.
68. Schultz RR, Weaver WL. Coupling the REALP5-3D advanced system analysis code with commercial and advanced CFD software. *Technical Meeting Use of CFD Codes for Safety Analysis of Reactor Systems, Including the Containment*, ISBN: 92-0-111003-0. Pisa, Italy: International Atomic Energy Agency; 2002.
69. N. A. Anderson, *Thesis: Coupling RELAP5-3D and FLUENT to Analyze a Very High Temperature Reactor (VHTR) Outlet Plenum*. Provo: Brigham Young University, URL: <http://hdl.handle.net/1969.1/4160>, 2006.
70. Schultz R, Weaver W, Schowalter D, Basu N. Evaluating fluid behavior in advanced reactor systems using coupled computational fluid dynamics and systems analysis tools. *ICONE-13: the 13th International Conference on Nuclear Engineering*, ISBN: 7-5022-3400-4. Beijing, China: Atomic Energy Press; 2005.
71. Cadinu F, Kozlowski T, Kudinov P. A closure-on-demand approach to the coupling of CFD and system thermal-hydraulic codes. *NUTHOS-7: the 7th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety*. Seoul, Korea: Korea Advanced Institute of Science and Technology; 2008.
72. Cadinu F, Kudinov P. Development of a “coupling-by-closure” approach between CFD and system thermal-hydraulics codes. *NURETH-13: the 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*. Ishikawa Prefecture, Japan: Kanazawa City; 2009.
73. Cadinu F, Kozlowski T, Dinh T-N. Relating system-to-CFD coupled code analyses to theoretical framework of a multi-scale method. *ICAPP 2007: International Congress on Advances in Nuclear Power Plants*, ISBN: 9781604238716, Paper ID: 7539. France: Nice; 2007.
74. Yan Y, Uddin R, Kim K. A coupled CFD-system code development and application. *PHYSOR 08: International Conference on the Physics of Reactors 2008*, ISBN: 9781617821219. Switzerland: Interlaken; 2008.
75. Yan Y, Rizwan-uddin. Coupled CFD-system-code simulation of a gas cooled reactor. *M&C 2011: International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering*, ISBN: 978-85-63688-00-2. RJ, Brazil: Rio de Janeiro; 2011.
76. Y. Yan, *Thesis: Development of a Coupled CFD-System-Code Capability (with a Modified Porous Media Model) and its Application to Simulate Current and Next Generation Reactors*, Urbana-Champaign: University of Illinois at Urbana-Champaign, <http://hdl.handle.net/2142/29660>, 2011.
77. Li W, Wu X, Zhang D, Su G, Tian W, Qiu S. Preliminary study of coupling CFD code FLUENT and system code RELAP5. *Annals of Nuclear Energy*. 2014;73:96-107.
78. Feng T, Zhang D, Song P, et al. Numerical research on water hammer phenomenon of parallel pump-valve system by coupling FLUENT with RELAP5. *Annals of Nuclear Energy*. 2017; 109:318-326.
79. Watanabe T, Anoda Y, Takano M. System-CFD coupled simulations of flow instability in steam generator U tubes. *Annals of Nuclear Energy*. 2014;70:141-146.
80. Martelli D, Forgone N, Barone G, Nevo AD, Piazza ID, Tarantino M. Coupled simulations of natural and forced circulation tests in NACIE facility using RELAP5 and ANSYS Fluent codes. *ICONE 22: the 22nd International Conference on Nuclear Engineering*, DOI: 10.1115/ICONE22-30552. Prague, Czech Republic: American Society of Mechanical Engineers; 2014.
81. Martelli D, Forgone N, Barone G, Piazza I d. Coupled simulations of the NACIE facility using RELAP5 and ANSYS FLUENT codes. *Annals of Nuclear Energy*. 2017;101:408-418.
