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CFD Analysis and Benchmarking of XX09 Subassembly for EBR-II Shutdown Heat Removal Tests SHRT-45

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1. Introduction

EBR-II, also known as the Experimental Breeder Reactor II, was designed and constructed by the Argonne National Laboratory (ANL) in 1964 and operated in Idaho. Functioning as a sodium-cooled reactor, EBR-II had a thermal output of 62.5MW and an electrical output of 20MW. During its early stages, EBR-II was operated with the aim of demonstrating the feasibility of a closed fuel cycle reactor by using only uranium as an addition.

In 1984, the experiment SHRT-45 was conducted to prove its ability to safely remove decay heat without core damage under anticipated abnormal conditions and severe accidents at a liquid metal reactor power plant. The SHRT-45 experiment tested a loss-of-flow accident scenario where the operation of primary and secondary pumps was stopped and the reactor protection system did not function. A Liquid Metal Cooled Reactor (LMR) is a type of nuclear reactor system that utilizes liquid metal, typically lead or sodium, as the coolant, operating under high temperature and pressure conditions. LMRs offer numerous advantages compared to traditional water-cooled reactors, including high heat transfer capability and fuel efficiency [1,2].

Performance prediction is a crucial aspect of LMR design and operation. To achieve these objectives, advanced modeling and simulation techniques such as Computational Fluid Dynamics (CFD) is employed. CFD is a computational tool used to numerically model various physical phenomena, including fluid flow, heat transfer, and mass transport.

In this paper, we present a study that compares and validates the performance results obtained using CFD for the EBR-II. The objective of this study is to evaluate the flow, heat transfer of EBR-II under specific operating conditions using CFD to compare the results of this code to verify their reliability and consistency. This study aims to provide guidelines for the selection and application of credible modeling tools in LMR design and operation.

2. Plant and Test Overview

2.1 Plant Overview

EBR-II is a loop-type nuclear reactor that is connected by pipes from the primary system to the intermediate heat exchanger. Figure 1 depicts the schematic diagram of the EBR-II plant. The reactor operates using liquid sodium, and the primary system and intermediate heat exchanger are filled with a pool of approximately 340 m^3 of sodium at a temperature of 371°C.

The EBR-II plant is equipped with two main pumps that draw sodium from the pool and supply it to the high-pressure inlet plenum and the low-pressure inlet plenum. The high-pressure inlet plenum accounts for about 85% of the total flow and delivers sodium to the core region. In contrast, the low-pressure inlet plenum supplies sodium to the outer blanket region.

The heated sodium from the subassemblies gathers in a common upper plenum and is then supplied to the intermediate heat exchanger through the Z-pipe. After undergoing heat exchange in the intermediate heat exchanger, the sodium goes back to the pool and the cycle repeats. The intermediate heat exchanger utilizes the heat received from the primary system to cool down via the superheater and steam generator. By exchanging heat in the intermediate heat exchanger, the sodium carries the heat back to the primary system, and this process is cyclically repeated. This enables the heat generated in the primary system to be cooled down through the superheater and steam generator, forming a complete cycle.

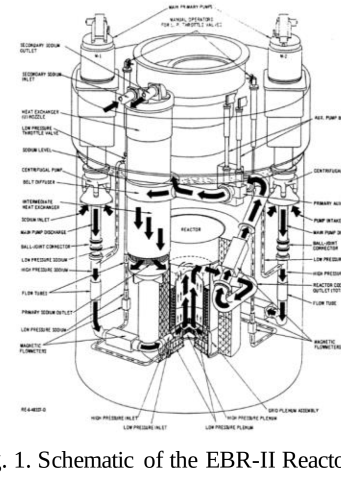

Fig. 1. Schematic of the EBR-II Reactor[1]

2.2 XX09 Subassembly Overview

XX09 was designed to provide benchmark validation data, and it is a fuel assembly equipped with various sensors as depicted in Fig 2, 3. The shape information of the aggregate is shown in Table I. It has 61 pins, out of which 59 are driver fuel pins.

Thermocouples are placed on the space wires of 22 individual pins to provide temperature profiles. The MTC is a thermocouple attached at a height of 0.172 meters, the TTC is attached at a height of 0.322 meters, and the 14TC is attached at a height of 0.48 meters.

In this paper, validation and comparison with Computational Fluid Dynamics (CFD) were conducted using the XX09 Experiment data [3].

