An Implementation of A Boron Transport Equation into the CUPID Code

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1. Introduction

This paper presents the implementation of a boron transport into the CUPID code[1] and some validation calculations for it. Boron is dissolved into water and transported with it. The molecular diffusion of solute boron was not considered, and boron assumes to be moved along water flow. It is also assumed that the water mass, energy and momentum are not influenced by the dissolved boron. The present model has been verified against a two-dimensional conceptual problem and applied to the analysis of the ROCOM TEST1.

2. Mathematical Model

2.1 Governing Equations

With the assumptions of introduction, the governing equations for the boron transport are as follows:

$$\frac{\partial}{\partial t}\left[\left(1-\alpha_g\right)\rho_l C_B\right]+\nabla\cdot\left(\alpha_l\rho_l C_B\vec{u}_l\right)+\nabla\cdot\left(\alpha_d\rho_l C_B\vec{u}_d\right)=0 \quad (1)$$

where, $\alpha, \rho, \vec{u}, C_B$ are volume fraction, density, velocity, boron concentration for unit-mass water, and the subscript, g, l, d , indicate gas, liquid, liquid droplets, respectively. The additional momentum and energy equations are not needed because the momentum and energy changes due to the solute boron are assumed to be negligible. Thus, the equation (1) is the only additional equation to be added in the CUPID two-fluid, three-field model, and C_B is the only additional variable for the CUPID code.

2.2 Discretized Equations

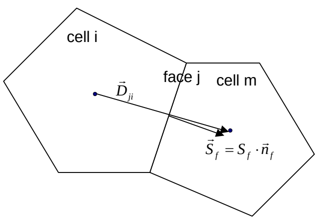

Fig. 1 Control Volume for the CUPID Code

The control volume for the CUPID code is given in Figure 1, in which $\vec{D}_{ji}, \vec{S}_f, \vec{n}_f$ are distance vector, surface vector, and surface normal vector to outer direction. Subscripts, i, j, f , indicate current control volume, neighbor cell, and cell face.

The equation (1) was discretized by using FVM (Finite Volume Method) and the Green-Gauss theorem was applied to the volume integral of the convective term as follows:

$$\left\{\left[\left(1-\alpha_g\right)\rho_l C_B\right]^{n+1}-\left[\left(1-\alpha_g\right)\rho_l C_B\right]^{n}\right\}V_i/\delta t = \sum_f\left(\alpha_l^n\rho_l^n C_B^n\vec{u}_l^{n+1}\right)\cdot\vec{S}_f+\sum_f\left(\alpha_d^n\rho_l^n C_B^n\vec{u}_d^{n+1}\right)\cdot\vec{S}_f \quad (2)$$

where $V_i, \delta t$ are i-th cell volume and time step, and superscripts, $n, n+1$, indicate previous time step and next time step. The discretized equation (2) can be solved explicitly after solving the original CUPID governing equations as follows:

$$C_B^{n+1}=\{\sum_f\left(\alpha_l^n\rho_l^n C_B^n\vec{u}_l^{n+1}\right)\cdot\vec{S}_f+\sum_f\left(\alpha_d^n\rho_l^n C_B^n\vec{u}_d^{n+1}\right)\cdot\vec{S}_f + \left[\left(1-\alpha_g\right)\rho_l\right]^n V_i/\delta t\}/\{\left[\left(1-\alpha_g\right)\rho_l\right]^{n+1}V_i/\delta t\} \quad (3)$$

The equation (3) is not valid any more if α_g goes to one. Then, the equation (3) will be not solved, and the boron concentrations of the previous step are used.

3. Verification and Application

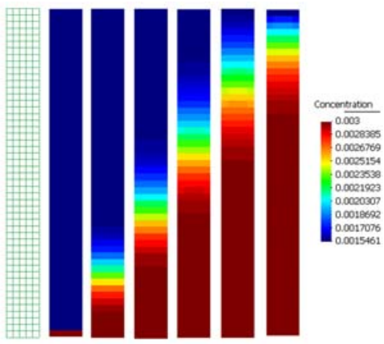

Fig. 2 Grid and Calculated Boron Concentration with the Interval of 2 Seconds.

The verification of the implementation of the boron transport equation was accomplished by simulating constant boron concentration convection problems. The boric water of 3000 ppm is injected with 2.0 m/s to the bottom inlet and is extracted from the upper outlet in the 2-dimensional duct of 0.5 m x 5.0 m. A computation grid with 5x50 cells is used to represent the flow duct.

