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Assessing multi-dimensional thermal effects with NACIE-UP coupled analysis

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1. Introduction

The ENEA (Italian national agency for new technologies, energy and the environment) has designed, constructed, and is operating the NACIE-UP (NAtural CIrculation Experiment-Upgrade), a natural circulation loop experimental device using liquid metal LBE (Lead-Bismuth Eutectic) as the working fluid [1]. This program shares its benchmark results through the IAEA CRP [2]. It includes unprotected loss of flow transient experiments and provides both one-dimensional and three-dimensional data to enable the validation of safety analysis and coupled analysis tools.

Korea Atomic Energy Research Institute (KAERI) utilized this data for the validation of the GAMMA+ code [3] for Sodium-cooled Fast Reactors (SFR).

LBE exhibits properties similar to those of liquid sodium in terms of pressure drop and heat transfer. The benchmark geometry of the heated section represents a typical configuration in a SFR's fuel assemble. KAERI is engaged in the benchmark program to validate the GAMMA+ code within the SFR framework. Nonetheless, the 1-D based system code is limited in its capacity to model complex geometries, such as wire-wrapped fuel pins, in detail.

To avoid such issues, the use of Computational Fluid Dynamics (CFD) may be considered. However, using CFD alone to analyze the entire system can be challenging due to difficulties in simulating two-phase flow, control logic, etc., and it can be time-consuming. Under these conditions, coupled analysis between CFD-TH system codes is feasible. This allows for the advantages of each program to be utilized and can also be expected to improve accuracy.

The study is based on the benchmark experimental data (ADP 06) to analyze the multi-dimensional effects, compares them with CFD coupled analysis results, and confirms the necessity of coupled analysis.

2. Methods

2.1 Overview of experimental apparatus

Fig. 1 illustrates the primary system of the NACIE-UP test apparatus. The loop is composed of a fuel pin simulator (FPS), a cooler (pressurized water-cooled perfusion-type heat exchanger), an expansion tank, and a thermal flow meter. No pumps are installed within the loop, and forced circulation of the coolant is achieved using a gas lifting method by injecting argon gas. The secondary system cools the primary system using pressurized water at 16 bar, and boiling does not occur during the experiment. Fig. 2 displays the design specifications of the FPS. 19 fins, equipped with wire spacers, are installed within a hexagonal duct; detailed specifications are presented in Table I.

Fig. 1 NACIE-UP primary system

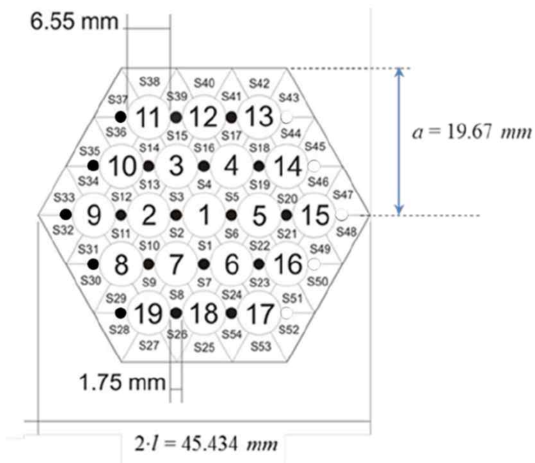

Fig. 2 Cross-section of the FPS

Table I: FPS design specifications

Parameter	Value	Parameter	Value
D_{pin}	6.55 mm	P/D	1.2824

$Pitch_{pin}$	8.4 mm	L_{total}	2000 mm
D_{wire}	1.75 mm	L_{active}	600 mm
$Pitch_{wire}$	262 mm	D_H	3.84 mm

2.2 ADP 06 experimental conditions

Fig. 3 presents the experimental conditions for ADP 06. Of the 19 fins, only the central seven generated heat at 30 kW. The experiment started from steady state 1 conditions which simulated forced-convection flow using argon gas injection with 10 Nl/min. After ~1000 sec later, gas injection suddenly stopped and the flow transited to steady state 2 conditions. Under steady state 2 conditions, flow occurred due to natural convection. The flow rate and temperature of the water on the secondary side were maintained at 10 m³/h and 170°C, respectively.

