Development progress of plate-out estimation code for micro modular S-CO_2 cooled reactor (KAIST-MMR)

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1. Introduction

Although a nuclear system is clean, efficient, and most dense energy source in the world, the current large scale nuclear power plant faces many challenges. Due to the large scale of a plant, the initial investment becomes substantial which increases the economic risk. Moreover, a huge electricity generating station require constructions of large-scale transmission facilities as well, which often involves another technical and societal challenges. In order to overcome these challenges and sustainably utilize nuclear energy, development of a Small Modular Reactor (SMR) became active all over the world in recent years.

SMRs are expected to require smaller footprint, better safety and higher flexibility. In Korea Advanced Institute of Science and Technology (KAIST), a research team has previously developed KAIST-MMR concept, which is an innovative supercritical CO_2 (S-CO_2) cooled direct-cycle Gas-cooled Fast Reactor (GFR) that can achieve SMRs' expected advantages [1].

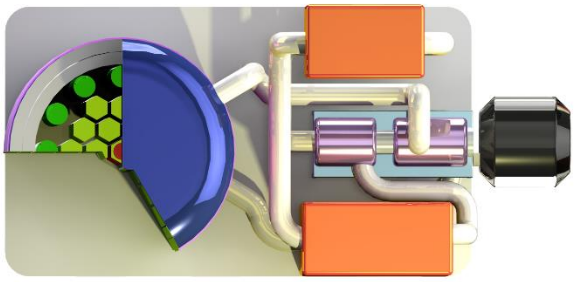

Figure 1. Conceptual figure of KAIST-MMR [1]

One of the most important features of KAIST-MMR is that it is a direct-cycle type gas cooled reactor (GCR). The direct-cycle type GCR is a nuclear reactor type which is directly sending reactor coolant to turbine. This type has advantages to achieve higher turbine inlet temperature (TIT) because intermediate heat exchanger (IHX) is not needed, resulting in higher efficiency, lower manufacturing cost, and simpler system layout. However, according to USNRC Reports "Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)" [2], Direct-cycle type GCR has the potential risk of operation and maintenance due to plate-out in turbine blades and recuperator. According to the HTGR-GT Report produced by JAERI [3], if a HTGR is configured as a direct-cycle, the turbine blades can be contaminated by radioactive ^{137}Cs and ^{110m}Ag. In the case of 600MWth plant, 159.76mSv/h dose rate is expected after 450days of continuous operation. This means that maintenance workers can only work 11 minutes per year. In this study, it was shown that the occupational dose by the plate-out decreases sharply as the system capacity decreases. For example, for 300MWth plant case, the dose rate is expected to become only 5.44mSv/h after 960 days of continuous operation. As such, even with similar reactors, the plate-out behavior can vary significantly, so the plate-out evaluation of the S-CO_2 direct-cooled GCR, which has not been seen until now, is an essential task for further refinement of the concept.

In this study, it is aimed to evaluate the radiation dose rate by plate-out in the KAIST-MMR. Because KAIST-MMR uses S-CO_2 instead of helium as its working fluid and it has a very different system and component geometries, so new analysis tools are needed. In this paper, the authors present the initial phase of developing the tools including the methodology required to evaluate plate-out in KAIST-MMR.

2. Methodology

2.1. Governing Equations

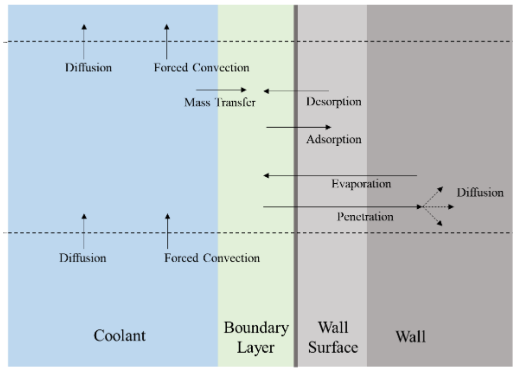

Figure 2. Mechanisms of Plate-out

As shown in Figure 2, plate-out is a complex fission product mass transfer process that occurs between fluid,

