Computational Analysis Code Development for core and primary system thermal hydraulic design of SFR

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Abstract. A thermal-hydraulics analysis code has been developed by China Institute of Atomic Energy for fast reactor core design and optimization. The code supplies the abilities such as quick modelling of full core by GUI (Graphical User Interface), automatic fine sub-channel meshing, thermal-hydraulic analysis considering heat transfer among neighbor assemblies, automatically optimized flowrate zoning. A simple core thermal-hydraulics case plus a zoning case had been tested, and the results confirmed that this code is applicable to the design and optimization of SFR core. Furthermore, the code will be used to support the independent intellectual technology innovation of commercial fast reactor power plant.

Key Words: SFR; Sub-channel Analysis; Flowrate Zoning

1. Introduction

Contraposing the hexagon box assemblies in fast reactor, COBRA IV and THAS-PC1/2 provide a quick modelling of transient or steady state analysis for single assembly according to mass conservation, energy conservation and momentum conservation in axial and transverse direction. Meanwhile, SUPERENERGY offers a steady state thermal-hydraulic analysis for both single assembly and whole core for fast reactor considering mass conservation and heat transfer between assembles, but the temperature distribution of fuel rod and the transverse flow information cannot be provided. To satisfy the requirements of full core fine steady/transient state thermal-hydraulic analysis for SFR, the program is developed by China Institute of Atomic Energy for full core GUI (Graphical User Interface) modelling, flowrate zoning and steady/transient state thermal-hydraulic analysis with consideration of heat transfer between assemblies. The GUI and solver were developed by C# and Fortran 95. In addition, text modelling is also provided in this code.

2. Thermal-hydraulics Basic Theory and Modeling

2.1. Inner-assembly Thermal-hydraulics

2.1.1. Governing Equations

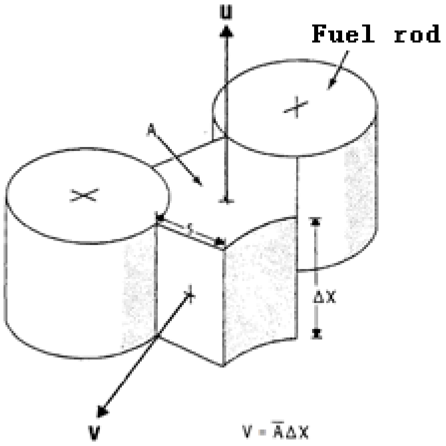


Fig.1 Subchannel Control Volume

The thermal-hydraulic calculation of medium in assemblies could be converted to the solve of four governing equations (mass, energy, axial and lateral momentum) in Separated Flow Model.

Mass Conservation Equation:

$$A\frac{\partial}{\partial t}<<\rho>>_V+\frac{\partial}{\partial X}<\rho u>_A A+\left\{D_C^T\right\}<\rho v>_S S=0 \tag{1}$$

In the above equation, the variables of A, V are sub-channel flow area and volume, S represent the width between gaps (see *Fig.1*), D_C^T is the transposed adjacent relation matrix between channels. $<<\rho>>_V=\frac{1}{V}\int_V \rho dV\,;<\rho u>_A=\frac{1}{A}\int_A \rho(\vec{u}\cdot\vec{n})dA\,;<\rho v>_S=\frac{1}{S\Delta X}\int_{A=S\Delta X}\rho(\vec{v}\cdot\vec{n})dA$。

Energy Conservation Equation:

$$\begin{aligned}&A\frac{\partial}{\partial t}<<\rho h>>_V+\frac{\partial}{\partial X}<\rho uh>_A A+\left\{D_C^T\right\}\left\{<\rho vh>_S S\right\}=\\&\left\{D_r^T\right\}\left[P\emptyset H\right]\left[D_r\right]\left\{T\right\}+\left\{D_w^T\right\}\left[LH\right]\left[D_w\right]\left\{T\right\}+\frac{\partial}{\partial X}A<k\frac{\partial T}{\partial X}>_A-\\&\left\{D_C^T\right\}\left[\frac{SC<k>}{L_C}\right]\left[D_C\right]\left\{T\right\}-\left\{D_C^T\right\}\left[w'\right]\left[D_C\right]\left\{h'\right\}\end{aligned} \tag{2}$$

The symbols D_r and D_w represent the adjacent relation matrix of channel with rods and walls. The symbols P, $\emptyset$, H, L, k, L_C, C, W′, h′, are the perimeter of rod, the fraction of perimeter, the heat transfer coefficient, width of walls, thermal conductivity of fluid, centroids distance between channels, the empirical coefficient, lateral mass flux every axial length, enthalpy of lateral flow.

