# Coupling Considerations

Initially, the project group set out to have a fully coupled thermal hydraulics and neutronics transient code. The desire was to couple the temperature along a fuel rod with the cross sections, which would provide feedback to the neutronics model. It was proposed that a conduction solver for the fuel temperature would be coupled with a drift flux solver for the coolant temperature and void fraction. From that information, the cross sections could be developed for a 1-d case. Then, a transient diffusion solver could provide the flux (and thus power) profile, and a spatial kinetics code could provide the flux amplitude. From the amplitude and shape of power, the conduction/drift flux code could then update the temperature for the next time step.

The thermal hydraulics section of the code was very complex. The drift flux model (as described in Appendix A), has four major unknowns and many considerations for equation closure. Coupling this with the conduction code was time intensive and was not completed. As this was not completed, the consistency of the model was degraded.

Because of the degraded consistency of the model, the inclusion of a diffusion model for flux shape was inappropriate. The model and solver for the diffusion model are provided in (Appendix C). The flux shape will not change in an adiabatic model, so the addition of the diffusion model into the solver loop was unnecessary.

The cross section generation part of the model was very important, and essentially distilled 3 dimensional geometry into 1 dimensional cross sections, and would be essential to create a spatially dependent kinetics code. The specifics of the cross section code are provided in Appendix D.

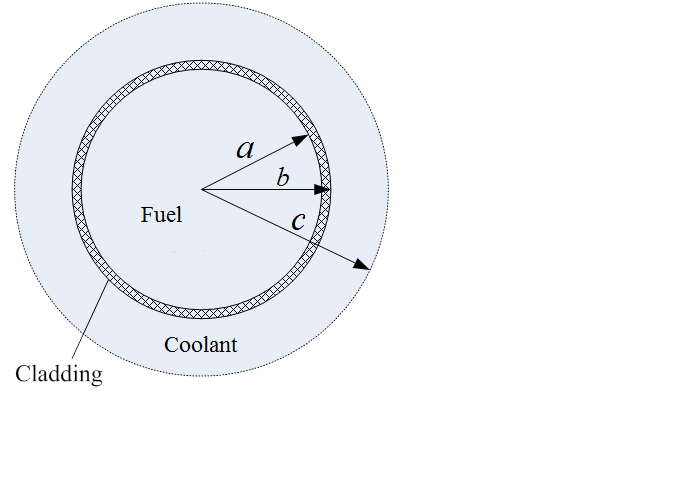
It is recommended that for future work, the thermal hydraulics considerations would be solved, whether through actually solving the drift flux model, or through the use of another thermal hydraulics code to provide results given a power distribution.

# Appendices

## Appendix A: Drift Flux Model

Problem:

Develop a single channel thermal-hydraulic model to couple the neutron kinetics and the drift flux model for coolant.



# 1. Geometrical dimensions

|  |  |  |
| --- | --- | --- |
| **Item** | **unit** | **Value** |
| Fuel rod outside diameter | mm | 12.27 |
| Fuel rod cladding thickness | mm | 0.8126 |
| Coolant channel outside diameter | mm | 16.256 |

# 2. Governing equations

(1) The fuel part



(2) The cladding part



(3) The coolant part (drift flux model)







Assumptions to simplify the field equations

(1) Neglect covariance term in momentum equation and energy equation

(2) Neglect conduction heat flux, turbulent diffusion energy flux, and compressive term

(3) The gas phase is treated as saturated phase, and liquid phase is either superheated or subcooled.

(4) Neglect axial shear forces due to velocity gradient in the fluid

(5) Neglect frictional dissipation









Constitutive relations:























Four parameters p, ,, are chosen as the fundamental unknowns.

