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MULTIDIMENSIONAL BORON TRANSPORT MODELING IN SUBCHANNEL APPROACH

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Abstract

The main objective of this study is to implement a solute tracking model into the subchannel code CTF for simulations of boric acid transients. Previously, three different boron tracking models have been implemented into CTF and based on the applied analytical and nodal sensitivity studies the Modified Godunov Scheme approach with a physical diffusion term has been selected as the most accurate and best estimate solution [1]. This paper will present the implementation of a multidimensional boron transport modeling with Modified Godunov Scheme within a thermal-hydraulic code based on a subchannel approach. Based on the cross flow mechanism in a multiple-subchannel rod bundle geometry, heat transfer and lateral pressure drop effects will be discussed in deboration and boration case studies.

Introduction

In Pressurized Water Reactors (PWR), Boron-10 is added to the reactor coolant and used as a neutralizer to absorb the neutrons inside primary coolant in order to control and maintain the system criticality [2]. In normal operation condition it is important to preserve the boric acid (H_3BO_3) concentration equally inside the primary coolant by forced primary coolant circulation or the natural circulation [2]. Since homogenous boron concentration helps to uniform the reactivity in PWR, boron dilution can increase the risk of local or whole core criticality with threatening the fuel integrity [3].

During standard operation, it is possible to investigate boron dilution before the system reaches its critical point. The large volume and the characteristics of the primary system limit the rate of boron free coolant injection and allow operators to detect slow boron-free coolant mixing process [3]. However, when the uncontrolled boron dilution occurs more rapidly in the reactor systems there is a possibility to have positive reactivity excursion that causes supercritical state in the reactor core.

There are two main scenarios which could result in uncontrolled boron dilution:

i. Accidental unborated water injection to the primary cooling system;
ii. Evaporation of primary coolant in the core and condensation of boron-free water in the steam generator (reflux condensation).

The risk of reflux condensation especially during Small Break Loss Of Coolant Accident (SB-LOCA) and complications of tracking the boron concentration experimentally inside the primary coolant had increased the number of computational studies of accurate boron tracking simulations in nuclear reactors. Different boron tracking models were implemented into several thermal-hydraulic system codes such as TRACE [4] and RELAP5[5] and were improved in terms of their accuracy. The challenges in the system codes are their numerical instability and high diffusive behavior of the implemented slug tracking models [6]. In spite of their high accuracy in tracking the solute inside primary coolant, system codes were capable of modeling only the solute transient in a one-dimensional (1-D) representation. Lack of higher order numerical methods and turbulence models [7] and necessity of two-dimensional (2-D) or three-dimensional (3-D) modeling of the mixing of unborated water (for example in the downcomer [8]) have led to the use of the Computational Fluid Dynamic (CFD) codes for investigation of the mixing inside the core region. However, despite of their higher accuracy in prediction the boron concentration distribution, the CFD calculations are computationally expensive and so far have been limited to the pressure vessel simulations due to the size of the problem [3].

In this work, the Reactor Dynamics and Fuel Management Group (RDFMG) version of the COBRA-TF (CTF) [9] code is being used. The COBRA-TF (COolant Boiling in Rod Arrays-Two Fluid) computer code was originally developed in 1980's by the Battelle Northwest Laboratories under the sponsorship of the United States Nuclear Regulatory Commission (NRC) as a reactor vessel module of the coupled code system COBRA/TRAC [10]. Since then, various academic and industrial organizations have adapted, developed and modified the code in many directions. The CTF version owned by the Pennsylvania State University (PSU) originates from the code version modified in cooperation with the FLECHT SEASET program [11]. Besides the code utilization to teach and train students in the area of nuclear reactor thermal-hydraulic safety analyses, during the last few years, the theoretical models and numerics of the code were substantially improved [12]. The code was subjected to an extensive verification and validation program and was applied to variety of Light Water Reactor (LWR) steady state and transient simulations.

Despite its high accuracy in reactor transient simulations, and particularly the loss of coolant accident (LOCA) analysis, CTF does not have a boron tracking model available to measure the unborated water transient and corresponding density variation inside the reactor vessel. Therefore, when there is a risk of reflux condensation and unborated slug insertion to the system such as during small break loss of coolant accident (SB-LOCA) condition, the code is incompetent to provide realistic reactor core simulations.

The main objective of this study is to implement a solute tracking model into CTF for simulations of boric acid transients. Such improvements will provide a multi dimensional boron transport model based on a subchannel approach and it will make CTF capable of analyzing the solute transients and the boron mixing effects inside the reactor core region at the same time. This novel method will allow more detailed calculations of the time and location of the boron dilution transient inside the reactor core and will compensate the current drawbacks in other numerical studies.