Table I: XX09 Subassembly Geometry Parameter

Parameter[unit]	XX09
Clad Outer/Inner diameter [mm]	4.419/3.81
Pin pitch [mm]	5.664
Spacer wire diameter [mm]	1.2446
Spacer wire pitch [mm]	152.4
Total pin length [mm]	612
Heated length [mm]	343

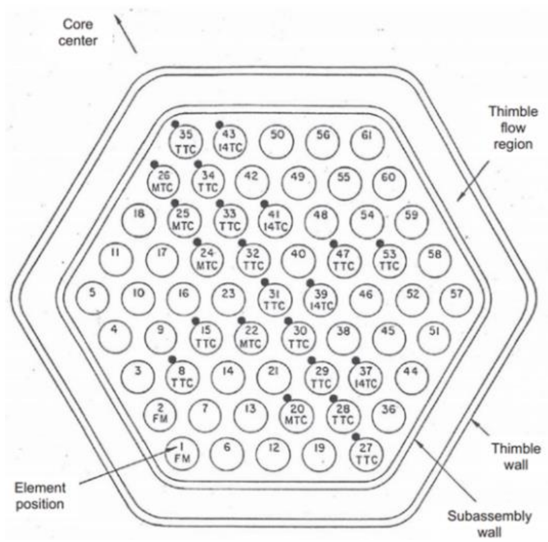

Fig. 2. XX09 Instrumented Subassembly Cross-section[1]

2.3 SHRT-45 Test

The SHRT-45 experiment was conducted to demonstrate the passive feedback effects in EBR-II. The experiment simulated an unprotected Loss of Flow (LOF) accident by tripping the main pumps in the primary system and the pumps in the intermediate system. The auxiliary EM pump was not shut down, and the reactor protection system was not activated. As the SHRT-45 test progressed, the reactor power decreased due to reactivity feedback. The initial conditions of the experiment are presented in Table II.

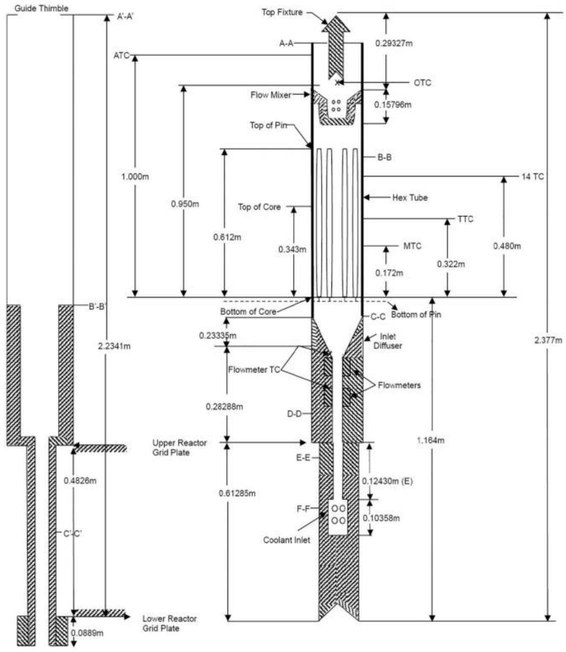

Fig. 3. XX09 Instrumented Subassembly Vertical Cross-section[1]

Table II: EBR-II SHRT-45 Test Initial Conditions

Parameter [unit]	Values and Condition
Initial Power [MW]	60
Initial core flow [kg/s]	481.01
Initial core inlet temperature [K]	616.92
Reactor protection system	No Activation

3. CFD Methodology and Grid System

3.1 CFD Methodology

Figure 4 presents a schematic overview of the XX09 subassembly of EBR-II, utilized for CFD analysis. The simulation encompasses the representation of pins and spacer wires. The boundary conditions are specified in Table III.

The analysis was conducted using the Ansys CFX software, and the SST turbulence model was employed for the simulations [4].

Table III: SHRT-45 XX09 CFD Boundary Condition

Parameter [unit]	XX09
Inlet Temperature [K]	616.4
Inlet mass flow [kg/s]	2.427
Qin [kW]	379.8
Working Fluid	sodium

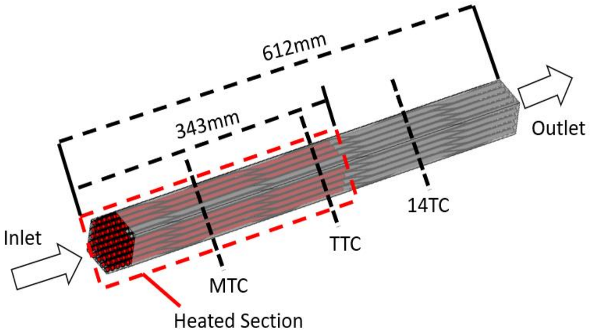

Fig. 4. EBR-II XX09 Subassembly CFD Schematic

3.2 Grid System

The grid configuration of the XX09 subassembly is depicted in Fig 5, consisting of 14,400,000 aligned grids. An innovative grid generation method was applied using a Fortran-based in-house code. To simulate heat transfer, two interface elements were added by creating additional grids of rods and wires. By accurately simulating the actual wire shape without distortion, more precise predictions of the contact area between the wire and the rod can be made.