# 3. Spatial Discretization

Control volume approach for flow equations

By integrating Eq. over the main control volume i (zi-1 ≤ z ≤zi), the mass balance equation for the node i is obtained as



where





By integrating Eq. ,



By integrating Eq. over the main control volume



Using the continuity equation in Eq. , Eq. can be rewritten as



The momentum balance equation for the node i is obtained by integrating Eq. over the momentum control volume i (zi-1+ △zi /2≤ z ≤ zi+ △zi /2) . For a constant flow area, this integration over the momentum control volume results in



To obtain a stable solution,









The density is then computed from a pressure-enthalpy state relation as







For an upward flow in a constant flow area, the mass, energy and momentum equations are reduced to









Semi-Implicit Scheme









## Appendix B: Steady State Drift Flux Solving Methodology

## Appendix C: Diffusion Model and Solving Methodology

## Appendix D: Cross Section Generation for Spatially Dependent Kinetics Solver

Core simulators use macroscopic cross sections which are functionalized on boron concentration (B, in ppm), square root of the effective fuel temperature, moderator temperature and density, void fraction (α) and the effective rodded fractions (ξ). Only the linear dependence of cross sections is considered on these state variables except for the moderator density and void fraction for which the quadratic variation is additionally considered.

For the BWR case the interesting instantaneous variables are fuel temperature, moderator density and void fraction (α). Moderator density perturbation was used to represent the physics before boiling, while the void fraction perturbation was used to represent the phenomena after boiling. As shown in Table1, two group data for the next stage flux solver was calculated by MATLAB code. The history variables are not considered here. In order to obtain the right cross section representing the reaction rate in different operation condition, the coefficients corresponding to fuel temperature and void were calculated. These coefficients were determined by running several CASMO cases. Pin cell calculation model in CASMO was used to calculate the two group data. Based on the GE BWR 9\*9 fuel assembly design parameters, a 2x2 segment symmetry model were used in CASMO pin cell calculation model. In neutronics model, the gap of fuel pin was neglect, and the cladding thickness was increased from 1.42 mm to 1.84 mm. Table 2 shows the design parameters for fuel pin and corresponding thermal hydraulic data.

From PARCS manual:

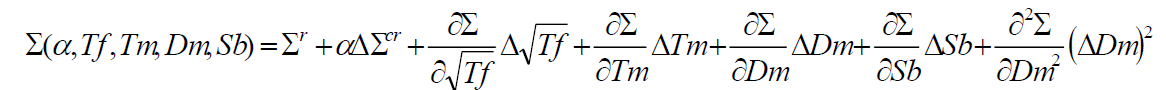


Table1 CASMO-4 Data Functionalization for BWR Case

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter P | | Notation in MATLAB code | | Cross section functionalization |
| D1 | D2 | D1 | D2 | Σ(Tf, ρm, α)= Σ0 x (1 + c1(√Tf-√Tf0) + c2(Δρm) + c3(Δρm 2)+ c4(Δα) + c5(Δα2)) |
| Σa,1 | Σa,2 | Sigma\_a\_g1 | Sigma\_a\_g2 |
| νΣf,1 | νΣf,2 | nuSigma\_f\_g1 | nuSigma\_f\_g2 |
| Σ1→2 |  | Sigma\_s\_g1\_2 |  |

Table2 Fuel Pin Design Parameters for BWR Case

|  |  |
| --- | --- |
| GE BWR 9\*9 Specification | |
| Pellet OD, mm | 9.55 |
| Air Gap, mm | 0.105 |
| Cladding ID, mm | 9.76 |
| Cladding OD, mm | 11.18 |
| Fuel Pin Pitch, mm | 14.27 |
| CASMO Output Specification | |
| Pin Pitch, mm | 14.27 |
| Segment Width, mm | 28.54 |
| Number of Fuel Pin in Assembly | 4 |
| Fuel Pellet Diameter, mm | 9.55 |
| Fuel Rod Diameter, mm | 11.18 |
| Channel Inside Width, mm | 28.54 |
| Wet Perimeter, mm | 140.49 |
| Hydraulic Diameter Channel, cm | 12.01 |
| Flow Area, cm2 | 4.22 |

For the cross section coefficient calculation, the based case was set the fuel temperature to 810 K, moderator temperature to 560 K, and void fraction equal to 40%. As shown in Table3, these coefficients were determined at various fuel temperature and void fraction. With these coefficients, MATLAB code was used to calculate the XS at different operation conditions. In order to verify the MATLAB code of XS generation, several cases were chosen to test the accountability. Fuel temperature ranged from 560 K to 1800 K, and void fraction ranged from 0% to 80%. The comparison of the calculated XS between CASMO and MATLAB was shown in Table4. The XS generated by the two codes were essentially identical. The largest relative error is the diffusion coefficient for group 2 with the magnitude of 2.6%.

