Boron Transport Model in the SPACE code

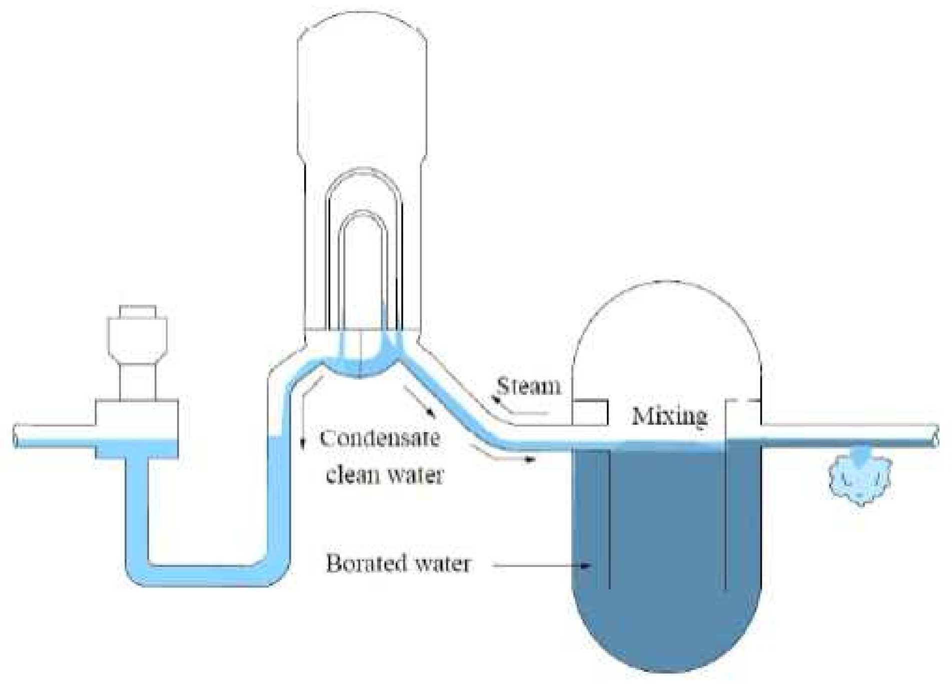
Chan Eok Park*, , Je Woo Cho, Young Tae Han, Myeong Hoon Lee

Safety Analysis Group, KEPCO-E&C, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Rep. of KOREA

**Corresponding author: cepark@kepco-enc.com*

Introduction

Generally in PWR, the boron concentration is controlled to preserve the core criticality. In normal operations, it is important to maintain the boron concentration equally distributed inside the primary coolant. On the other hand, in an accidental condition, such as SLB(steam line break), highly borated water is injected by the emergency core cooling system(ECCS) to maintain the core subcritical. In case of SB-LOCA(small break loss of coolant accident) reflux condensation phase, accumulation of the condensed water in the crossover legs may generate deborated water slugs. When the system reaches to natural circulation with the ECCS or the reactor coolant pumps restart, the deborated water slugs in the crossover legs may flow towards the core, resulting in positive reactivity insertion. Therefore, from a safety point of view, the simulation capability of the boron transport phenomena is important in the system thermal hydraulic codes. In this paper, the boron transport models used in SPACE, and their application test results are presented.



Conceptual diagram of boron mixing induced by reflux condensation & restart of circulation during SBLOCA (Okzan Emre Ozdemir, Multi-dimensional Boron Transport Modelling in Subchannel Approach, doctoral dissertation, Penn State Univ, 2012)

Governing Equation

Assumptions

- *Boron concentration does not affect the properties of continuous liquid (liquid hereafter) or dispersed liquid (droplet hereafter).*
- *Boron is transported by the droplet field as well as the liquid field*
- *Transport velocity of boron is the same as the liquid or the droplet velocity carring it*
- *Boron precipitation and dilution are based on boron solubility limit*