fluid boundary layer, wall surface and wall. In some cases, all of these phenomena are individually modeled and analyzed [4-5]. But generally, in the US PADLOC code [5] and the Korean POSCA code [7] used the sorption model to utilize the fission product transport equation for coolant, boundary layer, and base material sets. For this work, the authors adopted the POSCA code methodology. The governing equations used are shown below:

$$\boldsymbol{\frac{\partial C_i}{\partial t} = q_c - \lambda_i C_i + \frac{1}{A_z}\frac{\partial}{\partial z}\left(A_z D_i \frac{\partial C_i}{\partial z} - A_z v_z C_i\right) + \frac{P_w}{Az} h(B_i - C_i)} \,..\, \mathbf{(1)}$$

$$\boldsymbol{\frac{\partial S_i}{\partial t} = q_s - \lambda_i S_i - h(B_i - C_i)} \,..\, \mathbf{(2)}$$

$$\boldsymbol{B_i = f(S_i)} \,..\, \mathbf{(3)}$$

Equation (3) is called "sorption isotherm". This is a different type of equation depending on the base material and fission product where the plate-out occurs. This is a property that is also affected by fluids, but it is assumed that CO_2 and helium have the same properties because of their similar chemical behavior. (This is a matter that requires experimental verification later.) Therefore, the authors will apply the sorption isotherm model presented in IAEA-TECDOC-978 [8]. In the process of solving the governing equation, the part that differs the most from the method used in the existing studies is the mass transfer coefficient (h). Unlike previous studies, KAIST-MMR requires a mass transfer coefficient for supercritical fluids because all parts are in supercritical phase during normal operation. In this study, the mass diffusivity was obtained through the correlation with He and Yu (1998) [9], and heat and mass transfer analogy was adopted [10].

Mass diffusivity of S-CO₂ (He and Yu, 1998)

$$D_{AB} = \alpha * 10^{-5}\left(\frac{T}{M_A}\right)^{\frac{1}{2}} \exp\left(-\frac{0.3887}{V_{\gamma B} - 0.23}\right)$$

$$\alpha = 14.882 + 0.005908\frac{T_{cB}V_{cB}}{M_B} + 2.0821 * 10^{-6}\left(\frac{T_{cB}V_{cB}}{M_B}\right)^2$$

D_{AB}	Diffusion coefficient of solute A in solvent B, cm^2/s
V_{cB}	Critical volume of solvent in cm^3/mol
T_{cB}	Critical temperature of the solvent in K
$V_{\gamma B}$	V_B/V_{cB}

Heat and mass transfer analogy

$$\boldsymbol{Nu\, Re^{-1}\, Pr^{-1/3} = Sh\, Re^{-1}\, Sc^{-1/3}}$$

2.2. Numerical method

The governing equation of Equation (1)-(3) cannot be solved analytically considering the nonlinear real fluid properties. Therefore, discretization is necessary to obtain numerical solution.

The numerical solution was calculated in 1D using the Finite Difference Method. The staggered mesh is used for discretization, shown as Figure 3. KAIST-MMR does not use natural convection under normal operation. Therefore, to reduce the complexity of the problem, the diffusion term in Equation (1) ($\boldsymbol{\frac{1}{A_z}\frac{\partial}{\partial z}\left(A_z D_i \frac{\partial C_i}{\partial z}\right)}$) is ignored. The numerical discretization is written as a fully-implicit manor with linearized sorption model for stability of convergence. The formula written is shown in Equation (4)-(6).

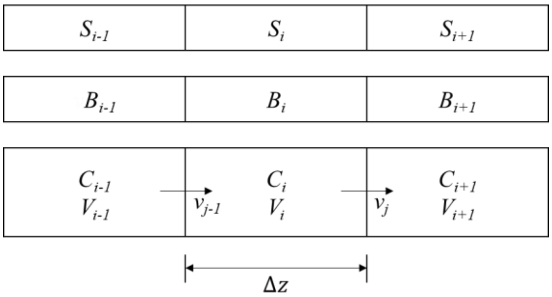

Figure 3. Staggered Mesh

$$\left(-\frac{A_{j-1}v_{j-1}}{\Delta V_i}\right)C_{i-1}^{n+1} + \left(\frac{A_j v_j}{\Delta V_i} + \frac{1}{\Delta t} + \lambda_i + \frac{P_w}{A_j}h\right)C_i^{n+1} - \frac{P_w}{A_j}h\left[\frac{\partial f}{\partial S}\right]_{S_i=0} S_i^{n+1} = q_c + \frac{C_i^n}{\Delta t} + \frac{P_w}{A_j}hf(0) \;...\;(4)$$