Axial Momentum Conservation Equation:

$$\begin{aligned}&\frac{\partial}{\partial t}<<\rho u>>_V A+\frac{\partial}{\partial X}<\rho u^2>_A A+\left\{D_C^T\right\}<\rho uv>_S S=\\&-A\frac{\partial}{\partial X}<p>_A-\frac{1}{2}\left(\frac{f'}{D_h}+\frac{K}{\Delta X}\right)<\rho u^2>_A A-A<<\rho>>_V\cos\theta-C_T\left\{D_C^T\right\}\left[W'\right]\left[D_C\right]\left\{u'\right\}\end{aligned} \tag{3}$$

The symbols of θ, f', C_T, u', K, D_h represent the relative angle of channel, friction coefficient, Turbulent transport constant, axial velocity additions by lateral mass flux, axial shape loss coefficient and hydraulic diameter.

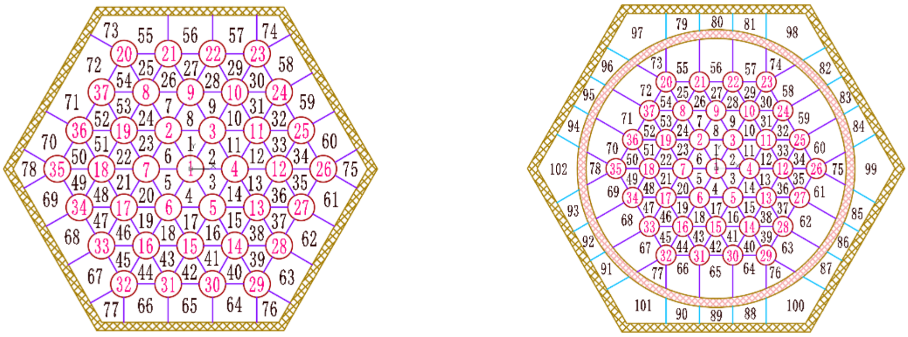
Lateral Momentum Conservation Equation:

$$\begin{aligned}&\frac{\partial}{\partial t}<<\rho v>>_{V'} S+\frac{\partial}{\partial X}<\rho v u>_{A'} S+C_S\left\{D_C\right\}\left[D_C^T\right]\left\{(N)\frac{S}{l}<\rho v^2>_S \cos\Delta\beta\right\}= \\ &\frac{S}{l}\left\{D_C\right\}\left\{<p>_A\right\}-\frac{1}{2}\frac{S}{l}K_G<\rho v^2>_S-<<\rho>>_{V'} S\sin\theta\cos\beta\end{aligned} \tag{4}$$

The symbols of β, V', l, K_G, C_S represent the reference angle of gap, the control volume around gaps, the equivalent length of gap control volume, friction pressure drop coefficient (between rods is 0.5), gap poor coupling factor (approximately to 1.0).

2.1.2. Inner-assembly Meshing and Numbering

For regular fuel assembly, inner-assembly meshing scheme is shown as follows (see *FIG. 2 a*). For control assembly including an inner duct, the side channels and corner channels are divided into two parts by the duct on the basis of regular fuel assembly scheme (*see FIG. 2 b*).



a)37-rod assembly *b)37-rod control assembly*

FIG. 2. Inner-assembly sub-channel meshing and Numbering.

Ignore the radiation, there is no heat source in the sub-channel between the sleeve and box. The heat exchange is only by heat connection and the contiguous sub-channel in the sleeves. Thus, the calculation model for regular fuel assembly can be used for control assembly.

2.2. Interassemblies Heat Transfer

The basic thought of interassemblies heat transfer is using the thermal resistance method among inter-assembly channels and inner-assembly channels. The temperature of inter-assembly channel can be found, and then it can be used to calculate the heat flux among assemblies, and then the heat flux is used as the heat boundary to the channels adjacent walls in assemblies.