In this paper, first the implementations of three different boron tracking models in CTF are reviewed. Based on applied analytical and nodal sensitivity studies, the Modified Godunov Model has been selected as giving the best estimate solutions in CTF [1] and it is further developed according to the subchannel approach. In order to check the transverse cross flow mechanism and its effect in boron dilation, a 2×2 mini rod bundle geometry has been generated by using General Electric (GE) nine-rod bundle experiments [13,14] and results are discussed.

1. Boron Dilution Transient

The boron dilution phenomena can be classified into two groups [15]. The first one is the homogeneous dilution, which is a slow dilution processes with enough time to generate homogeneous mixing. The second one is the heterogeneous dilution due accumulation of the unborated water. If the heterogeneous unborated slug is transported to the reactor core (RC) by natural circulation or the restart of the reactor coolant pumps (RCP), there is a high risk of insertion of hazardous positive reactivity in to the RC.

Similar to previous research studies, Queral et al. [15] further categorized the heterogeneous dilution according to different reasons: extrinsic and intrinsic sequences. The extrinsic sequence can be defined as a slow unborated water injection to the system, which accumulates inside the reactor coolant system (RCS) without mixing. Leakage from the unborated secondary coolant into the steam generator and accumulation in the RCP suction piping during shutdown condition was given as an example for the extrinsic scenario. The intrinsic sequence, however, occurs due to accumulation of condensed unborated coolant inside primary coolant when the reflux cooling mechanism starts. The condensed steam can mix with the borated coolant at the upflow side of the core or it can accumulate at the cross over leg and mix at the downflow side of the core.

There are three main intrinsic scenarios listed by Queral et al. [15]:

i. Loss of Residual Heat Removal System (RHRS) at midloop condition;
ii. Large Break - Loss of Coolant Accident (LB-LOCA) - Emergency Core Cooling System (ECCS) hot leg recirculation;
iii. Small Break Loss of Coolant Accident (SB-LOCA).

In the Resolution of Generic Safety Issue 185, the U.S. Nuclear Regular Commission (NRC) has mentioned that if the accident happens early in the fuel cycle, the unborated slug can generate sufficient excess reactivity in the core even though all the control rods have been inserted. That may result in severe damage to the core even though the ECCS has kept the core covered with coolant sufficiently [16]. The high possibility of a positive reactivity insertion accident due boron dilution exists when the excess reactivity of the system is greater than the rod worth, which depends on burnup and reactor coolant system (RCS) thermal-hydraulic condition [15]. In addition, Diamond et al. [17] reported that the restart of the reactor coolant pump (RCP) results in higher positive reactivity insertion as compared to the restart of natural circulation. The main reason for the high risk of fuel damage with restart of RCP was explained with the 25 % higher mass flow rate than the natural circulation of the unborated slug entering the reactor core lower plenum.

The boron dilution phenomena can be analyzed in five steps [18]:

i. Formation of the diluted boron slug;
ii. Transport of the diluted boron slug;
iii. Mixing of the diluted boron slug;
iv. Deboration (net loss of boron from primary system) and boration (net boron gain with ECCS);
v. Reactivity feedback.

In this study, transport and mixing of diluted boron slug, deboration and boration aspects were aimed to be investigated by implementing a boron tracking model in CTF.

2. Boron Tracking Model Implementation in CTF

In several system codes such as RELAP5 and TRACE, boron concentration is assumed to be sufficiently low and the following assumptions are applied [4, 5]:

i. Sufficiently dilute solute;

ii. Negligible liquid property change by the presence of the solute;
iii. Negligible energy transfer and inertia of the solute.

According to these assumptions, the solute field is described separately from the rest of the flow fields by a three-dimensional hyperbolic transport equation. The molecular and turbulent diffusions are neglected to simplify the numerical solution. In this section, three different numerical schemes used in the system codes RELAP5 and TRACE are summarized.

First Order Accurate Upwind Difference Scheme:

Based on the linear convection equation, the one dimensional field equation for the conservation of the boron can be written as:

$$\frac{\partial \rho_b}{\partial t} + \frac{1}{A}\frac{\partial(\rho_b v_f A)}{\partial x} = 0 \qquad (1)$$

where the spatial boron density, ρ_b, is defined as:

$$\rho_b = \alpha_f \rho_f C_b = \rho_m (1-x) C_b \qquad (2)$$

Eq. 3 can be discretized by calculating the volume averaged solute density at the cell center (*L*), while evaluating the velocity field at the cell faces (*j* and *j+1*) as:

$$V_L(\rho_{b,L}^{n+1} - \rho_{b,L}^{n}) + (\rho_{b,L}^{n} v_{f,j+1}^{n+1} A_{j+1} - \rho_{b,K}^{n} v_{f,j}^{n+1} A_j)\Delta t = 0 \qquad (3)$$

First order upwind approach has been reported being stable and its robustness was given as an advantage in the solution of the general flow equations. However, it has been emphasized that the first order scheme generates numerical diffusion, which can overshadow the performance of the flow model [6]. For example, in order to have a detailed description of spatial and temporal distribution of the flow filed such as heterogeneous solute field inside reactor vessel; numerical diffusion can generate unrealistic results from a safety point of view [3].