82. Angelucci M, Martelli D, Barone G, Piazza ID, Forgone N. STH-CFD codes coupled calculations applied to HLM loop and pool systems. *Science and Technology of Nuclear Installations*. 2017;2017:1-13. <https://doi.org/10.1155/2017/1936894>.
83. Toti A, Vierendeels J, Belloni F. Improved numerical algorithm and experimental validation of a system thermal-hydraulic/CFD coupling method for multi-scale transient simulations of pool-type reactors. *Annals of Nuclear Energy*. 2017;103:36-48.
84. Toti A, Vierendeels J, Belloni F. Extension and application on a pool-type test facility of a system thermal-hydraulic/CFD coupling method for transient flow analyses. *Nuclear Engineering and Design*. 2018;331:83-96.
85. Toti A, Vierendeels J, Belloni F. Coupled system thermal-hydraulic/CFD analysis of a protected loss of flow transient in the MYRRHA reactor. *Annals of Nuclear Energy*. 2018;118: 199-211.
86. Aumiller D, Tomlinson E, Bauer R. A coupled RELAP5-3D: CFD methodology with a proof-of-principle calculation. *Nuclear Engineering and Design*. 2001;205:83-90.
87. Weaver W, Tomlinson E, Aumiller D. A generic semi-implicit coupling methodology for use in RELAP5-3D. *Nuclear Engineering and Design*. 2002;211:13-26.
88. Aumiller D, Tomlinson E, Weaver W. “An Integrated RELAP5-3D and Multiphase CFD Code System Utilizing a Semi-Implicit Coupling Technique,” in *RELAP5 International Users Seminar*. Idaho: Sun Valley; 2001.
89. Aumiller D, Tomlinson E, Weaver W. An integrated RELAP5-3D and multiphase CFD code system utilizing a semi-implicit coupling technique. *Nuclear Engineering and Design*. 2002;216:77-87.
90. L. Mengali, M. Lanfredini, F. Moretti and F. D’Auria, “Stato dell’arte sull’accoppiamento fra codici di sistema e di fluidodinamica computazionale Applicazione generale su sistemi a metallo liquido pesante,” University of Pisa, RdS-2012-052, <http://hdl.handle.net/10840/4449>, Pisa, 2012.
91. Papukchiev A, Lerchl G. Extension of the simulation capabilities of the 1D system code ATHLET by coupling with the 3D CFD software package ANSYS CFX. *NURETH-13: The 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*. Kanazawa City, Ishikawa Prefecture, Japan: Atomic Energy Society of Japan; 2009.
92. Papukchiev A, Lerchl G. Extension and application of the coupled 1D-3D thermal-hydraulic code ATHLET-ANSYS CFX for the simulation of liquid metal coolant flows in advanced reactor concepts. *International Conference on Nuclear*

- Engineering Collocated with the ASME 2012 Power Conference*, DOI: 10.1115/ICONE20-POWER2012-54872. California, USA: Anaheim; 2012.
93. Theodoridis G, Papukchiev A, Scholz D, Lerchl G. A new data-driven ATHLET-ANSYS CFD coupling method for efficient simulation of nuclear power plant circuits. *ICAPP 2014: International Conference on Nuclear Engineering*, ISBN: 978-0-89448-776-7. Prague, Czech Republic: American Nuclear Society; 2014.
  94. Geffray C, Macián-Juan R. Multi-scale 2D sensitive analysis of the TALL-3D experiment. *ICONE 2014: International Conference on Nuclear Engineering*, DOI: 10.1115, ICONE22-31022. Prague, Czech Republic: American Society of Mechanical Engineers; 2014.
  95. Geffray C, Macián-Juan R. Multi-scale uncertainty and sensitivity analysis of the TALL-3D experiment. *Nuclear Engineering and Design*. 2015;290:154-163.
  96. Macek J, Vyskoci L. Simulation of SDA opening test at VVER-1000 NPP by coupling system of ATHLET, DYN3D and FLUENT codes. *NURETH-15: the 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics*, ISBN: 978-88-902391-2-0. Pisa, Italy: Grafiche Caroti - Pisa; 2013.
