CFD-Aided Design of a Small Modular SFR

Churl Yoon*, Huee-Youl Ye, Jae Hyuk Eoh
Versatile Reactor Technology Development Division, Korea Atomic Energy Research Institute,
111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon 34057, Korea
**E-mail: cyoon@kaeri.re.kr*

1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been developing a design and analysis technique for a pool-type sodium-cooled fast reactor called SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR), which would generate 100MWe with a long refueling period of around 20 years. The overall design of SALUS is based on 150MWe PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) design. It is a pool type reactor including two pumps, four IHXs, and four DHXs. The IHTS(Intermediate Heat Transport System) is composed of two loops and the DHRS(Decay Heat Removal System) is composed of two passive trains and two active trains.[1]

In this study, CFD(Computational Fluid Dynamics) analysis was performed to get the fluid flow field and temperature distribution over the PHTS (Primary Heat Transfer System) being directly contact with HAA(Head Access Area) and RVCS (Reactor Vault Cooling System) for verifying and developing the SALUS design.

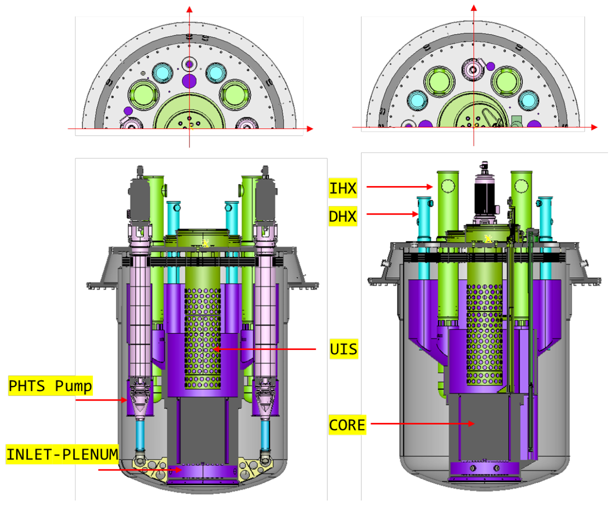
2. CFD Analysis Model

The computational domain for the CFD analysis was the SALUS PHTS including HAA and RVCS. The analytical tool is a commercial CFD code, STAR-CCM+ [2].

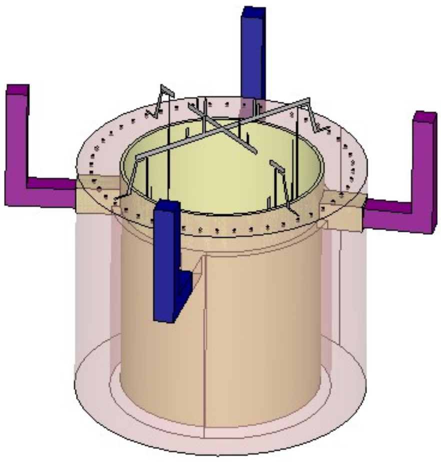
2.1. Geometry and Mesh

Since the SALUS design of PHTS combined with HAA and RVCS does not have any symmetricity, a circular-shaped geometry was generated for the sodium pool being attached to the HAA and surrounded by the RVCS. Figure 1 shows a side-view of the SALUS reactor vessel and head and an iso-view of the RVCS for the CFD calculation. Geometries were made as close to the real as possible, however small detailed parts such as bolts and small gaps were eliminated since they would not affect the main fluid flow significantly. The secondary loop of IHX(Intermediate Heat Exchanger) or DHX(Decay Heat Exchanger) were ommitted, and the tube bundles which PHTS sodium flows across were approximated as porous media having proper hydraulic resistance and heat removal rate.