Simulation results using this methodology have demonstrated the ability to accurately predict pressure drop and perform flow analysis of the fuel assembly [5,6].

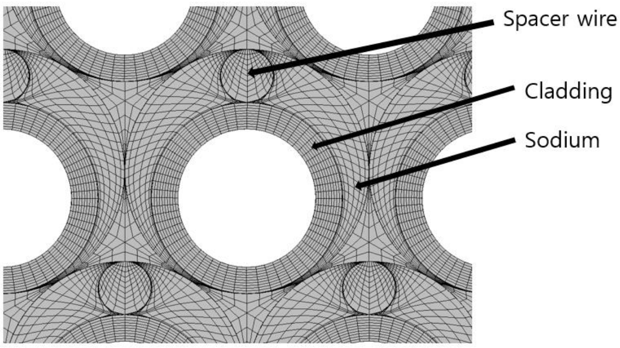

Fig. 5. Computational Grid System of XX09

4. Result

4.1 Steady-state CFD Result

The temperature results at the TTC location of the XX09 subassembly during the EBR-II SHRT-45 accident are presented in Fig 6, respectively. The maximum temperature of sodium within the cross-section was determined to be 762K. The maximum discrepancy between the measured values and the CFD results was 12.7% at TTC 34 Pin. The RSME(Root mean square error) between the experimental and CFD for TC Temperature at TTC Location is 8.86%.

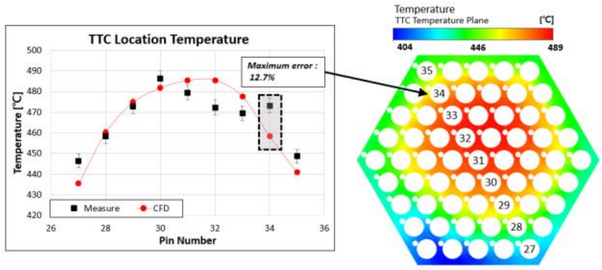

Fig. 6. XX09 Subassembly TTC Location Temperature Profile and Contour

The temperature results at the 14TC location of the XX09 subassembly during the EBR-II SHRT-45 accident are presented in Fig 7, respectively. The maximum temperature of sodium within the cross-section was determined to be 754K. The maximum discrepancy between the measured values and the CFD results was 4.9% at 14TC 39 Pin. The RSME between the experimental and CFD for TC Temperature at 14TC Location is 3.57%.

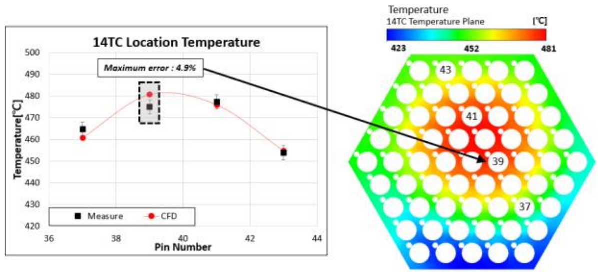

Fig. 7. XX09 Subassembly 14TC Location Temperature Profile and Contour

Figure 8 depicts the flow field at the TTC location of the XX09 subassembly. It was observed that the velocity distribution within the subassembly shows higher velocities near the duct walls compared to the center. The analysis of three vortex structures induced by the wire wrap was conducted, demonstrating that the thickness of the boundary layer is reduced, which enhances heat transfer performance and equalizes the temperature distribution.

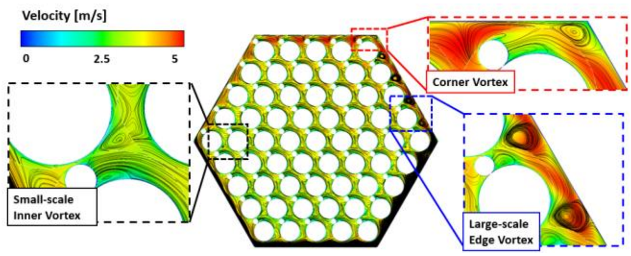

Fig. 8. XX09 Subassembly TTC Location Velocity and Streamline

5. Conclusions

EBR-II (Experimental Breeder Reactor II) was a sodium-cooled fast reactor designed and constructed to demonstrate the feasibility of a closed fuel cycle reactor. The SHRT-45 experiment proved its capability to safely remove decay heat without core damage even under severe accident conditions. This research evaluated the flow and heat transfer of EBR-II under operational conditions using Computational Fluid Dynamics (CFD), thereby verifying the reliability and consistency of modeling tools. Validation and comparison using XX09 Experiment data confirmed the accuracy of CFD in predicting pressure drops, flow analysis, and temperature predictions within the nuclear fuel assembly. Notably, during the SHRT-45 accident scenario, the maximum temperature differences at the TTC and 14TC locations were measured to be 12.7% and 4.9%, respectively, demonstrating CFD's capability to closely predict experimental values.

ENDNOTES

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