Second Order Accurate Godunov Scheme:

Based on *Finite Volume Method*, and using the divergence theorem, Eq. 1 can be re-written in a control volume (*V)* and with a surface area (*A)* :

$$\int_V \frac{\partial \rho_b}{\partial t} dV + \int_A \rho_b v_f \bullet dA = 0 \qquad (4)$$

Based on Fig.1, the upward difference discretization of Eq. 4 gives the solution of *First Order Accurate Godunov Scheme* with respect to mass flux F_j and F_{j+1} :

$$\left[\rho_{b,L}^{n+1} - \rho_{b,L}^{n}\right] + \left[\frac{\Delta t}{V_L}\left(A_{j+1}F_{j+1}^{n} - A_j F_j^{n}\right)\right] = 0 \qquad (5)$$

Since the velocity (*v*) is known in both old (*n*) and new (*n+1*) time steps, it can be linearly interpolated to generate approximation based on time centered velocity ($v^{n+1/2}$) as:

$$v_{f,j+1}^{n+\frac{1}{2}} = v = \frac{1}{2}(v_{f,j+1}^{n+1} + v_{f,j+1}^{n}) \tag{6}$$

Then the flux terms F_j and F_{j+1} in old time domain n in Eq. 5 can be defined as:

$$F_{j+1}^{n} = \left[v_{f,j+1}^{n+\frac{1}{2}} \frac{\left(\rho_{b,j+1}^{n,L} + \rho_{b,j+1}^{n,M}\right)}{2} + \left| v_{f,j+1}^{n+\frac{1}{2}} \right| \frac{\left(\rho_{b,j+1}^{n,L} - \rho_{b,j+1}^{n,M}\right)}{2} \right] \tag{7}$$

$$F_{j}^{n} = \left[v_{f,j-1}^{n+\frac{1}{2}} \frac{\left(\rho_{b,j-1}^{n,K} + \rho_{b,j}^{n,L}\right)}{2} + \left| v_{f,j-1}^{n+\frac{1}{2}} \right| \frac{\left(\rho_{b,j-1}^{n,K} - \rho_{b,j}^{n,L}\right)}{2} \right] \tag{8}$$

As a result, the *First Order Godunov Scheme* increases its accuracy and becomes *Second Order Accurate*. However, this scheme introduces spurious oscillations into the solution, where discontinuities and shocks are present. A cell centered gradient limiter can be defined to reduce the oscillatory behavior of the numerical solution as:

$$\overline{S_L} = \Phi(S_j, S_{j+1})(1 + \theta_L \omega_L) \tag{9}$$

The presented cell centered gradient limiter, S_L, can be defined in two steps. First, in order to reduce the oscillatory behavior in the central differencing method a compressive limiter was recommended such as *Super Bee Limiter* [19]. Super Bee Limiter is a *slope limiter*, which can be obtained by taking the ratio between the cell centered variables and the cell lengths as: $\Phi(S_j, S_{j+1})$

$$S_j = \frac{\rho_{b,L}^{n} - \rho_{b,K}^{n}}{\Delta x_j} \quad \text{(a)} \quad , \quad S_{j+1} = \frac{\rho_{b,M}^{n} - \rho_{b,L}^{n}}{\Delta x_{j+1}} \quad \text{(b)} \tag{10}$$

or, by taking the ratio:

$$r = \frac{S_j}{S_{j+1}} \tag{11}$$

$$\Phi(S_j, S_{j+1}) = \Phi(r,1) S_{j+1}, \tag{12}$$

where

$$\Phi(r,1) = \max[0, \min(2r,1)\min(r,2)] \tag{13}$$

Additionally, in order to make sure that solution is continuous an artificial compression term should be introduced $(1 + \theta_L \omega_L)$, where the discontinuity detector θ_L is given as:

$$\theta_L = \frac{|1-r|}{1+|r|} \tag{14}$$

The parameter ω_L is chosen to be a function of the local Courant number $C_{r_L} = {v_L \Delta t}/{\Delta x_L}$

$$\omega_L = \min(C_{r_L}, 1 - C_{r_L}) \tag{15}$$

Then cell-centered limited gradient $\overline{S_L}$ can be re-written as:

$$\overline{S_L} = (1+\theta_L\omega_L)\Phi(r,1)S_{j+1} = (1+\theta_L\omega_L)\Phi(r,1)\left(\frac{\rho_{b,M}^{n} - \rho_{b,L}^{n}}{\Delta x_{j+1}}\right) \tag{16}$$