Hexa meshes with prizm layer in the fluid region were generated, since this type of meshes can cover complex geometries and provide relatively less number of meshes than tetra meshes. Based on the research



(a) PHTS Assembly



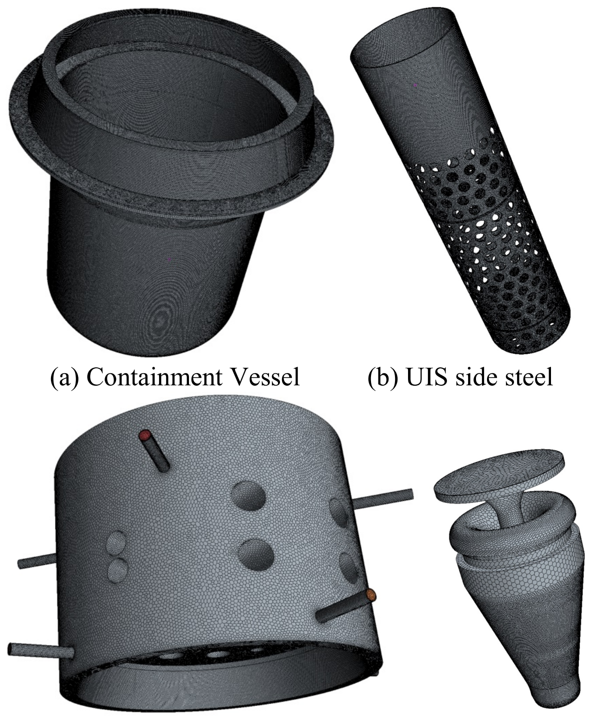
(b) Reactor Vault Cooling System (RVCS)

Fig. 1. SALUS geometries generated for the CFD simulation

achievement of Ryu, et al.[3], totally about 32 million cells were generated for the whole computational domains. Figure 2 shows meshes on some selected parts of SALUS.

2.2. Physics Models

The fluid flows and heat transfer phenomena found inside the PHTS assembly are very complicated including turbulent liquid and gas flows and conjugated heat transfer by convection and radiation as well as conduction. Therefore, SST (Shear Stress Transport) turbulence model was adopted since it is good for predicting recirculating flows due to complex geometry


(a) Containment Vessel (b) UIS side steel

(c) HAA (d) PHTS pump internal

Fig. 2. Meshes on some selected SALUS parts

and relatively efficient than Reynolds stress turbulence model.

2.3. Reactor Core Model

The SALUS reactor core consists of 253 assemblies, generating 268.0MWth heat. Fuel assemblies are classified as inner (IC), middle (MC), and outer (OC) assemblies. These fuel assemblies are surrounded by reflector and shield assemblies, and 9 control assemblies are positioned in proper locations.

For CFD simulation, SALUS reactor core was simplified as 4 annular areas as shown in Figure 3. The orifice regions, where sodium coolant coming from inlet plenum at the bottom, were not modelled in detail, and rather modelled as blank porous media attached to the bottom of fuel regions

2.4. Analytic Conditions for Steady-State Calculation

Table 1 and 2 summarize the major analytic conditions and the outermost boundary conditions for the SALUS CFD simulation, respectively. In Table 1, the total volumetric flow rate of HAA air consists of the volumetric flow rates through all four HAA air inlets. Similarly, the total mass flow rates of RVCS air and PHTS pump sodium also cover two inlet flows.

3. Results and Discussion

Figure 4 presents the pressure and temperature distributions, with velocity field on a cross-section of PHTS. Due to the slow converging speed of the segregated equation solver, the simulation has not been fully converged yet. However, the results show that sodium coolant and Argon cover gas flow over the whole fluid region, and that heat is transferred across the fluid-solid interfaces as well as the fluid-fluid interfaces.

Figure 5 presents the streamlines and temperature contour on the PHTS pump cut plane of the HAA air. The cold inlet fluid flows, coming through the 4 inlets located at the upper HAA region, collide with each others and go down to the reactor head surface. Therefore, regional temperatures above the reactor head center are relatively low than other region in Figure 5(b).