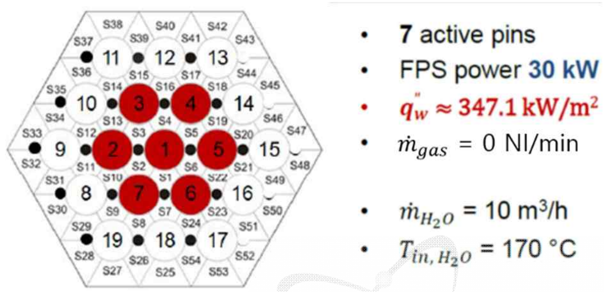

Fig. 3 ADP 06 steady-state 2 conditions

2.3 1-D GAMMA+ modeling approach

As shown in Fig. 4, the entire loop system was modeled by dividing it into fluid domains and solid domains (gray). The fluid regions in the riser and expansion tank, where argon gas and LBE are mixed, are modeled as two-phase flow. The expansion tank has a free liquid surface, and all argon gas exits through the gas circulation system. The two valves in the experimental loop are simulated using form loss pressure coefficients. A 10 cm insulation layer is also considered, and the thermal conductivity and external environment (10°C) are applied as stated in reference [2]. For the FPS, the Cheng and Todreas pressure drop correlation [4] and the modified Schad heat transfer correlation (P/D < 1.3) [5], which are applied to SFR fuel assemblies, are used. The modified Chexal & Lellouche slip model [6] was considered to LBE properties.

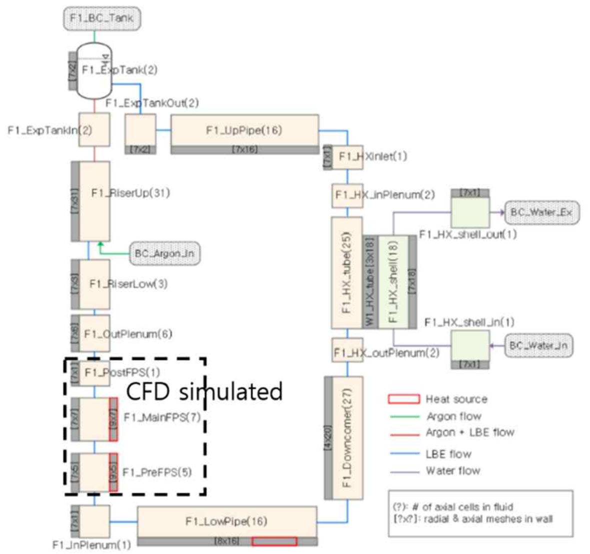

Fig. 4 GAMMA+ 1-D nodalization

2.4 CFD coupling approach of FPS

To examine the merit of the CFD coupled analysis, the steady state 2 conditions were analyzed in this work. CFD analysis was utilized to model the PreFPS, MainFPS, and half of the postFPS sections as depicted in Fig. 4, under the assumption of fully developed flow conditions inferred from measured temperatures. The reason for simulating half of the postFPS is to apply the outlet pressure from the CFD to the postFPS in the GAMMA+ code during coupled analysis.

In the CFD simulation, pressure drop calculations were performed using the Reynolds-Averaged Navier-Stokes equations. Detailed information on the CFD analysis model is presented in Table II.

Table II: CFD analysis model information

CFD code	STAR-CCM+
Governing equations	Steady, gravity
Discretization	2nd-order
Turbulence model	k- ω SST
# of meshes	112,351,679
Y+	0.64

The logic for coupling between CFD-TH system codes is as shown in Fig. 5. For steady-state calculations, the flow rate, inlet temperature, and outlet pressure calculated in GAMMA+ are input into CFD, and the outlet flow rate, outlet temperature, and inlet pressure calculated in CFD are input into GAMMA+. As shown in Fig. 6, based on the code coupling classification [7], the methods of in-line, sequential, and decomposition were adopted.