The cell-centered limited gradient $\overline{S_L}$ provides higher order accuracy in space and time interpolation for cell edge values of ρ_b with respect to the changes in the neighboring cells from the flux at their common interface [19] as:

$$\rho_{b,j+1}^{n,L} = \rho_{b,L}^{n} + \left(\frac{1}{2}\Delta x_L\right)\left(1 - \frac{v\Delta t}{\Delta x_L}\right)\overline{S_L} \tag{17}$$

$$\rho_{b,j+1}^{n,M} = \rho_{b,M}^{n} - \left(\frac{1}{2}\Delta x_M\right)\left(1 + \frac{v\Delta t}{\Delta x_M}\right)\overline{S_M} \tag{18}$$

The solution of second scheme is the *Second Order Accurate Godunov Scheme*, which reduces the numerical diffusion and increases the accuracy significantly by re-defining the boron transport.

Modified Godunov Scheme:

In recent studies, RELAP5 became an important tool for investigating the variation in the boron concentration numerically in different SB-LOCA tests with boron dilution. In 2007, Freixa et al. studied the RELAP5 schemes in terms of numerical and physical diffusions [6]. Despite its capability of reducing the numerical diffusion, Godunov scheme was reported as not simulating the physical diffusion such as turbulent diffusion, which is present in the nature. Thus, an additional diffusion term was suggested and defined within the Godunov solution by replacing the integrated boron field Eq. 4 and the third model *Modified Godunov Scheme* was defined as:

$$\int_V \frac{\partial \rho_b}{\partial t} dV + \int_A \left(\rho_b v_f - D\frac{\partial \rho_b}{\partial t}\right) \bullet dA = 0 \tag{19}$$

There were two physical diffusion terms (D) defined based on the collision of the boron particles and turbulent phenomena which are Brownian diffusion and Eddy diffusion. Comparing to the eddy diffusion coefficient, Brownian coefficient is obtained giving a lower scale ordered between 10^{-6} and 10^{-7} [6] .Thus, only Eddy diffusion is included in the equation as

$$D_{Eddy} = G_o v \mathrm{Re}^{7/8}\ , \tag{20}$$

where diffusion coefficient, G_o, was taken as 1.35. Following the similar procedure, Eq. 18 and 19 are rewritten including the eddy diffusion coefficient D_{Eddy} as:

$$\rho_{b,j+1}^{n,L} = \rho_{b,L}^{n} + \left[\left(\frac{1}{2}\Delta x_L \right)\left(1 - \frac{v_L \cdot \Delta t}{\Delta x_L} \right) - \varphi_L \right] \overline{S}_L \ , \tag{21}$$

where φ is the limited diffusion term:

$$\varphi_L = \min\left\{ \frac{\Delta x}{2C_r}, \frac{D_{Eddy}}{v_L} \right\} \tag{22}$$

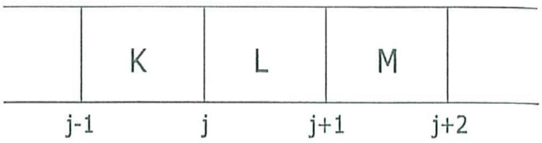


Figure 1: Nomenclature Used

All three different boron tracking models presented in here were implemented in CTF and compared based on their accuracy and spatial nodal mesh sensitivity. Similar to Frexia et al.'s study the most accurate prediction were obtained by the Modified Godunov Scheme. Since other two models lack a capability of simulating the physical diffusion, the truncation error was higher. Thus, it is concluded that the Modified Godunov scheme approach provides the most accurate and stable results in CTF [1].

3. Subchannel Approach and Cross Flow Mechanism

The importance of the mixing in the transport of the diluted boron slug has been previously emphasized, and the lack of a higher order numerical method and reliable turbulence models were given as the limitations of the current system codes in the modeling of the mixing effects. Due to its higher accuracy and numerical stability, the Modified Godunov Model was selected as a basis for further analysis of the transport and the mixing of the diluted boron slug by using the subchannel approach of CTF.

