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Development of multidimensional entire fuel rod analysis module (MERCURY) for simulation of fuel behavior during LOCA

Hyochan Kim[a], Sunguk Lee[a], Jinsu Kim[b], Junghwan Yoon[b]
[a]*Nuclear Fuel Safety Research Division, Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, 34057, Korea*
[b]*Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Korea*
[*]*Corresponding author: hyochankim@kaeri.re.kr*

1. Introduction

The study of fuel behaviour under accidental conditions is a major concern in the safety analysis of the pressurized water reactors (PWRs). The consequences of design basis accidents (DBA) such as loss of coolant accident (LOCA) and reactivity initiated accident (RIA) have to be investigated and quantified in comparison to the related safety criteria already defined, so as to prevent from severe core damage that could result from fuel rods failure, fuel ejection into coolant, loss of core coolability and fission products release into the primary circuit.

Loss of coolant accidents (LOCA) are used to design the emergency core cooling system (ECCS) of the nuclear power reactors. The performance of this system is assessed by means of an evaluation model and should comply with the acceptance criteria [1]. Recently, revision of ECCS (emergency core cooling system) acceptance criteria will be performed in Korea [2]. In the revised criteria, safety analysis evaluation should take into account fuel behaviors. The thermo-mechanical behavior of fuel rod such as clad ballooning and burst affects safety criteria and long term coolability of the reactor because the ballooned fuel can block the flow channel.

Therefore, thermalhydraulic code should couple with transient fuel models in order to evaluate nuclear reactor safety during LOCA. U.S. NRC developed the coupled TRACE/FRAPTRAN/DAKODA code system to study fuel rod behavior and uncertainty during LBLOCA [3]. In Korea, system analysis codes such as SPACE and MARS-KS were coupled with transient fuel module based on FRAPTRAN2.0 [4, 5].

However, 1.5D fuel module coupled with system code was limited to describe multidimensional clad behavior. The lumped thermo-mechanical calculation results in highly conservative or unrealistic results because the flow blockage ratio predicted by 1.5D fuel module can be too conservative as well as the ratio is highly sensitive with axial node length. In addition, heat transfer of fuel rod along axial direction at reflood phase is significant whereas the 1.5D fuel module was also limited to simulate multidimensional heat transfer analysis. To overcome the limitations due to dimension, BISON which is finite-element based fuel performance code was developed to simulate multidimensional fuel behavior during normal and offnormal conditions [6]. IRSN developed DRACCAR code system which was a multirod 3D thermo-mechanics code, with mechanical and thermal interactions between rods, coupled with subchannel type two-phase flow codes [7].

In this work, multidimensional entire fuel rod analysis module (MERCURY) for transient based on finite element method (FEM) has been developed and the verification of the module was carried out. The MERCURY incorporates transient fuel models which can classify thermos-mechanical model and fuel specified model. Mapping methodology was proposed to take into account burnup profile and fuel performance results calculated by FRAPCON4.0P1 [8]. Thermo-mechanical model in the module has been verified against results of commercial FEM code. The MERCURY can be used as stand-alone code or as a module of system code to couple fuel behavior with thermal-hydraulic code.

2. Development of MERCURY code

2.1 overall flowchart

Based on reference fuel codes, transient thermal analysis model, nonlinear mechanical model, thermo-mechanical model, multidimensional gap conductance model, burnup dependent material properties, high temperature oxidation of clad based on cathcart-pawel model, rupture model and transient creep model for clad ballooning are required to simulate fuel behavior during LOCA. The above 8 models were implemented into MERCURY.

As shown in Fig.1, MERCURY's flowchart to simulate fuel behavior during LOCA was proposed. At the beginning of MERCURY, reading input file and setting initial values are carried out for the further calculation. In terms of I/O, fuel information file and mesh information file are separated because fuel fabrication and power input depends on reactor and its scenario. On the other hands, mesh information is not modified as long as the geometry of fuel is not modified. Output files are also separated as fuel performance results and FEM results. To facilitate the review of FEM results, FEM results can be read by PARAVIEW [9] whereas fuel performance results can be read by text viewer.