  97. Vyskocil L, Macek J. Coupling CFD code with system code and neutron kinetic code. *Nuclear Engineering and Design*. 2014;279:210-218.
  98. Huber K, Zhou C, Sonntag M, Cheng X, Otic I. Coupled ATHLET-OpenFOAM calculations for PHENIX natural convection test. *NURETH-15: the 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics*, ISBN: 978-88-902391-2-0. Pisa, Italy: Grafiche Caroti - Pisa; 2013.
  99. Bertolotto D, Manera A, Frey S, Prasser H-M, Chawla R. Single-phase mixing studies by means of a directly coupled CFD/system-code tool. *Annals of Nuclear Energy*. 2009;36:310-316.
  100. D. Bertolotto, *Thesis: Coupling a System Code with Computational Fluid Dynamics for the Simulation of Complex Coolant Reactivity Effects*, Villigen, Switzerland: Paul Scherrer Institute, DOI: <https://doi.org/10.5075/epfl-thesis-5227>, 2011.
  101. Ku Y, Tseng Y, Yang JH, Chen S, Wang J, Shin C. Developments and applications of TRACE/CFD model of Maanshan PWR pressure vessel. *NURETH-16: 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, ISBN: 978-0-89448-722-4. Chicago, U.S.: American Nuclear Society; 2015.
  102. Grunloh T, Manera A. A novel domain overlapping strategy for the multiscale coupling of CFD with 1D system codes with applications to transient flows. *Annals of Nuclear Energy*. 2016;90:422-432.
  103. Grunloh T, Manera A. A novel multi-scale domain overlapping CFD/STH coupling methodology for multi-dimensional flows relevant to nuclear applications. *Nuclear Engineering and Design*. 2017;318:85-108.
  104. T. P. Grunloh, *A Novel Multi-Scale Domain Overlapping CFD/STH Coupling Methodology for Multi-Dimensional Flows Relevant to Nuclear Applications*, Michigan: University of Michigan, <http://hdl.handle.net/2027.42/133243>, 2016.
  105. Grunloh TP, Manera A. Comparison of overlapping and separate domain coupling methods. *NURETH-16: 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, ISBN: 978-0-89448-722-4. Chicago, USA: American Nuclear Society; 2015.
  106. Perdu F, Vandroux S. System / CFD coupling for reactor transient analysis. An application to the gas fast reactor with CATHARE and TRIO\_U. *ICAPP 2008 International Congress in Advances in Nuclear Power Plants*, ISBN: 0-89448-061-8. CA USA: Anaheim; 2008.
  107. Tenchine D, Baviere R, Bazin P, et al. Status of CATHARE code for sodium cooled fast reactors. *Nuclear Engineering and Design*. 2012;245:140-152.
  108. Baviere R, Tauveron N, Perdu F, Garré E. System-CFD coupled simulation of the PHENIX reactor natural circulation test. *NURETH-15: the 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics*, ISBN 978-88-902391-2-0. Pisa, Italy: Grafiche Caroti - Pisa; 2013.
  109. Baviere R, Tauveron N, Perdu F, Garré E, Li S. A first system/CFD coupled simulation of a complete nuclear reactor transient using CATHARE2 and TRIO U. preliminary validation on the Phénix reactor natural circulation test. *Nuclear Engineering and Design*. 2014;277:124-137.
  110. Park I, Lee SLJR, Yoon H, Jeong J. An implicit code coupling of 1-D system code and 3-D in-house CFD code for multi-scaled simulations of nuclear reactor transients. *Annals of Nuclear Energy*. 2013;59:80-91.
  111. Cho HK, Cho YJ, Yoon HY. Heat structure coupling of CUPID and MARS for the multi-scale simulation of the passive auxiliary feedwater system. *Nuclear Engineering and Design*. 2014;273:459-468.