According to subchannel coordinate system (axial *X*, lateral *Z*), the conservation equation of boron, i.e. Eq. 1 can be rewritten as:

$$\underbrace{\frac{\partial \rho_b}{\partial t} + \frac{1}{A}\frac{\partial(\rho_b v_f A)}{\partial X}}_{\text{Axial Change } (X)} + \underbrace{\frac{1}{A}\sum_k (\rho_b w_f L_g)_k}_{\text{Total Transverse (or Lateral) Gain}} = 0 \tag{23}$$

Based on Eq. 23, for multiple subchannel geometry it was necessary to include the transverse boron exchange between subchannels at each gap location. CTF takes into account the amount of lateral fluid transfer in its axial momentum calculations. Therefore, rather than calculating the amount of solute transfers, it was sufficient to include the total boron mass gain and loss at each gap location and add it in to the axial boron transport model. By doing so, the mass of boron particles is calculated based on solute concentration and included at every lateral flow transfer locations along the axial length. For the two channels axial nodalization given in Fig. 2, the calculation of the boron mass and boron concentration at time step n can be given as follows:

- Assume that there are two channels, *channel ii* and *channel jj*, modeled in CTF. Along the axial length (*j-1, j ,j+1* etc.), the two channels are connected by the gap *k*:

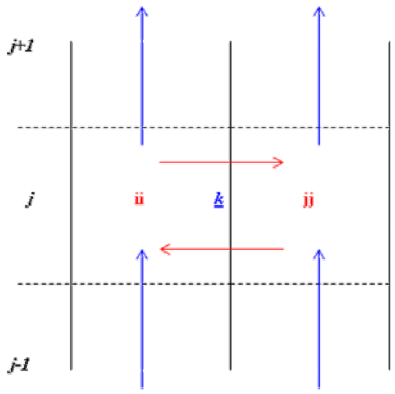


Figure 2: CTF Two Subchannel Axial and Lateral Nodalization

- For the gap *k* , amount of boron in each subchannel can be written as:
  - If lateral flow is from *channel ii* to *channel jj* then:

$$m_b(ii,j) = m_b(ii,j) + \Delta m_b(ii)\Big|_{j-1}^{j} - \Delta m_b(k)\Big|_{ii}^{jj} \quad (24 - a)$$

$$m_b(jj,j) = m_b(jj,j) + \Delta m_b(jj)\Big|_{j-1}^{j} + \Delta m_b(k)\Big|_{ii}^{jj} \quad (24 - b)$$

  - The axial boron mass transfer to *channel ii* and *channel jj* is respectively:

$$\Delta m_b(ii)\Big|_{j-1}^{j} = \left(\dot{m}_b(ii,j-1) - \dot{m}_b(ii,j) \right)\Delta t \quad (25 - a)$$

$$\Delta m_b(jj)\Big|_{j-1}^{j} = \left(\dot{m}_b(jj,j-1) - \dot{m}_b(jj,j) \right)\Delta t \quad (25 - b)$$

  - The lateral boron mass transfer to *channel ii* and *channel jj* is respectively:

$$\Delta m_b(k)\Big|_{ii}^{jj} = \left(\frac{C_b(ii,j)}{10^6 - C_b(ii,j)} \right)\left(\dot{m}_f(k,j) \right)\Delta t \quad (26 - a)$$

$$\Delta m_b(k)\Big|_{jj}^{ii} = \left(\frac{C_b(jj,j)}{10^6 - C_b(jj,j)} \right)\left(\dot{m}_f(k,j) \right)\Delta t \quad (26 - b)$$

where, m_b is the total subchannel boron mass and C_b is the boron concentration in unit of ppm.

4. 2×2 Multiple Subchannel Rod Bundle Test Study

In this case study, it was aimed to assess the boron tracking model performance and to measure the cross flow mechanism effect in multiple subchannel geometry, where each subchannel is connected to its neighbors via more than one gap. Therefore, a sub-assembly geometry is generated consisting of 4 fuel pins and simulated in CTF. In order to have a more realistic approach, geometric parameters and initial conditions are selected based on GE 3×3 Test Run 2B2 [13, 14]. In Fig. 3 the cross-sectional geometry of both subchannels is illustrated and the geometric parameters with initial conditions are summarized in Table 1 and Table 2.

In order to have a better understanding, in this study the results for corner subchannels (subchannel 1 and 3) are represented in blue, the side subchannels (subchannel 2 and 8) are represented in red and the central subchannel (subchannel 5) is represented in green color.