$$\left(\frac{1}{\Delta t} + \lambda_i + h\left[\frac{\partial f}{\partial S}\right]_{S_i=0}\right)S_i^{n+1} - hC_i^{n+1} = \frac{1}{\Delta t}S_i^n - hf(0) \;...\;(5)$$

$$B_i^{n+1} = f(0) + \left[\frac{\partial f}{\partial S}\right]_{S_i=0} S_i^{n+1} \;...\;(6)$$

3. Analytic Benchmark

In order to confirm the accuracy and feasibility of the numerical method presented above, the authors analyzed an analytical benchmark problem similarly solved in PADLOC [6] code. In this case, since the space difference can be ignored, an analysis solution can be obtained by calculating '*C + Pw/A S'* when the sorption model is linear. The sorption model used is the same model in the PADLOC example as the Equation (7).

$$\boldsymbol{B = \frac{N_A S}{RT_{wall}10^{20}} 10^{3.88 - 3730/T_{wall}}} \;...\;\mathbf{(7)}$$

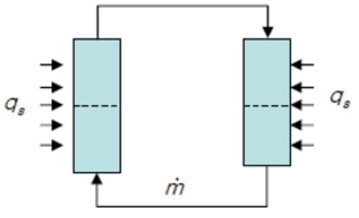

Figure 4. Single loop problem

Table 1. Problem condition

Parameters	Value
Loop length (cm)	20
Pipe diameter (cm)	2
Mesh spacing (cm)	5
Initial coolant concentration (#/cm^3)	0
Initial surface concentration (#/cm^2)	0
Decay constant (1/s)	10
Helium flow rate (g/s)	42.085
Coolant/wall temperature (°C)	800/800
Coolant pressure (atm)	50
Coolant source rate (#/cm^{3}s)	0
Surface source rate (#/cm^{2}s)	2.20E+07

Analytic and numerical solutions are shown in Figure 5.

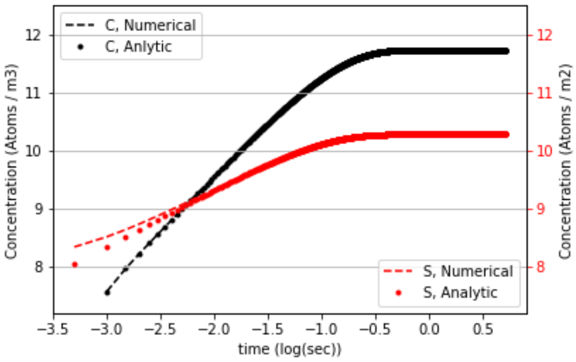

Figure 5. Analytic and numerical solutions

The results show that the proposed numerical discretization correctly predicts the convergence point. With this, it can be confirmed that the semi-implicit expression proposed in Equations (4-6) is numerically appropriate.

4. Conclusion and Further works

Plate-out estimates are underway for basic operation and management evaluation of the KAIST-MMR, a small module type S-CO$_2$ direct-cycle GFR. Mass diffusivity and mass transfer coefficient correlations were determined for plate-out estimation of an S-CO$_2$ system. In addition, a semi-implicit discretization for numerical computation is presented, and the feasibility of the proposed methodology is confirmed through an analytic benchmark problem.

The authors plan to estimate the plate-out of the KAIST-MMR while considering the system design information and the geometry information of turbomachinery and heat exchangers. This will enable to determine the appropriate maintenance cycle and to provide the source term of the fission product release in case of an accident of a similar system in the future.

ACKNOWLEDGEMENT

This study was mainly supported by the KUSTAR-KAIST International joint research project (N11190061) of KAI-NEET Institute, KAIST. Also, the authors would particularly like to thank Dr. Nam-Il Tak in KAERI for his valuable advices to this research.

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