Coupled Calculation of SPACE and FRAPTRAN

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1. Introduction

System analysis code, SPACE[1] is equipped with thermal-hydraulic analysis models, heat structures analysis models including fuel behavior analysis model, trip and control systems and so on. However, the fuel deformation model of SPACE is not a delicate mechanistic model but similar to that of RELAP5[2] developed in early 1980s. On the other hand, FRAPTRAN[3] is equipped with delicate fuel model but limited thermal hydraulics model compared with SPACE. Therefore, to compensate the weakness and preserve the analyzing capability of both codes, a linkage function between two codes using the features of the Dynamic Link Library (DLL) has been developed. In this coupling scheme, FRAPTRAN deals with heat conduction including fuel deformation of single fuel rod and SPACE takes charge of calculation of all hydraulic cells and heat structures except for the fuel rod coupled with FRAPTRAN.

2. Coupling of SPACE and FRAPTRAN

For coupling of both codes, the interface variables have been defined as shown in Table I.

Table I. Interface variables for coupling

Data transfer	Variables	Remarks
SPACE → FRAPTRAN	Time increment	
	LHGR	
	Total heat transfer coeff.	h_{tot} in Eq. (4)
	Local cell pressure	
	Bulk fluid temperature*	Mass-weighted
	Temporary heat flux	θ_0 in Eq. (4)
FRAPTRAN → SPACE	Surface heat flux	
	Center / surface temperature	
	Clad outer diameter	

*Bulk fluid temperature is not used for coupled calculation but reserved for future use

2.1 Overview of Code Coupling

In SPACE-FRAPTRAN coupling, SPACE is a master program and FRAPTRAN is linked with SPACE as a dynamic link library (DLL) through direct memory access (DMA) and various export functions. Fig. 1 shows the overview of linkage between SPACE and FRAPTRAN.

2.2 Synchronization Scheme

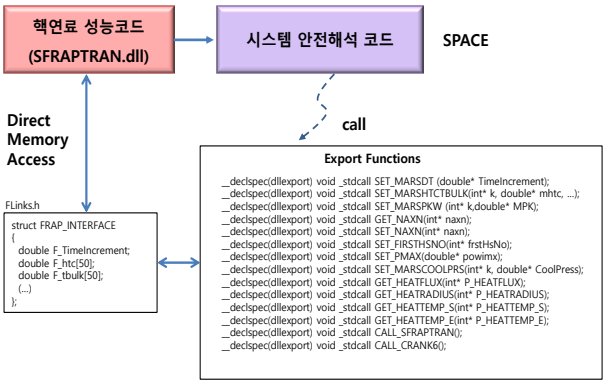

Fig. 1. Overview of SPACE-FRAPTRAN coupling

Heat structure calculation of SPACE is executed in the iterative loop named as 'fail loop' in Fig. 2. If the calculation of SPACE fails to meet the convergence criteria, the time step size is reduced and time advance proceeds with it. As for FRAPTRAN, however, iterative calculation is not allowed. Accordingly, if SPACE calculation fails in the 'fail loop', the synchronization between SPACE and FRAPTRAN will not be guaranteed. Therefore, a special treatment for synchronization has been introduced to resolve this problem. Fig. 3 shows the conceptual description for the synchronization scheme.