The mesh and the calculated time-dependent boron contours are presented in Figure 2. In the Figure 3, calculated boron fluxes at 100 seconds are the same to the 11th decimal place as 0.29949681124 2212 and 0.29949681125 6347 for inlet and outlet, respectively.

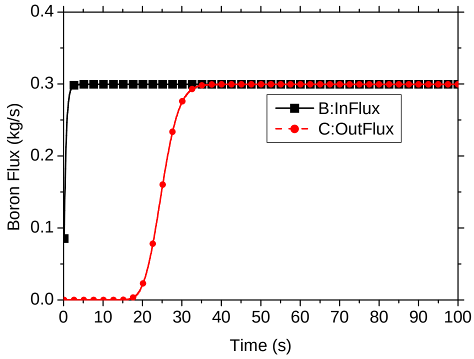

Fig. 3 Calculated Boron Flux at Inlet and Outlet

Next, the effect of the 2^{nd} order convective scheme was tested with the inlet boron concentration of Figure 4 on the same geometry and flow condition of the previous calculation. The stepwise boron concentration was endowed to the inlet water from 30 second to 40 second. The numerical diffusion of the boron concentration was mitigated in case that the 2^{nd} order convective concept is applied to both governing equations for the boron and the flow as show in Figure 5, where BiFj indicate i-th and j-th order convective terms of boron transport equation and flow governing equations.

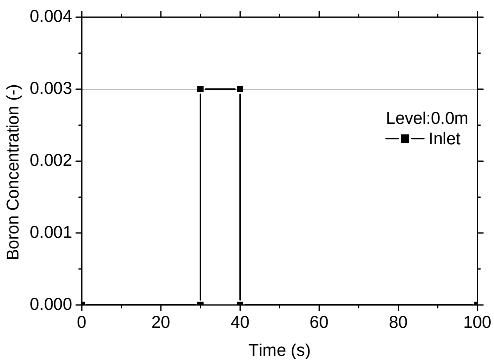

Fig. 4 Stepwise Inlet Boron Concentration

Finally, the boron cencentration transport phenomena are simulated in the ROCOM vessel, with which the thermally non-symmetric coolant mixing behaviors due to one steam line break are experimented by using the electolytic water[2]. Then, the concentration distribution of the electolyic water is converted into the temperature distribution of the water. This data can be used for the concentration distribution of the boric water. The temperature, mass flow rate, density are 153.0 ^{o}C, 257.4 kg/s, 915.9 kg/m^3 at the one leg, and 236.1 ^{o}C, 69.0 kg/s, 819.9 kg/m^3 at the other three legs. The calculation grid, calculated velocity vector and boron concentration contours are presented in Figure 6, which shows non-symmetric behaviors reasonably.

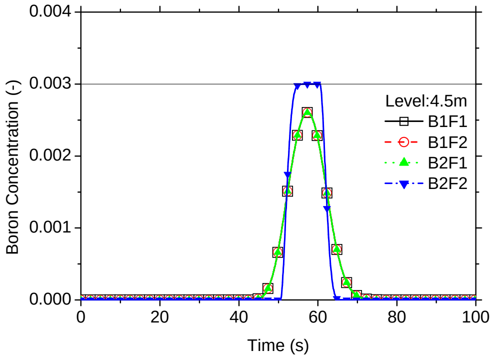

Fig. 5 Effect of 2^{nd} Order Convective Concept

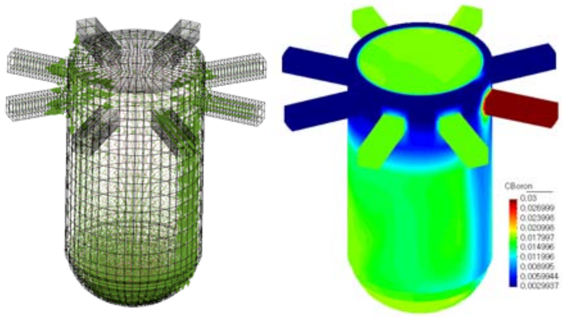

Fig. 6 Grid and Calculated Boron Concentration for ROCOM TEST1

4. Summary and Conclusions

In this study, the boron transport equation has been implemented into the CUPID code and some verification and validation calculations are discussed. The inlet and outlet boron fluxes are the same each other to the 11^{th} decimal place in the 2-dimensional verification. The 2^{nd} order convection scheme reduced the numerical diffusion clearly. The application of the CUPID code has been validated by simulating the ROCOM TEST1.

ACKNOWLEDGEMENTS

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