Boron transport equation in the liquid field

$$\frac{\partial\left(\varepsilon\alpha_l\rho_l\omega_l\right)}{\partial t}+\nabla\cdot\left(\varepsilon^E\alpha_l\rho_l\omega_l\mathbf{U}_l\right)=-\varepsilon\omega_l S_E+\varepsilon\omega_d S_D$$

Boron transport equation in the droplet field

$$\frac{\partial\left(\varepsilon\alpha_d\rho_d\omega_d\right)}{\partial t}+\nabla\cdot\left(\varepsilon^E\alpha_d\rho_d\omega_d\mathbf{U}_d\right)=-\varepsilon\omega_d S_D+\varepsilon\omega_l S_E$$

First Order Upwind Scheme

Forward Euler scheme in time

Upwind(donor) scheme in space

$$\varepsilon V_P\frac{\alpha_l^n\rho_l^n\omega_l^n-\alpha_l\rho_l\omega_l}{\Delta t}+\sum_{E\in P}\varepsilon^{E}\,{}^{d}\alpha_l^{E}\,{}^{d}\rho_l^{E}\,{}^{d}\omega_l^{E}\left(\iota_P^E U_{ln}^n A^E\right)=\varepsilon V_P\left(-S_E\omega_l+S_D\omega_d\right)+B_l^{total}$$

$$\varepsilon V_P\frac{\alpha_d^n\rho_d^n\omega_d^n-\alpha_d\rho_d\omega_d}{\Delta t}+\sum_{E\in P}\varepsilon^{E}\,{}^{d}\alpha_d^{E}\,{}^{d}\rho_d^{E}\,{}^{d}\omega_d^{E}\left(\iota_P^E U_{dn}^n A^E\right)=\varepsilon V_P\left(S_E\omega_l-S_D\omega_d\right)$$

where

$$B_l=\left[\max(0,\ \omega_l^n-B^s)\right]\alpha_l^n\rho_l^n\varepsilon V_P\qquad B_d=\left[\max(0,\ \omega_d^n-B^s)\right]\alpha_d^n\rho_d^n\varepsilon V_P$$

$$\omega_l^n=B^s\ \text{for}\ B_l>0\qquad \omega_d^n=B^s\ \text{for}\ B_d>0\qquad B_l^{total}=B_l+B_d$$

Numerical Diffusion

Typical advection equation

$$\frac{\partial\phi}{\partial t}+u\frac{\partial\phi}{\partial x}=0$$

Truncation error induced by first order upwind scheme

$$\varepsilon_t=\frac{\Delta t}{2}\left(\frac{\partial^2\phi}{\partial^2 t}\right)_i^n-u\frac{\Delta x}{2}\left(\frac{\partial^2\phi}{\partial^2 x}\right)_i^n+O\left(\Delta t^2,\Delta x^2\right)$$

Numerical diffusion

$$\varepsilon_t=D_{num}\left(\frac{\partial^2\phi}{\partial^2 x}\right)_i^n\quad D_{num}=\frac{u\Delta x}{2}\left(1-\frac{u\Delta t}{\Delta x}\right)$$

Second Order Godunov Scheme

Newly implemented to reduce numerical diffusion

Time centered velocity in time

Godunov scheme with slope limiter in space

$$\varepsilon V_P\frac{\alpha_l^n\rho_l^n\omega_l^n-\alpha_l\rho_l\omega_l}{\Delta t}+\sum_{E\in P}\varepsilon^{E}\,{}^{d}\alpha_l^{E}\,{}^{d}\rho_l^{E}\,{}^{G}\omega_l^{E}\left(\iota_P^E U_{ln}^* A^E\right)=\varepsilon V_P\left(-S_E\omega_l+S_D\omega_d\right)+B_l^{total}$$

$$\varepsilon V_P\frac{\alpha_d^n\rho_d^n\omega_d^n-\alpha_d\rho_d\omega_d}{\Delta t}+\sum_{E\in P}\varepsilon^{E}\,{}^{d}\alpha_d^{E}\,{}^{d}\rho_d^{E}\,{}^{G}\omega_d^{E}\left(\iota_P^E U_{dn}^* A^E\right)=\varepsilon V_P\left(S_E\omega_l-S_D\omega_d\right)$$