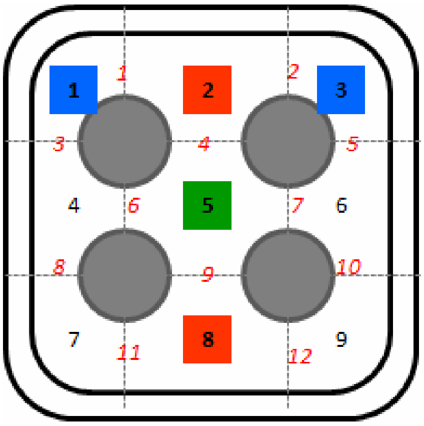


Figure 3: Cross-Sectional Area of 2×2 Rod Bundle

Table 1: Subchannel Geometric Parameters and Initial Conditions of 2×2 Rod Bundle

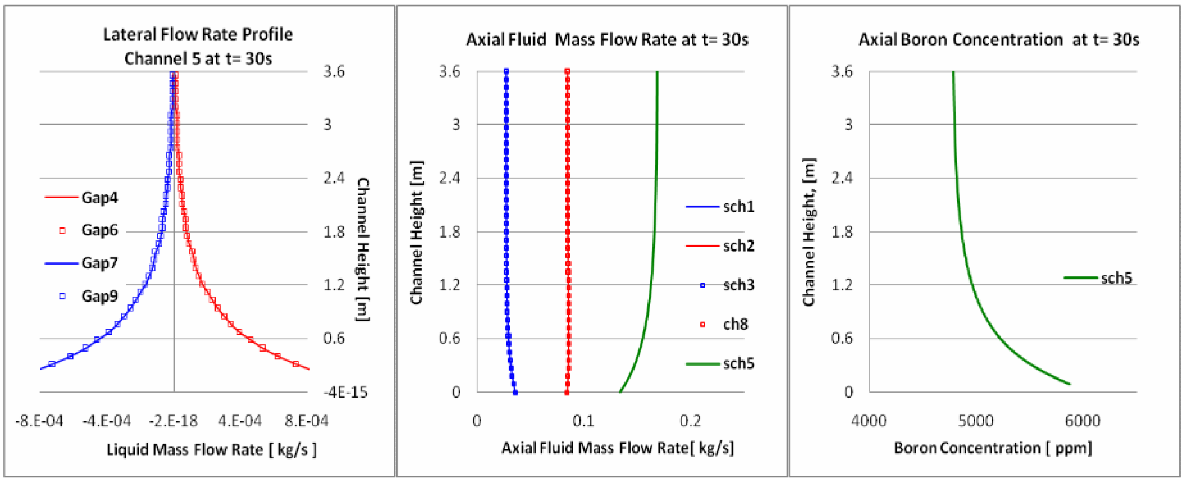
Subchannel Type	Area [m^2]	Perimeter [m]	D_h [m]	C_b (t < 10s) [ppm]	C_b (t ≥ 10s) [ppm]	Re_{in} [-]
Corner (# 1,3,7 9)	5.52 x 10^{-5}	0.0283	0.0071	0	0	41279
Side (# 2,4,6,8)	1.17 x 10^{-7}	0.0415	0.0113	0	0	65712
Internal (# 5)	1.87 x 10^{-4}	0.0455	0.0164	0	6000	95133

Table 2: Transverse Connections (Gap) Parameters

Gap Type	Gap width [m]	Gap length [m]
Corner-Side	3.429 x 10^{-5}	0.0147
Side-Internal	4.267 x 10^{-4}	0.0147

The transient was started as the 486 °K single phase water injection with total mass flow rate of 0.618 kg/s was inserted from the bottom section of the 3.6 m vertical pipe under operating pressure 70 bar. Initially, at t =0 s both subchannels have 0ppm boron concentration. At time equal to 10s, when the flow reached to steady state condition, 6000ppm boron concentration is introduced at the inlet of subchannel 5, while keeping 0ppm in neighboring subchannels. By doing so, it was intended to measure the effect of lateral mixing from subchannel 5 to its neighboring subchannels.