Note the inter-assembly channel as 0, and the adjacent channels in assemblies can be counted as 1 to i (i is the number of adjacent channels). Taking in account of the conduction thermal resistance among inter-assembly channel and channels in assemblies and the flow thermal resistance calculated by Lyon-Martinelli relation, neglecting the axial conduction of inter-assembly channel, the total resistance expression is:

$$R_k = \frac{\sigma}{k_w} + \frac{D_0}{\lambda_{f,0}\left[0.025\left(RePr\right)^{0.8} + 7.0\right]_0} + \frac{D_k}{\lambda_{f,k}\left[0.025\left(RePr\right)^{0.8} + 7.0\right]_k} k = 1, \ldots, i \tag{5}$$

The symbol R_k、σ、k_w、D、k_f are the total thermal resistance of the k_{th} channel in assemblies, wall thickness, wall conductivity, thermal equivalent diameter of inter assembly channel and fluid thermal conductivity.

Assuming no heat brought from previous layer the thermal resistance balance is:

$$\sum_{k=1}^{i} \frac{T_k - T_0}{R_k} = 0 \tag{6}$$

Concerning of flow heat added from previous layer and the thermal resistance balance is:

$$\sum_{k=1}^{i} \frac{T_k - T_0}{R_k} = \frac{T_0 - T_0^{'}}{C_p f} \tag{7}$$

The above symbol T_k、T_0、T_0'、C_p、f represent temperature of the k_{th} channel in assemblies, temperature of inter-assembly channel on current layer, temperature of inter-assembly channel on previous layer, specific heat of liquid, mass flowrate of inter assembly channels.

The temperature of inter-assembly channels, T_0, can be calculated using the above equation, and then we can use the equation below to get the heat added to adjacent channels in assemblies through wall.

$$Q_k = \frac{T_k - T_0}{R_k} \qquad (k = 1, \ldots, i)$$

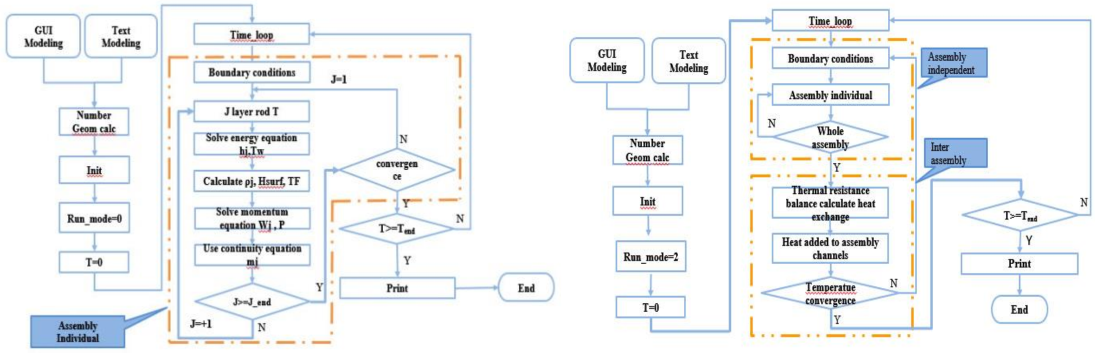
(8)

2.3. Analysis Process of Full Core Thermal-hydraulics

The running modes of code are individual assembly calculation and whole core calculation (*see FIG. 3*).

In the individual assembly mode, the discretized equations will be firstly solved at the inlet layer, and then next layer until to the exit of axial layer. In every layer, the energy equation will firstly be solved, then we can get the corresponding enthalpy, wall temperature, surface heat transfer coefficient and coolant temperature. Then the axial, lateral momentum equations are solved and the lateral mass flowrate could be got. The solving of the continuity equation can get the axial mass flowrate. The external solution is considered to be converged when the maximum change in crossflow, axial flow and enthalpy is simultaneously less than the specified input value between successive external iterations. For the transient case, the calculation will be stopped when the current time is greater than the total time.