MERCURY can be called by thermalhydraulic code when it is coupled with system code. It also can calculate fuel as stand-alone code. Therefore, calling sequence is separated whether it is coupled with another code or not. To reflect burnup material properties of clad and pellet, result of fuel performance code for steady-state should be stored before the calculation. MERCURY can store result file calculated by FRAPCON4.0P1.

Once transient calculation begin, thermo-mechanical calculation is carried out iteratively until convergence criteria are satisfied. In thermo-mechanical calculation, fuel specified models are also called.

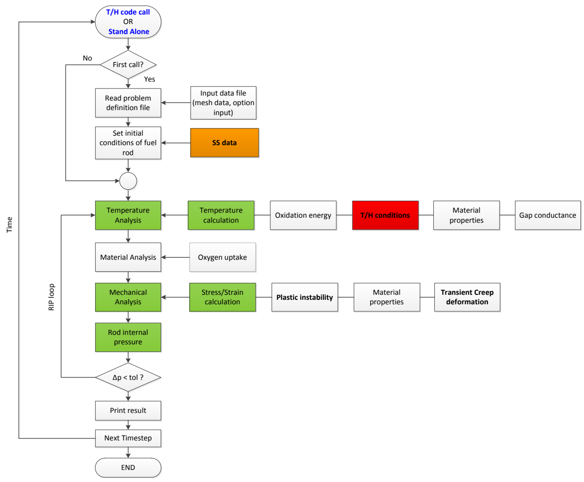

Fig. 1. Overall flowchart of MERCURY

Thermalhydraulic conditions (coolant pressure, heat transfer coefficient, coolant temperature etc.) are calculated or provided by system analysis code. Once the convergence criteria are satisfied in current time step, next time step proceed.

2.2 Thermo-mechanical model

MERCURY employs finite element method to simulate multidimensional fuel behavior. Fig.2 shows flowchart of FEM solver to calculate thermo-mechanical behavior. With the thermal boundary conditions, transient thermal analysis begins. The temperature distribution based on thermal analysis results are transferred to mechanical analysis. The thermal strains induced by temperature differences load thermal stress. The temperatures at integration point determine material properties. In structural analysis, hypoelastic constitute equations are formulated as governing equation to take into account geometrical nonlinearity of clad like large deformation. Stress update algorithm is applied.

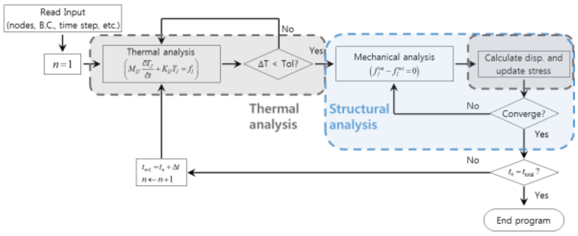

Fig. 2. Flowchart of thermo-mechanical model

2.3 Fuel specified models

Multidimensional gap conductance model, burnup dependent material properties, high temperature oxidation of clad based on cathcart-pawel model, rupture model and transient creep model for clad ballooning are classified in fuel specified models. The models are strongly specified with transient fuel behavior.

Source codes for burnup dependent material properties are originated from MATPRO 11 which is widely used in fuel performance code. Also, high temperature oxidation model based on cathcart-pawel model are well established in fuel performance and safety analysis codes.

Unlike well-defined models, multidimensional gap model and transient creep model should be improved by validation and code-to-code benchmark. Original model of gap conductance model is Ross and Stoute model [10]. In the reference code, original model was modified a lot to match experimental result. In addition, approach of original model was 1D methodology. Original gap conductance model was implemented without any modifications. As a further work, the model will be improved by validation and code-to-code benchmark. As same manner of gap model, creep model which is implemented based on Rosinger correlation should be improved by the validation of out-of-pile experiment [11]. Well-developed rupture criteria based on experiment result also was implemented. It will be evaluated by validation and code-to-code benchmark.