  112. H. Y. Yoon, I. K. Park and C.-H. Song, "Multi-scale thermal-hydraulic of safety systems of advanced PWRs using the CUPID code," in *NURETH-16: 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, ISBN: 978-0-89448-722-4, Chicago, USA, 2015.
  113. Lee JR, Yoon HY. Preliminary study for a PWR steam generator with CUPID/MARS multi-scale thermal-hydraulics simulation. *Appl Therm Eng*. 2017;115:1245-1254.
  114. T. H. Fanning and J. W. Thomas, "Advances in coupled safety modeling using systems analysis and high-fidelity methods," Argonne National Laboratory, DOI: <https://doi.org/10.2172/982349>, ANL-GENIV-134, Oak Ridge, U.S., 2010.
  115. P. Szymanski, *Thesis: Modeling RD-14M Header Conditions: Coupling of STAR-CCM+ and CATHENA*, Hamilton, Ontario, Canada: McMaster University, <https://macsphere.mcmaster.ca/bitstream/11375/13403/1/fulltext.pdf>, 2013.
  116. H. Gibeling and J. Mahaffy, "Benchmarking simulations with CFD to 1-D coupling," in *Technical Meeting on Use of Computational Fluid Dynamics (CFD) Codes for Safety Analysis of Reactor Systems, Including Containment*, ISBN: 92-0-111003-0, Pisa, Italy, 2002.
  117. Papukchiev A. Multiscale analysis of forced and natural convection including heat transfer phenomena in the TALL-3D experimental facility. *NURETH-16: the 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, ISBN: 978-0-89448-722-4. Chicago, USA: American Nuclear Society; 2015.
  118. Pialla D, Tenchine D, Li S, et al. Overview of the system alone and system/CFD coupled calculations of the PHENIX natural circulation test within the THINS project. *Nuclear Engineering and Design*. 2015;290:78-86.
  119. Bandini G, Polidori M, Gerschenfeld A, et al. Assessment of systems codes and their coupling with CFD codes in thermal-hydraulic applications to innovative reactors. *Nuclear Engineering and Design*. 2015;281:22-38.

120. Kliem S, Höhne T, Rohde U, Weiß F-P. Main steam line break analysis of a VVER-440 reactor using the coupled thermal hydraulics system/3D-neutron kinetics code DYN3D/ATHLET in combination with the CFD. *NURETH-9: Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, ISBN:0894486500 9780894486500. San Francisco: California; 1999.
121. Palazzi A, Bluck MJ, Lo S. A coupled RELAP5-3D/STAR-CCM+ simulation for the calculation of friction factor in pipes. *ICAPP 2014: the International Congress on Advances in Nuclear Power Plants*, ISBN: 978-0-89448-776-7. USA: Charlotte; 2014.
122. Cheng X, Hassan Y, eds. Thermal-hydraulic of innovative nuclear system (THINS). *Nuclear Engineering and Design*. 2015;290:1-164.
123. A. Gerschenfeld, S. Li, Y. Gorsse and R. Lavastre, "Development and Validation of Multi-Scale Thermal-Hydraulics Calculation Schemes for SFR Applications at CEA," Yekaterinburg, Russian Federation, 2017.
124. Jeltsov M, Kööp K, Kudinov P, Villanueva W. Development of a domain overlapping coupling methodology for STHCFD analysis of heavy liquid metal thermal-hydraulics. *NURETH-15: the 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics*, ISBN: 978-88-902391-2-0. Italy: Pisa; 2013.
125. Papukchiev A, Jeltsov M, Kööp K, Kudinov P, Lerchl G. Comparison of different coupling CFD-STH approaches for pre-test analysis of a TALL-3D experiment. *Nuclear Engineering and Design*. 2015;290:135-143.

**How to cite this article:** Zhang K. The multiscale thermal-hydraulic simulation for nuclear reactors: A classification of the coupling approaches and a review of the coupled codes. *Int J Energy Res*. 2020; 44:3295–3315. <https://doi.org/10.1002/er.5111>