In the whole core mode, in order to considering the calculation of heat transfer among assemblies, firstly, a calculation of individual assembly mode is used to all assemblies, secondly, according to the temperature distribution near walls among each assembly, a heat exchange model among assemblies is conducted to get the heat added to each channel adjacent to walls in assemblies. Thirdly, repeat the above iterations until the convergence of temperature in the whole core.



a) individual assembly mode *b) whole core independent mode*

Fig. 3 Thermal-hydraulic Analysis Flowchart of this code

3. Flowrate Zoning

For the purpose of minimizing the total flowrate through the core and reducing the kinds of assembly inlet size while each assembly's flowrate is matching its power to make sure that the fuel pellet and the clad will not melt, all the assemblies of core should be classified into several zones in which only one flowrate is assigned to every assembly according to the core's design parameters such as assembly powers, inlet temperature, total flowrate etc.

3.1. Basic algorithms

Three basic algorithms are provided in this program. Supposing there are M assemblies to be zoned into N zones, and the flowrates of all assemblies are in a descending order.

1) Exhaustive Enumeration Method (EEM). N-1 separating points can be placed to M-1 possible locations to result in C(M-1, N-1) configurations where C (M-1, N-1) is the combination number and equals to ((M-1)* (M-2)*…*(M-N))/((N-1)* (N-2)*…*1). Sum the M flowrates of each configuration and choose the configuration with smallest total flowrate.
2) Maximum Difference Method (MDM). Calculate M-1 flowrate differences between neighbour assemblies in the descending flowrate queue, find out the maximum P differences as possible location for N-1 separating points. Enumerate the C(P-1, N-1) configurations and choose one with smallest total flowrate.
3) Minimum-difference Merging Method (MMM). Find out the minimum flowrate difference between neighbour assemblies in the descending flowrate queue, set them into one zone with the bigger flowrate and treat the rest of M-2 assemblies as M-2 zone. Keep doing this until M assemblies merged into N zone.

3.2. Multi-region Zoning

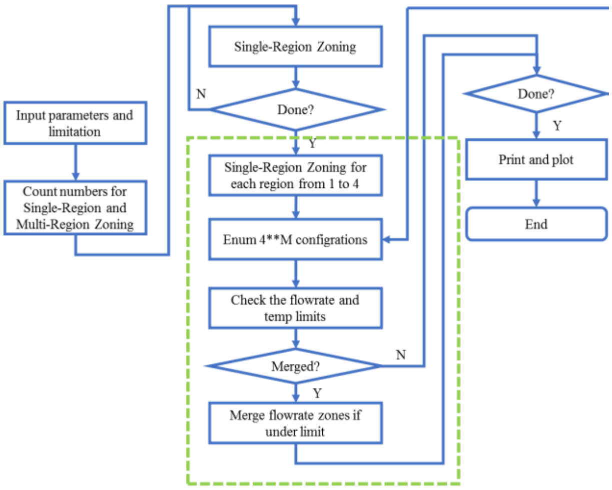


FIG. 4 Flowrate Zoning Flowchart

Normally shield, B region is zoned into a wanted N by basic algorithm, but all fuel regions such as inner fuel region, middle fuel region and outer fuel region are zoned together and the zoning numbers cannot be assigned for each region. When zoning m regions, this code zone every single region into 1 to 4 zones by using one of three basic algorithms, then enumerate 4**m possibilities, and choose the configurations under the limits of design total core flowrate, maximum temperature difference between neighbour assemblies, maximum exit temperature, zone flowrate merging.

4. Test Case

4.1. 7-assembly Demo Core Case

To exhibit the analysis abilities, a 7-assembly sample core with three type of assemblies is selected. Three types of assemblies as 7-pin, 19-pin and 37-pin have been set to different powers (see TABLE I). Different assemblies have the same mass flux of 1354.15 kg/(m^2 ·s), and mass flux in inter-assembly channels is set as 0.5 percent of the sum flux of adjacent channels in assemblies. The other parameters is set as inlet temperature of 358℃, system pressure of 202713Pa, and meanwhile an adiabatic wall boundary is adapted in the core. Three type of heat exchange mode among assemblies as no heat transfer mode, stagnation heat transfer mode and flow heat transfer mode have been used in test cases, and a preliminary comparison and analysis have been done among this code, COBRA IV and SUPERENERGY.