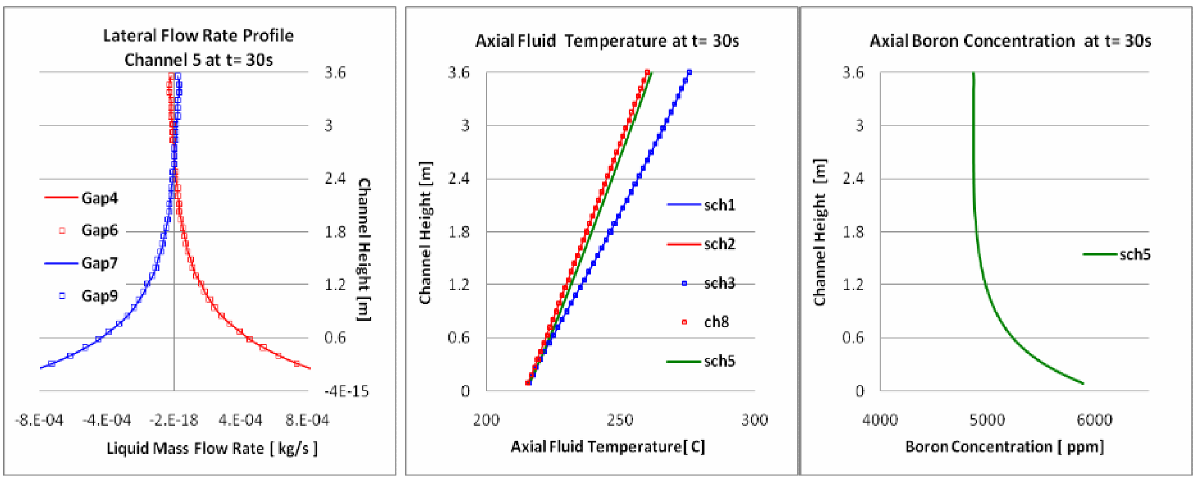
For the initial case study, the rods were kept unheated. Thus, fluid temperature remained constant and the lateral pressure gradient occurred only due to difference in subchannel cross-sectional flow areas. In Fig. 4 (a), the lateral gap flow across central subchannel 5 is presented. In CTF the positive sign represents the flow direction from lower numbered subchannel to higher number subchannel. Due to its higher cross-sectional flow area, continuous transverse flows into the central subchannel 5 from its neighboring subchannels were observed along the axial channel length. Thus, the axial flow rate in subchannel 5 is increased as shown in Fig. 4(b). This continues lateral unborated flow mixing caused boron dilution inside subchannel 5. As indicated in Fig. 4(c), the initial 6000ppm boric acid concentration is measured 4780 ppm when it reached to the exit.



(a) (b) (c)

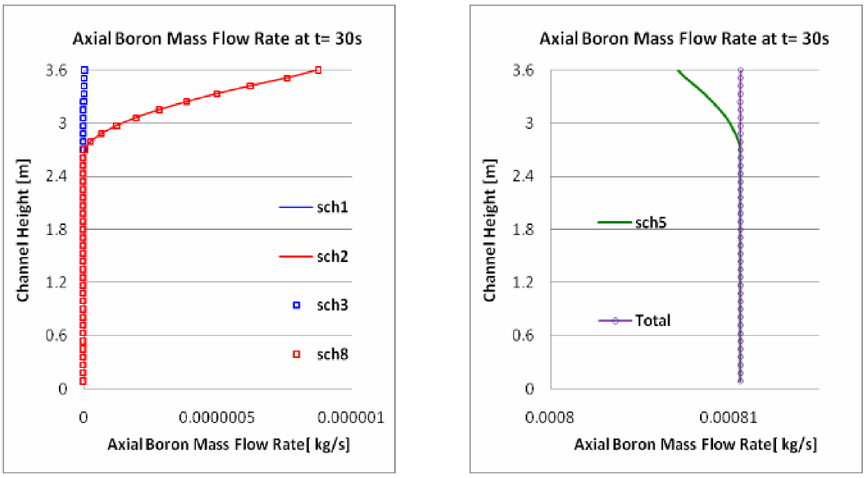
Figure 4: (a) Lateral Flow Rate around Subchannel 5, (b) Axial Flow Rate Profiles
(c) Axial Boric Acid Concentration in Subchannel 5

In the second case study cross flow mechanism is further investigated including the heat transfer effect. 140kW heat is distributed uniformly along 4 rods. Flow is kept in single phase and the resultant axial flow, temperature and cross-flow profiles are calculated. Similar to initial case study, boron is injected only to the central channel, subchannel 5 when the system reached steady state. This case was studied to capture the temperature effect on fluid properties and boric acid concentration. As it is shown in Fig. 5(a), the highly borated fluid in the central subchannel is transferred to the neighboring subchannels at higher elevation. Since as the temperature rises and the fluid expands, some of the liquid is pushed out of the active solute flow area. Boron is also moved out in the same ratio of the liquid, therefore the concentration remains constant in this region which is shown in Fig 5(c). However, as it is shown in Fig 6 (a) and (b) with moving the amount of boron, its flow rate decreased in the central subchannel while increasing at the neighboring subchannels.



(a) (b) (c)

Figure 5: (a) Lateral Flow Rate around Subchannel 5, (b) Axial Temperature Profiles
(c) Axial Boric Acid Concentration in Subchannel 5