where

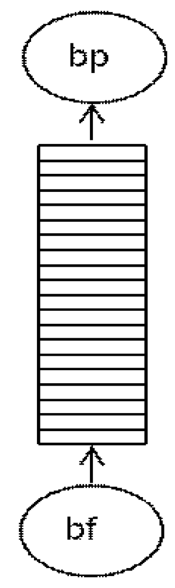
$${}^{G}\omega^E={}^{upstream}\omega+\left(1+\theta\omega\right)\Phi\left(r,1\right)\left(1-\frac{U^*\Delta t}{\Delta x^{upstream}}\right)\frac{1}{2}\Delta x^{upstream}\,gradient^E$$

$$U^*=\frac{1}{2}\left(U^n+U\right)\qquad gradient^E=\frac{\omega^{downstream}-\omega^{upstream}}{\Delta x^E}$$

$$\Phi\left(r,1\right)=\max\left[0,\min\left(2r,1\right),\min\left(r,2\right)\right]\qquad r=\frac{gradient^{upperface,E}}{gradient^E}$$

$$\theta=\frac{\left|1-r\right|}{1+\left|r\right|}\qquad \omega=\min\left(\frac{U^*\Delta t}{\Delta x^E},1-\frac{U^*\Delta t}{\Delta x^E}\right)$$