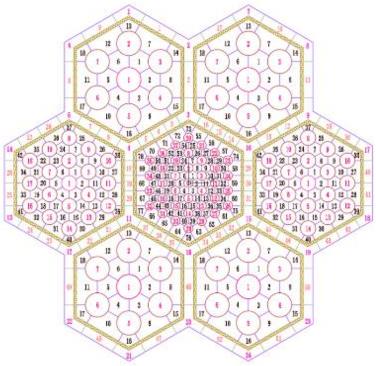


FIG. 5 Demo core consisting of 7, 19, 37-rod assemblies

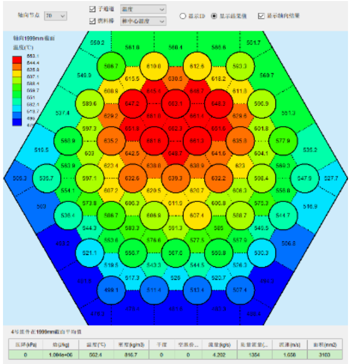


FIG. 6 Temperature distribution of assembly

TABLE I: INPUT POWER OF ASSEMBLIES

Assembly Type	Powers(W)
7-rod	301793.6722
19-rod	511914.3839
37-rod	978065.8483

The graphical interfaces of this code can present nephogram about the physical quantities of channels, rods and gaps at a defined axial position (*see FIG. 6*).

1) *No Heat Transfer Mode*: the results of this code have good agreements with the results of COBRA IV and SUPERENERGY. Take the number 5 channel in a 37-pin assembly of the sample core as an example. It's axial temperature distribution results agree well with the results of COBRA-IV, and the maximum relative error is 1.00375E-5(*see Fig. 7*). The results of axial average assembly temperature distribution between this code and SUPERENERGY also agree very well no matter in the high power 37-pin assembly or low power 7-pin assembly, and the maximum relative error is .91E-04(*see FIG. 8*).

2) *Different Heat Transfer Modes of this code*: The results in stagnation heat transfer mode and flow heat transfer mode have little difference. That means in the condition of minor inter assembly flux, the heat transfer carried by the flow medium can be ignored compared to the heat transfer by metallic conduction (*see FIG. 9*).

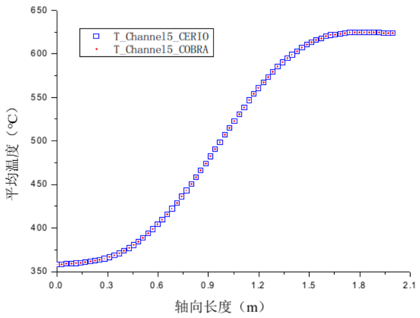


FIG. 7. Result comparison of the code and COBRA IV

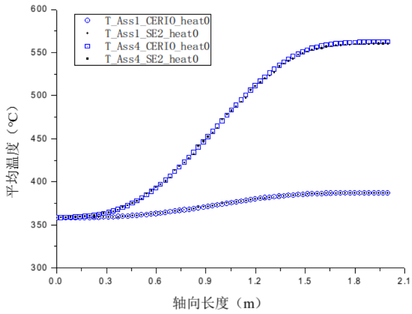
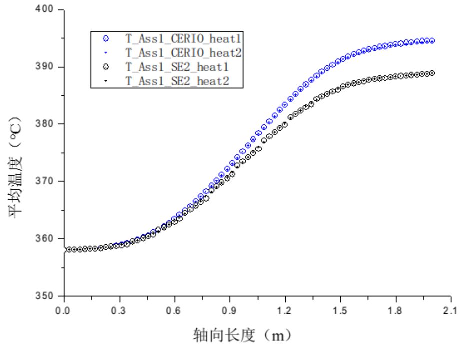
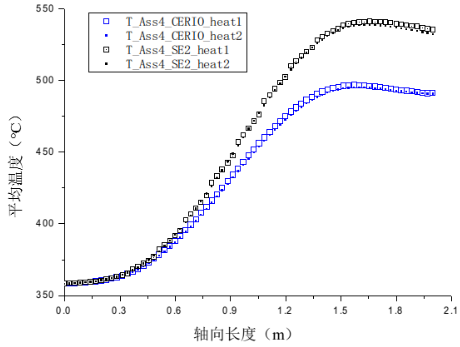