Table 1. Major analytic conditions for the SALUS CFD simulation

Location	Content	Value
HAA Air	Total volumetric flow rate [m^3/s]	5.72
	Temperature [^oC]	20
RVCS Air	Total mass flow rate [kg/s]	9.92
	Temperature [^oC]	40
PHTS Pump Sodium	Total mass flow rate [kg/s]	1365.63
	Temperature [^oC]	357.8

Table 2. Outermost boundary conditions for the SALUS CFD simulation

Location	Boundary	Content	Value
HAA Air	Top wall	Temperature [^oC]	40
	Side wall	Adiabatic	
RVCS concrete	Side wall	Temperature [^oC]	20
	Bottom wall	Adiabatic	
RVCS air	Bottom wall	Adiabatic	

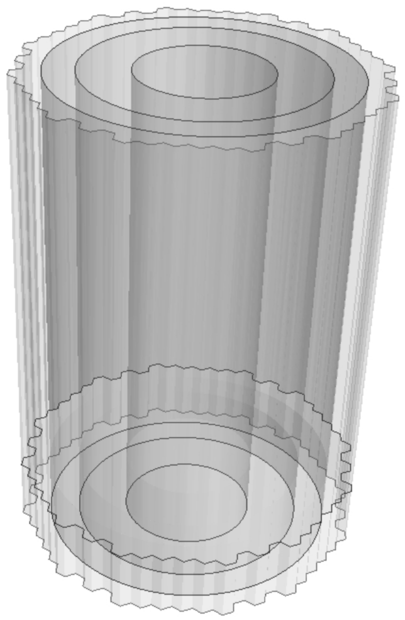


Fig. 3. Core geometries for SALUS CFD analysis

4. Conclusions

In this study, the geometries and meshes were generated for CFD analysis. With proper physical models such as *k-w* based SST turbulence model and Surface-to-Surface radiative heat transfer model, steady-state CFD analysis was performed to get the fluid flow and heat transfer distribution over the PHTS (Primary Heat Transfer System) being directly contact with HAA(Head Access Area) and RVCS (Reactor Vault Cooling System) for verifying and developing the SALUS design.

To meet the temperature limit requirement of the reactor vessel, a concept of the Main Vessel Cooling System (MVCS) had been developed. In the next stage, the effects of MVCS would be investigated by using CFD analytical technology. The parametric study of sodium flow rate to the MVCS would be also conducted.

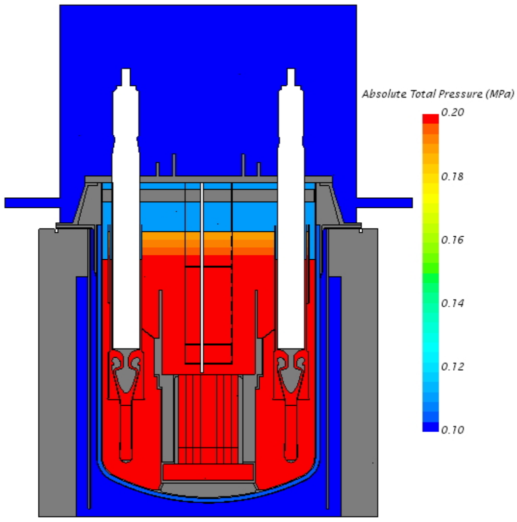
This steady-state result will be also used as an initial condition for transient accident analyses.

ACKNOWLEDGMENTS

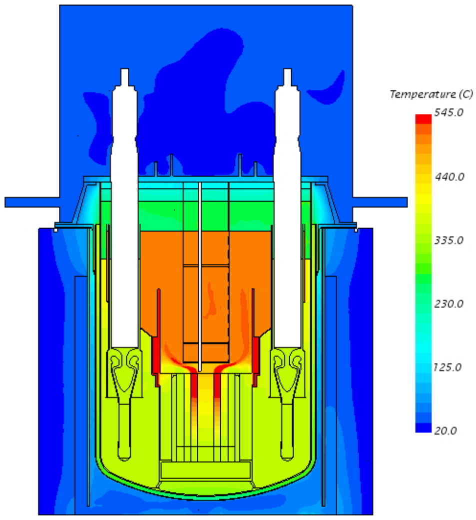
This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. 2021M2E2A1037871)