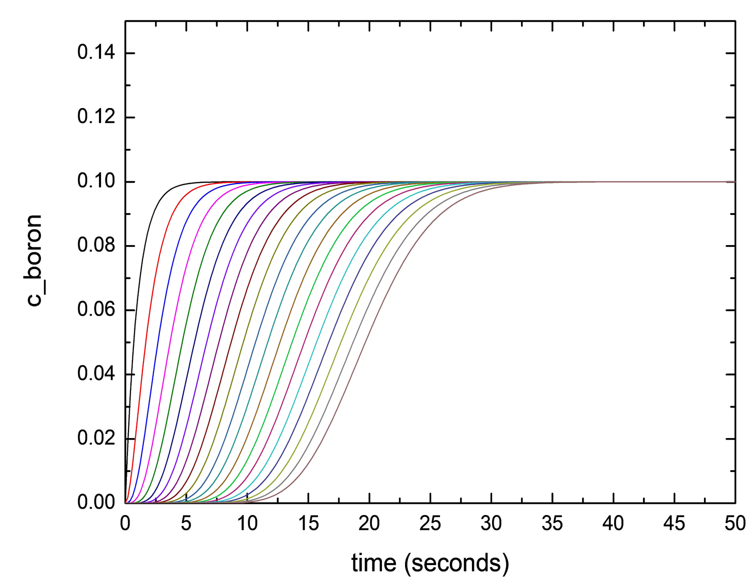
Application Result



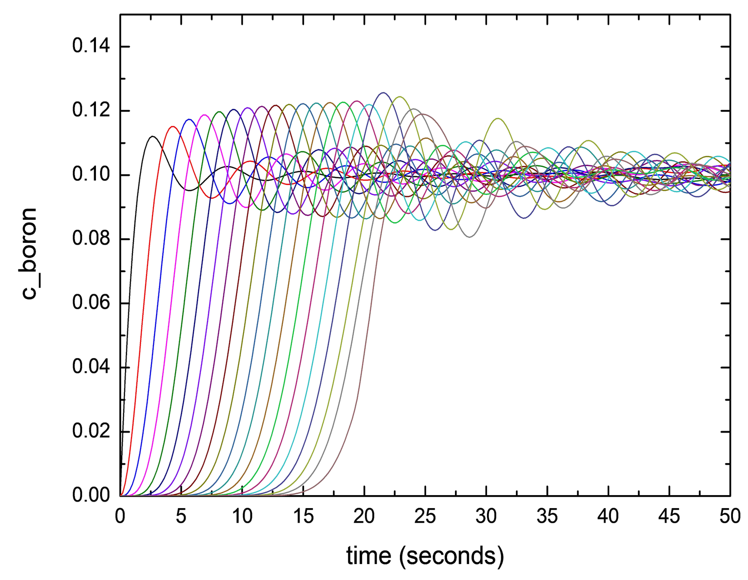
Test problem

Vertical pipe: 20 cells, 1m high each

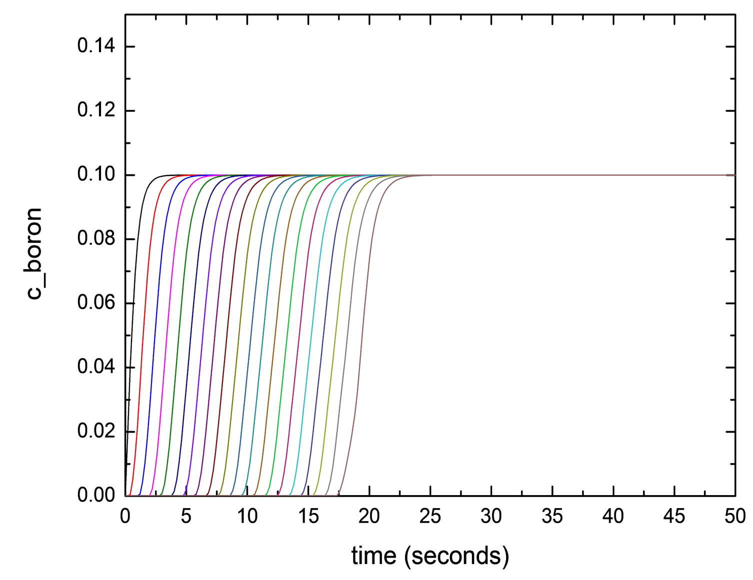
Boron injection at bottom: 10%, 1m/s



First order upwind scheme



Godunov scheme without slope limiter



Godunov scheme with slope limiter

Conclusion

The SPACE code has an advantage of three field representation of two-phase flow model, which allows the liquid and droplet fields to transport boron with individual phasic velocities. The first order upwind and the second order Godunov schemes are implemented to solve the liquid and droplet boron transport equations. A boron injection test in the vertical pipe is performed to check the performance of both the boron transport numerical models. It is concluded that the upwind scheme is stable but includes some numerical diffusion, and the Godunov scheme with gradient limiter can be used to eliminate the numerical diffusion with improved model accuracy.

Nomenclature

A^E	=	face area
B_ϕ	=	boron precipitation from liquid or droplet field
B^S	=	boron solubility limit
D_{num}	=	numerical diffusion coefficient
$E\in P$	=	every face belonging to the current cell, P
S_E	=	entrainment from liquid
S_D	=	de-entrainment to liquid
U_n^E	=	normal component of velocity vector at face
$U_{\phi n}$	=	face-normal velocity of each field
$\mathbf{U}_\phi$	=	velocity vector of each field
u	=	advection velocity
V_P	=	volume of the current cell, P
α_ϕ	=	volume fraction of each field
ε	=	porosity
ϕ	=	property carried by advection
Γ_ϕ	=	evaporation from liquid or droplet field
Γ_ϕ^w	=	near wall evaporation from liquid or droplet field
ι_P^E	=	direction factor of face at a cell, P (1 for outward face, -1 for inward face)
ρ_ϕ	=	phasic density of each field
ω_ϕ	=	boron concentration of each field

Subscripts

d	=	droplet
l	=	liquid
n	=	face normal component of velocity vector
ϕ	=	phase or field indicator

Superscripts

d	=	face property given by upwind (donor) scheme
E	=	current face (edge) property
G	=	face property given by Godunov scheme
n	=	next time step
$upperface,E$	=	upper face (edge) property
$upstream$	=	upstream cell property
w	=	near wall region