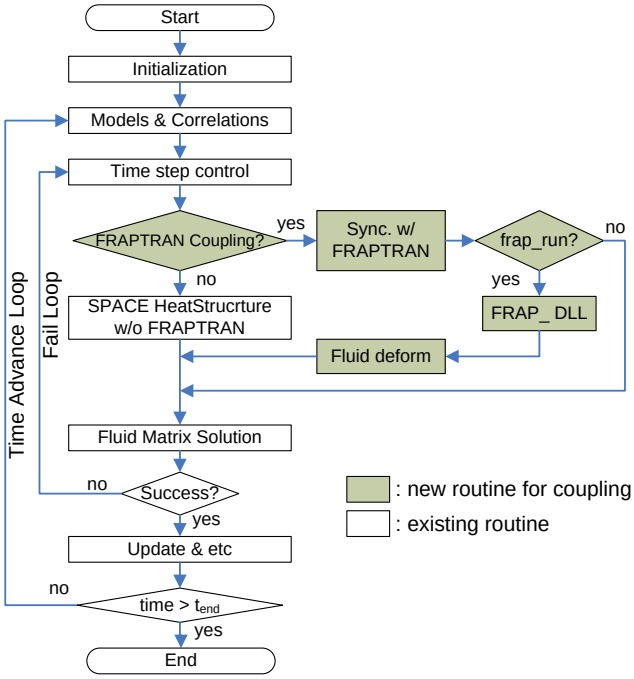

Fig. 2. Overall flow chart of coupled calculation

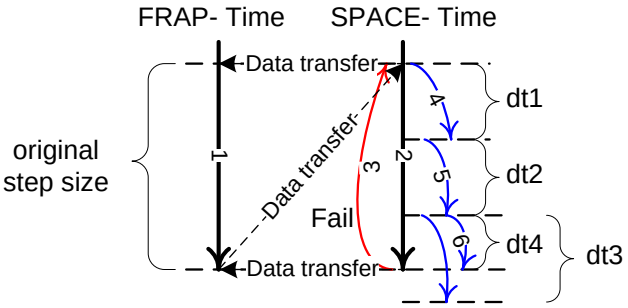

Fig. 3. Basic concept of synchronization

2.3 Heat Conduction Equation

The boundary condition in heat conduction equation of FRAPTRAN is as follows:

$$AT_w^{n+1} + B = \theta^{n+1} \quad (1)$$

where A and B are the coefficients in the heat conduction equation, and T_w^{n+1} and θ^{n+1} are the surface temperature and heat flux at new time step, respectively. In case of convective boundary, θ^{n+1} can be expressed using single HTC and fluid temperature as follows:

$$\theta^{n+1} = h(T_w^{n+1} - T_b) \quad (2)$$

where h and T_b are the convective HTC and bulk fluid temperature, respectively. However, there are various HTCs and fluid temperatures in SPACE because SPACE deals with three-field conservation equations. Therefore, it is required that a representative HTC and fluid bulk temperature should be provided by SPACE.

For this purpose, HTCs and fluid temperature could be averaged with some weighting factors but every averaging method has some weak points in that singular point exists. To overcome these weak points, we modified the boundary condition of the heat conduction equation for coupled calculation as follows:

$$\theta^{n+1} = \sum_{k=1}^{3} \begin{Bmatrix} h_k(T_w^{n+1} - T_k) + h_{spk}(T_w^{n+1} - T_{sp}) \\ +h_{stk}(T_w^{n+1} - T_{st}) \end{Bmatrix}$$

$$= \sum_{k=1}^{3} \begin{Bmatrix} h_k(T_w^{n+1} - T_w^n) + h_{spk}(T_w^{n+1} - T_w^n) \\ +h_{stk}(T_w^{n+1} - T_w^n) + h_k(T_w^n - T_k) \\ +h_{spk}(T_w^n - T_{sp}) + h_{stk}(T_w^n - T_{st}) \end{Bmatrix}$$

$$= \sum_{k=1}^{3} \begin{Bmatrix} h_k(T_w^{n+1} - T_w^n) + h_{spk}(T_w^{n+1} - T_w^n) \\ +h_{stk}(T_w^{n+1} - T_w^n) + \theta_k + \theta_{spk} + \theta_{stk} \end{Bmatrix} \quad (3)$$

Subscript k is a phasic index (liquid, vapor and droplet). T_k, T_{sp} and T_{st} are the each phasic temperature, partial saturation temperature and total saturation temperature, respectively. h_k, h_{spk} and h_{stk} are HTCs corresponding to each temperature, respectively. Rearranging Eq. (3), we can get the following equation.

$$\theta^{n+1} = \sum_{k=1}^{3} \{\theta_k + \theta_{spk} + \theta_{stk}\} + \sum_{k=1}^{3} \{h_k + h_{spk} + h_{stk}\}(T_w^{n+1} - T_w^n)$$

$$\therefore \theta^{n+1} = \theta_0 + h_{tot}(T_w^{n+1} - T_w^n) \quad (4)$$

where $\theta_0 = \sum_{k=1}^{3} \{\theta_k + \theta_{spk} + \theta_{stk}\}$ is a temporary heat flux based on old surface temperature, T_w^n and $h_{tot} = \sum_{k=1}^{3} \{h_k + h_{spk} + h_{stk}\}$ is a total HTC, simple summation of all HTCs.

If Eq. (4) is used as boundary condition of heat conduction equation in the coupled calculation, the fluid temperatures don't need to be used as the explicit interface variables any longer. In addition, we can get the single representative HTC. Therefore, temporary heat flux, θ_0 as well as total HTC, h_{tot} is added to the interface variables for coupling of SPACE-FRAPTRAN.