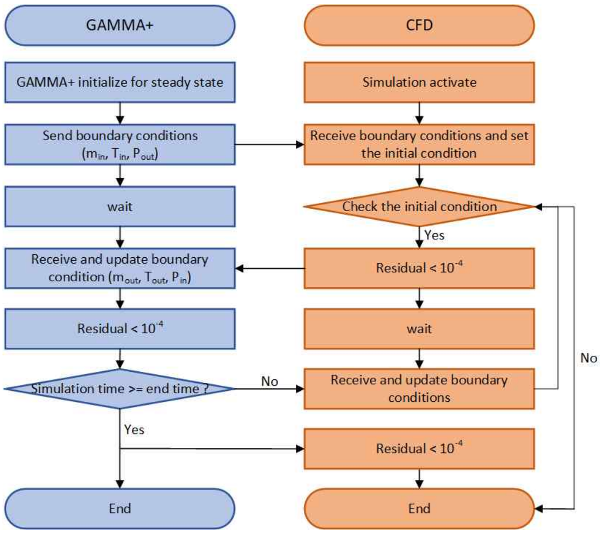

Fig. 5 Coupling logic for steady state

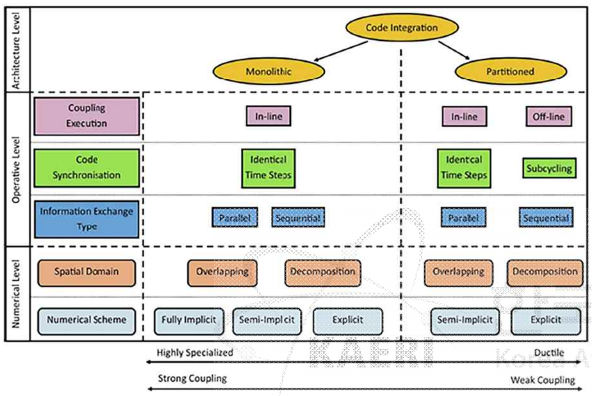

Fig. 6 Code coupling classification [7]

3. Results

Before validating the three-dimensional data, it was confirmed, as shown in Fig. 7 and 8, that the GAMMA+ results match well with globally measured variables such as the LBE flow rate, FPS, and heat exchanger outlet temperatures. To evaluate the multi-dimensional effects in FPS, the surface temperature calculation results for three representative pins are compared as shown in Table III. (Fig. 8 shows the locations where the coupling analysis results were extracted.) Obviously, the coupled analysis results show more accurate predictions. The error values used in the table are calculated using equation (1). It should be noted, in addition, the coupled analysis has a merit of providing a detailed temperature information as shown in Fig. 9.

$$\text{error } [\%] = \frac{x_{calculated} - x_{exp}}{x_{exp}} \times 100 \qquad (1)$$

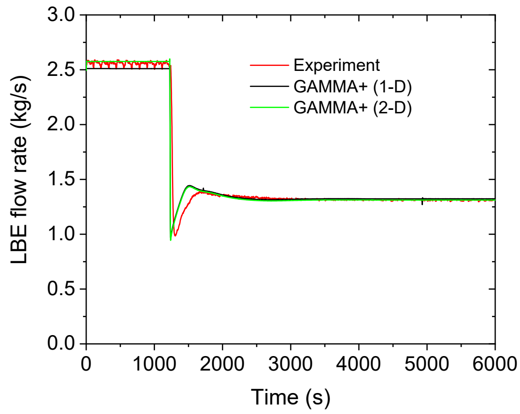

Fig. 7 Comparison between LBE flow rate: GAMMA+ calculations and experimental results

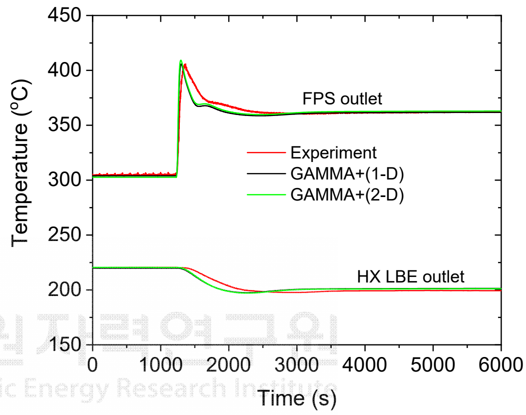

Fig. 8 Comparison between primary loop temperatures: GAMMA+ calculations and experimental results

Table III: Difference between analyzed temperatures and experimental values of steady state 2

	Pin 1	Pin 5	Pin 19
GAMMA+ 1-D model	-8.0%	-6.8%	20.3%
Coupled	0.2%	0.0%	0.8%

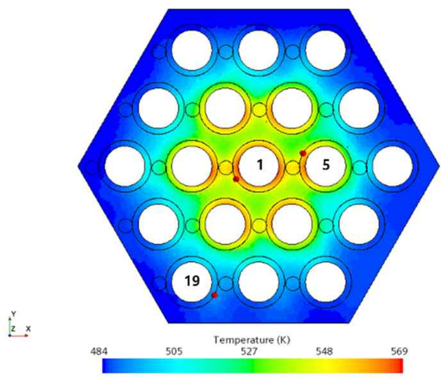

Fig. 9 Fluid and solid temperature distribution using coupled analysis (temperature measurement locations at 1, 5, 19-pin cladding)

4. Conclusions

In this study, a coupled analysis using CFD and GAMMA+ was used to validate the ADP06 data from the NACIE-UP experiment. As a result, it was found that the prediction accuracy can be significantly improved using the coupled analysis. Temperature difference of --8.0% to 20.3% in the GAMMA+ stand-alone result is reduced to -0.0% to 0.8% in the coupled calculation

As a follow-up study to this research, a transient analysis of the NACIE-Up experiment through coupling can be performed.

It is expected that the CFD-TH system code coupling can contribute to improvement on numerical predictions of multi-dimensional thermo-fluid phenomena in a pool type SFR.

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