REFERENCES

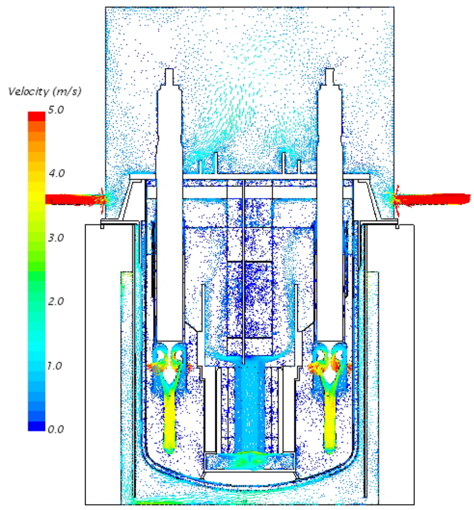
[1] Ji-Woong Han, Dehee Kim, and Huee-Youl Ye, "Design Feasibility Study on DHRS for 100MWe Long Fuel Cycle Sodium-cooled Fast Reactor," KNS Spring Meeting, Jeju, 2022.
[2] CD-adapco, STAR-CCM+ User's Manual, 2017.
[3] Seung Ho Ryu, Sujin Yeom, Tae-Ho Lee, "The Effect of Air Separator Geometry on the RVCS in PGSFR," KNS Autumn Meeting, Gyeongju, 2015.
[4] Sujin Yeom, J.-W. Han, S. Ryu, D. Kim, J.-H. Eoh, S.-R. Choi, "Design and Evaluation of Reactor Vault Cooling System in PGSFR," Nuclear Engineering and Design, Vol. 365, 2020.



(a) Pressure distribution on PHTS pump cut

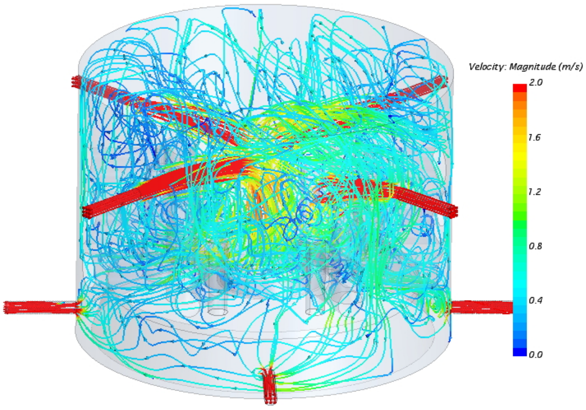


(b) Temperature distribution on PHTS pump cut

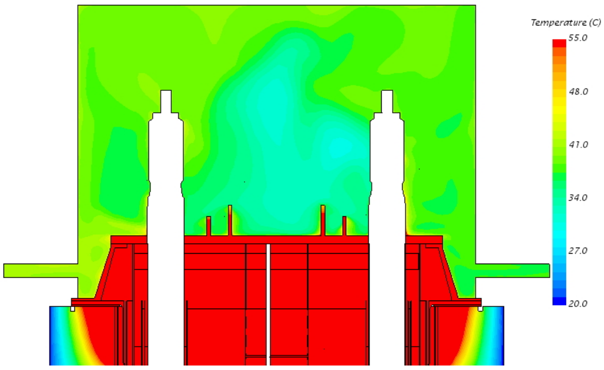


(c) Velocity vectors on PHTS pump cut

Fig. 4. Steady-state simulation results for SALUS



(a) Streamlines in the HAA region



(b) Temperature distribution on PHTS pump cut

Fig. 5. Streamlines and temperature distribution in the HAA for SALUS