FIG.8. Result comparison of the code and SE with no inter-assembly heat transfer

3) *Different Heat Transfer Modes Between this code and SUPERNERGY*: As the governing condition of the code have concerned the heat transfer by lateral mass flux, so the heat transfer among assemblies should have more intensive results than that calculated by SUPERENERGY. In the sample core case, the maximum axial average assembly temperatures of higher power 37-pin assembly have the values of 532.00℃ calculated by SUPERENERGY, 490.41℃ by this code. Meanwhile the maximum axial average assembly temperatures of lower power 7-pin assembly have the values of 388.80℃ calculated by SUPERENERGY, 394.35℃ by this code (*see FIG.8*).





a) Assembly 1(7-pin, low power) *b) Assembly 4(37-pin, high power)*

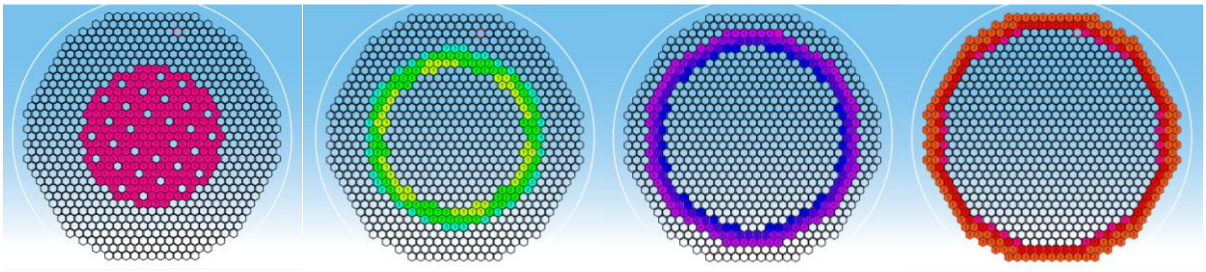
FIG.9. Result comparison of the code and SUPERENERGY with inter-assembly heat transfer

4.2 Flowrate Zoning Case

In this case a 781-assembly core is zoned by single region zoning algorithm for region B and multi-region zoning algorithm for inner, middle and outer fuel regions. The number of assemblies in those regions are 211, 156, 174, 210. 30 different control assemblies is placed among 3 fuel regions and are considered when zoning. Design parameters are 360℃ for inlet temperature, 467kg/s for flowrate of region B, 10290kg/s for flowrate of all fuel regions. Additional, the limit parameters are 612℃ for exit temperature of region B, 120℃ and 35℃ for maximum temperature difference between neighbor assemblies in region B and fuel regions, 50 kg/s and 0.3kg/s for total flowrate error and merging error in fuel regions.

TABLE II: Zoning results of multi-region

Config. of inner, middle, outer region	**Total Flowrate (kg/(m2s))**	**ΔTmax,nb (℃)**	**Corresponding Assembly IDs**
1/3/4	10287.790	32.039	149,12
1/4/3	10329.800	33.737	321,29
1/4/4	10274.270	32.039	149,12
2/1/4	10312.639	32.039	149,12
2/2/3	10261.827	33.737	321,29
3/1/3	10327.676	33.737	321,29
3/1/4	10272.146	32.039	149,12
4/1/3	10308.258	33.737	321,29
4/1/4	10252.729	32.039	149,12



a) Inner Fuel Region *b) Middle Fuel Region* *c) Outer Fuel Region* *d) Region B*

FIG.10. GUI for flowrate zoning results (Config 1/3/4/3)

When the design and limit parameters are provided, the code will list possible configurations automatically and display the chose one in the core layout (*see FIG.10*).

5. Conclusion

The thermal-hydraulic analysis and flowrate zoning function of the code are introduced in this paper. By now, Main programming and primary test work were done. The results show that the code is capable of using in design and optimization for SFR core, and the next step of validation and verification based on test facilities and reactor operation data can be started.

Appendix: Reference

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