Combining Eq. (1) and (4), we can get the new time surface temperature, T_w^{n+1} as follows:

$$\therefore T_w^{n+1} = \frac{B + h_{tot} T_w^n - \theta_0}{h_{tot} - A}$$

FRAPTRAN returns total heat flux to SPACE, so SPACE has to partition it into each phase. Heat flux ratio of k-phase to total heat flux is defined as follows:

$$P_k = \frac{\theta_k + \theta_{spk} + \theta_{stk}}{\theta_0}$$

3. Verification Test

Verification test has been performed to verify the coupling scheme of SPACE-FRAPTRAN through simulation of hypothetical LBLOCA of APR1400. In this calculation, heat structure of H141-00, which represents the hottest fuel pin in the reactor core, is selected as coupled heat structure. Main purpose of this test is to verify the preservation of the transferred energy from FRAPTRAN to SPACE.

Fig. 4 shows the result of time-integrated heat flux during simulation period. As shown in the figure, the time-integrated heat flux calculated by FRAPTRAN (qfrap) agrees with one transferred to SPACE (qspace). Therefore, it can be said that the coupling scheme of SPACE and FRAPTRAN has been successfully developed. Fig. 5 is the comparison of the peak cladding temperature (PCT) at the specified axial node (15^{th} node) during simulation. In the figure, the black line and symbol is the PCT result of SPACE standalone calculation and the red one is the result of SPACE-FRAPTRAN coupled calculation. The discrepancy in the two PCT lines implies the model difference between the built-in fuel deformation model in SPACE and FRAPTRAN model.

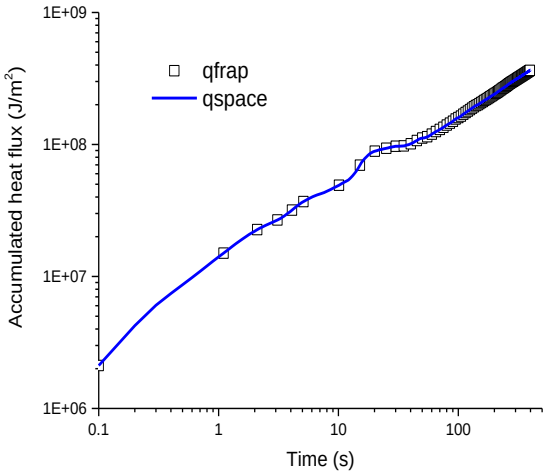

Fig. 4. Comparison of time-integrated heat flux

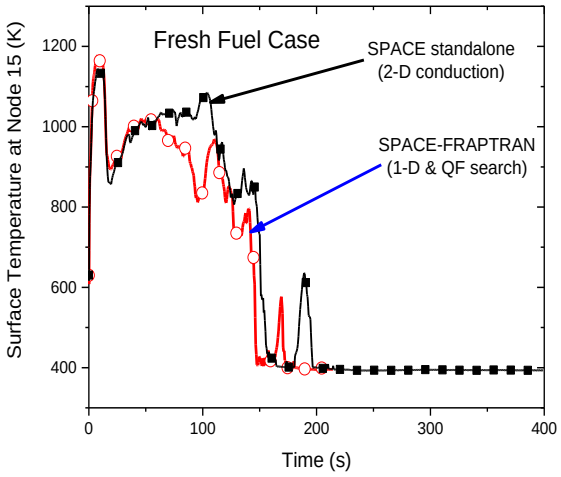

Fig. 5. Comparison of PCT from SPACE standalone and SPACE-FRAPTRAN coupling

4. Conclusions

FRAPTRAN has been converted into DLL and interlinked with SPACE to enhance the capability of fuel deformation analysis of SPACE. For the coupling of two codes, the interface variables were selected and synchronization function of two codes was also developed. In addition, to simplify the interface variables for the convective boundary condition such as HTC and bulk fluid temperature, the boundary condition of the heat conduction equation in FRAPTRAN has been modified by adding temporary heat flux as interface variable.

From the results of verification test, it was found that the values of time-integrated surface heat flux calculated by FRAPTAN and SPACE were exactly consistent with each other. In addition, It was also confirmed that a synchronization function was working properly. Despite the difference of fuel models, it was found that the peak cladding temperature of coupled calculation during a LBLOCA transient showed a similar trend as that of SPACE standalone calculation.

ACKNOWLEDGEMENT

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