Table3 Coefficient for XS Functionalization in BWR Case

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Σ(Tf, ρm, α)= Σ0 x (1 + c1(√Tf-√Tf0) + c2(Δρm) + c3(Δρm 2)+ c4(Δα) + c5(Δα2)) | | | | |
|  | C1 | C2 | C3 | C4 | C5 |
| D1 | -1.314E-04 | -3.549E-01 | 1.095E-01 | -5.710E-01 | 2.032E-01 |
| D2 | -3.749E-04 | -8.781E-01 | 6.473E-01 | -1.724E+00 | 2.349E+00 |
| Σa,1 | 2.594E-03 | 2.359E-01 | -1.526E-01 | 4.852E-01 | -6.803E-01 |
| Σa,2 | -6.134E-04 | 2.689E-01 | 1.490E+00 | 4.642E-01 | -4.874E-01 |
| νΣf,1 | -8.194E-05 | 2.177E-01 | -1.597E-01 | 4.833E-01 | -7.724E-01 |
| νΣf,2 | -6.322E-04 | 2.463E-01 | 1.494E+00 | 4.194E-01 | -5.253E-01 |
| Σ1→2 | -1.594E-03 | 1.786E+00 | 3.420E-02 | 2.857E+00 | 5.521E-01 |

Table4 Comparison of the Calculated XS Between CASMO and MATLAB

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Base Case | | XS calculated  by MATLAB | | XS calculated  by CASMO | | Difference  (MA-CA/CA, %) | |
| Tf =810 K , Void=40% | |
| D1 | D2 | 1.6032E+00 | 5.6379E-01 | 1.6032E+00 | 5.6379E-01 | 0.00 | 0.00 |
| Σa,1 | Σa,2 | 9.9259E-03 | 1.0050E-01 | 9.9259E-03 | 1.0050E-01 | 0.00 | 0.00 |
| νΣf,1 | νΣf,2 | 8.3088E-03 | 1.8297E-01 | 8.3088E-03 | 1.8297E-01 | 0.00 | 0.00 |
| Σ1→2 |  | 7.0324E-03 |  | 7.0324E-03 |  | 0.00 |  |
| Tf =810 K , Void=20% | |  | | | |  |  |
| D1 | D2 | 1.4815E+00 | 4.5370E-01 | 1.4800E+00 | 4.6573E-01 | 0.10 | -2.58 |
| Σa,1 | Σa,2 | 1.0468E-02 | 1.0607E-01 | 1.0395E-02 | 1.0564E-01 | 0.70 | 0.41 |
| νΣf,1 | νΣf,2 | 8.7451E-03 | 1.9183E-01 | 8.6698E-03 | 1.9099E-01 | 0.87 | 0.44 |
| Σ1→2 |  | 9.9204E-03 |  | 9.9616E-03 |  | -0.41 |  |
| Tf =810 K , Void=80% | |  | | | |  |  |
| D1 | D2 | 1.8849E+00 | 9.3957E-01 | 1.8846E+00 | 9.3957E-01 | 0.02 | 0.00 |
| Σa,1 | Σa,2 | 8.0490E-03 | 8.3606E-02 | 8.0494E-03 | 8.3610E-02 | 0.00 | 0.00 |
| νΣf,1 | νΣf,2 | 6.6822E-03 | 1.5396E-01 | 6.6832E-03 | 1.5397E-01 | -0.01 | -0.01 |
| Σ1→2 |  | 1.7125E-03 |  | 1.7122E-03 |  | 0.02 |  |
| Tf =560 K , Void=40% | |  | | | |  |  |