2.4 Verification of thermo-mechanical model

To verify the thermos-mechanical model of MERCURY, theoretical problem was defined and solved as shown in Fig.3. Thick pipe where hot fluid flow is modeled. The pipe experiences thermal behavior and thermo-mechanical behavior due to pressure. Fig. 4 shows that the results calculated by MERCURY match the results of commercial code (ABAQUS 14.0) within numerical tolerance.

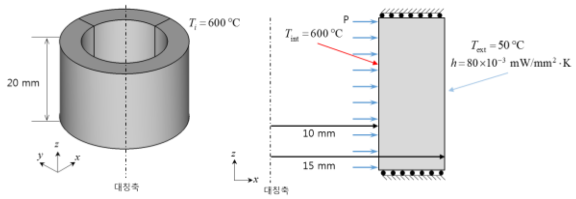

Fig. 3. Verification conditions of thermo-mechanical model

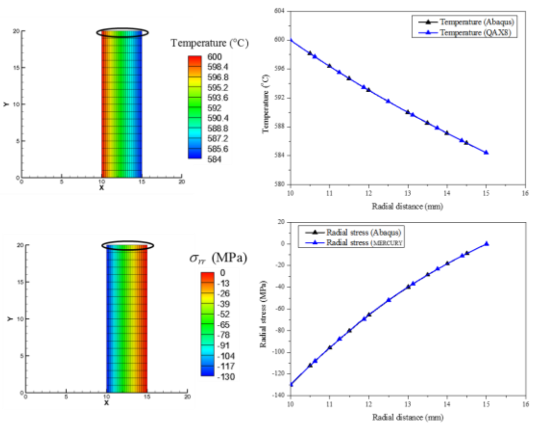

Fig. 4. Verification results of MERCURY

2.5 Simulation of transient fuel behavior

To demonstrate the code running successfully as alpha-version code, entire fuel rod based on FEM was modelled. Pellet and cladding material properties are imposed in the simulation. As shown in Fig. 5, it is confirmed that MERCURY was run successfully taking into account fuel models and MERCURY describes transient fuel behaviors such as transient temperature profile and ballooning.

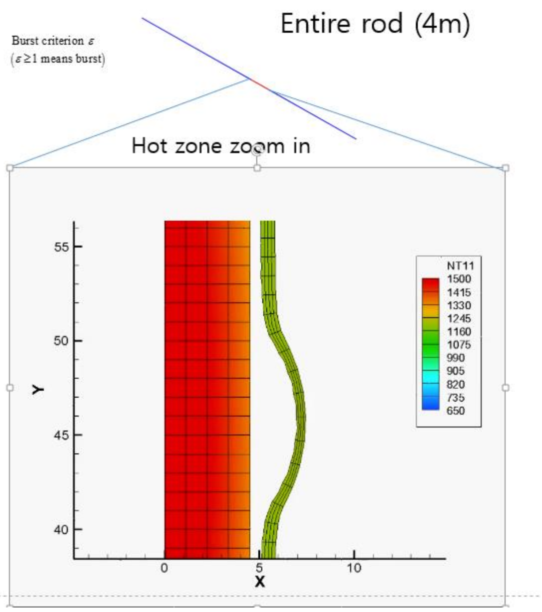

Fig. 5. Simulation result of MERCURY

3. Conclusions

MERCURY, which is multidimensional fuel behavior module during LOCA, has been developed to take into account multidimensional fuel behavior for evaluation of reactor safety analysis. MERCURY consists of transient thermal analysis model, nonlinear mechanical model, thermo-mechanical model, multidimensional gap conductance model, burnup dependent material properties, high temperature oxidation of clad based on cathcart-pawel model, rupture model and transient creep model for clad ballooning. Thermo-mechanical model based on FEM was verified against the result of commercial FEM code. Alpha-version of MERCURY has been developed and simulated entire fuel rod behavior taking into account the imposed fuel models.

For the future, fuel specified models in MERCURY will be validated against out-of-pile and in-pile experimental data. Code-to-code benchmark will also be carried out. Based on the V&V results, the fuel specified models will be improved. MERCURY module will be coupled with thermalhydraulic codes (MARS-KS, CUPID etc.).

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