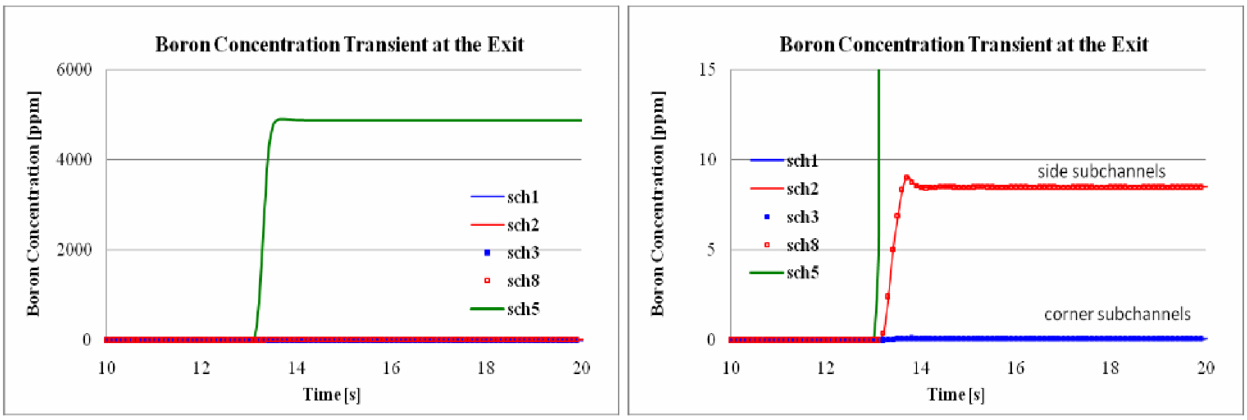


(a) (b)

Figure 6: Axial Boron Mass Flow Rate in Corner and Side Subchannels (a) and in the Central Subchannel (b)

It was important to check the consistency of the mixing model. Therefore, in order to determine if the boron flow conserves or not, the total boron flow rate are calculated and results are plotted in Fig. 6 (b). As it is shown in the figure, the total amount of boron flow at the exit was obtained equal to the inlet value and it is conserved and remained constant along the channel height.

Beside the axial variations, boron concentration transient was measured at the exit of two subchannels and results are presented in Fig. 7 (a) and (b). From the figures, the central subchannel 5's boric acid concentration is measured as 4860 ppm. In addition, as a result of the lateral borated flow from the central subchannel to its neighbors, the side subchannels concentration is increased up to 9 ppm after 4 seconds of the boron insertion at 10 s. This final case study concludes that the multidimensional modeling of the boron transport based on the subchannel approach provides the variation in the boron concentration accordingly to the flow operation conditions.



(a) (b)

Figure 7: Boron Concentration Transient at the Exit of Central Subchannel (a) and Corner and Side Subchannels (smaller scale) (b)

5. Conclusion

The second order Modified Godunov Scheme for boron tracking was successfully implemented in the thermal-hydraulic subchannel code CTF. Besides the modeling of the axial transport of boron, it was also anticipated to use the advantage of the subchannel approach to model the mixing of the diluted boron slug, the deboration and the boration effects. Based on the subchannel coordinate system formulation, the lateral boron mass transfer was calculated and included into the Modified Godunov Model's axial transport calculations. Using a 2×2 rod bundle geometry and changing the boundary conditions based on GE 3×3 Test Run, the deboration and boration model capabilities were analyzed at different cross flow conditions. For each case study, the total boron flow rate was conserved, which verified the consistency of the mixing results.

The performed studies have demonstrated the accuracy and the numerical stability of the new model under variety of geometrical and operational conditions. Currently, the CTF boron tracking model is being extended to analysis of the lateral flows inside larger and more complex bundle geometries. As a future work entrainment droplet field effect in the boron transportation at two phase flow conditions have been investigated to provide more realistic plant simulations. Such improvements will provide a multi dimensional boron transport model based on the subchannel approach and it will make CTF capable of analyzing the solute transients and the boron mixing effects inside the reactor core region at the same time.

6. Acknowledgment

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7. Nomenclature

A = cross-sectional area (m^2)
C_r = Courant number
C_b = boron concentration in the liquid (ppm)
D = diffusion coefficient
D_h = hydraulic diameter (m)
L_g = gap length (m)
m = mass (kg)
r = ratio of volume centered boron particles
Re = Reynolds number
S = source of boric acid particles
t = time (s)
T = temperature (°K)
V = volume (m^3)
v = axial velocity (m/s)
w = lateral velocity (m/s)
x = spatial coordinate (m)
X = axial coordinate direction

Symbols

α = void fraction
Δt = increment in time variable (s)
Δx = increment on spatial variable (m)
θ = discontinuity detector factor
ρ = density (kg/m^3)
ν = kinematic viscosity (m^2/s)
φ = limited diffusion term
Φ =Roe's superbee gradient limiter
ω = constant in Godunov solution

Subscripts

b = boron
f = liquid phase
ii, jj = adjacent subchannel indices
$j, j+1$ = spatial nodding indices for junction
k = lateral adjacent subchannel gap index
K, L, M= spatial nodding index for volume
m = mixture property
min = minimum
max = maximum

Superscripts

$n, n+1$ = time level index
$\bar{\ }$ = averaged quantity

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