| D1 | D2 | 1.6042E+00 | 5.6480E-01 | 1.6042E+00 | 5.6437E-01 | 0.00 | 0.08 |
| Σa,1 | Σa,2 | 9.8024E-03 | 1.0080E-01 | 9.8006E-03 | 1.0077E-01 | 0.02 | 0.03 |
| νΣf,1 | νΣf,2 | 8.3121E-03 | 1.8352E-01 | 8.3086E-03 | 1.8349E-01 | 0.04 | 0.02 |
| Σ1→2 |  | 7.0862E-03 |  | 7.0856E-03 |  | 0.01 |  |
| Tf =1200 K , Void=40% | |  | | | |  |  |
| D1 | D2 | 1.6019E+00 | 5.6248E-01 | 1.6019E+00 | 5.6211E-01 | 0.00 | 0.07 |
| Σa,1 | Σa,2 | 1.0085E-02 | 1.0012E-01 | 1.0084E-02 | 1.0010E-01 | 0.01 | 0.02 |
| νΣf,1 | νΣf,2 | 8.3046E-03 | 1.8226E-01 | 8.3019E-03 | 1.8219E-01 | 0.03 | 0.04 |
| Σ1→2 |  | 6.9631E-03 |  | 6.9626E-03 |  | 0.01 |  |
| Tf =1800 K , Void=40% | |  | | | |  |  |
| D1 | D2 | 1.6003E+00 | 5.6084E-01 | 1.6003E+00 | 5.5936E-01 | 0.00 | 0.26 |
| Σa,1 | Σa,2 | 1.0286E-02 | 9.9639E-02 | 1.0281E-02 | 9.9486E-02 | 0.05 |  |
| νΣf,1 | νΣf,2 | 8.2993E-03 | 1.8135E-01 | 8.2912E-03 | 1.8100E-01 | 0.10 | 0.19 |
| Σ1→2 |  | 6.8758E-03 |  | 6.8740E-03 |  | 0.03 |  |
| Tf =293 K , Void=0% | |  | | | |  |  |
| D1 | D2 | 1.3749E+00 | 3.9787E-01 | 1.3737E+00 | 3.9513E-01 | 0.09 | 0.69 |
| Σa,1 | Σa,2 | 1.0453E-02 | 1.1042E-01 | 1.0393E-02 | 1.1030E-01 | 0.58 | 0.11 |
| νΣf,1 | νΣf,2 | 8.9377E-03 | 1.9823E-01 | 8.9158E-03 | 1.9805E-01 | 0.25 | 0.09 |
| Σ1→2 |  | 1.3088E-02 |  | 1.3122E-02 |  | -0.26 |  |
| Tf =425 K , Void=20% | |  | | | |  |  |
| D1 | D2 | 1.4831E+00 | 4.5535E-01 | 1.4811E+00 | 4.6573E-01 | 0.14 | -2.23 |
| Σa,1 | Σa,2 | 1.0266E-02 | 1.0655E-01 | 1.0168E-02 | 1.0606E-01 | 0.96 | 0.46 |
| νΣf,1 | νΣf,2 | 8.7504E-03 | 1.9273E-01 | 8.6658E-03 | 1.9181E-01 | 0.98 | 0.48 |
| Σ1→2 |  | 1.0008E-02 |  | 1.0062E-02 |  | -0.54 |  |
| Tf =1200 K , Void=70% | |  | | | |  |  |
| D1 | D2 | 1.8084E+00 | 8.2487E-01 | 1.8120E+00 | 8.0494E-01 | -0.20 | 2.48 |
| Σa,1 | Σa,2 | 8.7766E-03 | 8.8168E-02 | 8.8484E-03 | 8.8819E-02 | -0.81 | -0.73 |
| νΣf,1 | νΣf,2 | 7.1789E-03 | 1.6191E-01 | 7.2841E-03 | 1.6314E-01 | -1.44 | -0.75 |
| Σ1→2 |  | 2.9162E-03 |  | 2.8772E-03 |  | 1.36 |  |