Implementation of fuel relocation and oxide thermal barrier model into MARS-KS/FRAPTRAN coupled code system

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1. Introduction

The study of fuel behavior under accidental conditions is a major concern in the safety analysis of the pressurized water reactors (PWRs). The consequences of design basis accidents (DBA) 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, loss of core coolability and fission products release into the primary circuit. Those criteria have been established in the 1970s on the basis of several experimental programs performed with fresh or low burnup irradiated fuel. However, economic concerns led utilities to consider the increase of the average burnup (up to 60 MWd/kgU) of the fuel subassemblies in view of optimizing the fuel management. At the present time, the increased industrial competition and constraints result in more aggressive conditions for the fuel (higher burnup, higher power, load follow) [1]. These long anticipated developments involved the need for new investigations of irradiated fuel behavior under accident conditions to check the adequacy of the current criteria and evaluate the safety margins.

Recently, revision of ECCS (emergency core cooling system) acceptance criteria (10CFR50.46c) will be conducted soon in Korea [2]. The revised criteria include that fuel models during LOCA (Loss of Coolant accident) should be taken into account because fuel behaviors affect PCT(Peak Cladding Temperature) and ECR(Equivalent Clad Reacted) that are figure of merit for safety analysis. It is understood that the fuel rod undergoes thermo-mechanical deformation of cladding, exothermic high temperature oxidation, cladding burst and FFRD (fuel fragmentation, relocation and dispersion) during LOCA. Therefore, previous researches have been studied regarding fuel models for safety analysis. U.S. NRC developed the coupled TRACE/FRAPTRAN/DAKODA code system to study fuel rod behavior and uncertainty during LBLOCA [3]. However, its methodology was limited as one way coupling. In Korea, KAERI and INU supported by KINS has developed fully coupled MARS-KS/FRAPTRAN code system to count for take into account fuel behavior for safety analysis [4]. However, the coupled fuel module cannot support simulation of high burnup characteristics such as fuel relocation and oxide thermal barrier.

In this study, fuel module in MARS-KS/FRAPTRAN code system has been updated to take into account fuel relocation and oxide/CRUD(Chalk River Unidentified Deposit) thermal barrier that affects PCT and ECR as high burnup fuel characteristics. To develop fuel relocation model in the coupled code, QT model in FRAPTRAN2.0P1 was employed as fuel relocation model. For simulation of oxide thermal barrier, thermal analysis solver was modified and verified against numerical solution.

2. Models and Implementation

2.1 Fully coupled MARS-KS/FRAPTRAN code

FRAPTRAN2.0 code was modularized to be implemented into MARS-KS. To couple variables of two codes, new module (MARSLINK) was created in the fuel module. Basically, MARS-KS controls main calculation of fully coupled code. Once MARS-KS calls FRAPTRAN module, calculation of fuel behavior begins for current step. For fuel calculation, time increment size, linear heat generation rate, coolant pressure, heat transfer coefficient, coolant temperature for all nodes are provided by MARS-KS. When the FRAPTRAN calculation is completed for current step, the deformed fuel diameter, heat flux and surface temperature are provided for MARS-KS calculation. Currently, the modularized fuel module does not take into account fuel relocation and oxide thermal barrier effect.

2.2 Fuel relocation model

Axial relocation of fuel fragments during a LOCA is a phenomenon that causes redistribution of heat within the rod potentially accelerating cladding failure. As the cladding balloons, fragmented and pulverized fuel pellets can fall from upper regions of the rod into the ballooned region. The reduced thermal conductivity of the crumbled fuel and plenum gas mixture, in addition to the increased heat load due to a larger mass of fuel in the ballooned region, results in higher cladding temperatures further exacerbating the cladding distention. The ability to model this complex phenomenon using fuel performance codes is of great importance to ensure accurate predictions of cladding temperature, cladding strain, and the mass of fuel available for dispersal. Fig. 1 shows the fuel fragmentation and pulverization of high burnup fuel. The phenomena were investigated in IFA650 experiment series that simulated LOCA scenario with high burnup fuel by OECD/NEA Halden reactor project [5].

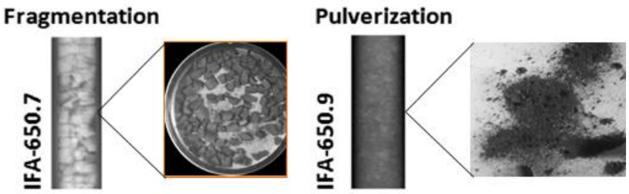

Fig. 1. Fuel fragmentation and pulverization in in-pile experiments

Recently, QT (Quantum Technology AB) model developed by Jernkvist and Massih [6] was implemented into FRAPTRAN2.0P1 to account for the axial relocation phenomenon during LOCA. As shown in Fig. 2, the QT model calculates amount of fuel relocation and power factor as followings; (i) the fuel fragmentation and pulverization model to quantify the number and size of fuel fragments and pulvers, the mass fractions of both fragments and pulvers, and an effective packing fraction of the fuel particles, (ii) the axial mass redistribution of the fuel, (iii) the thermal conductivity of the crumbled fuel, and (iv) the radial heat transfer in the fuel rod in presence of crumbled fuel and axial fuel relocation.

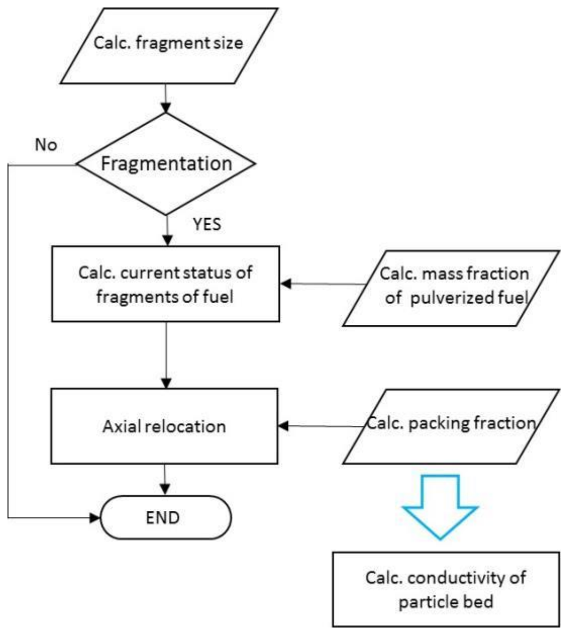

Fig. 2. Calculation flow of QT model

To apply QT model into the coupled code, calibrated power factor in fuel module was proposed. In the coupled code, LHGR(Linear Heat Generation Rate) for current step is provided by MARS-KS whereas stand-alone FRAPTRAN read LHGR information in input file. When fuel relocation occurs, QT model calculates power shifting factor that depends on amount of relocated fuel due to axial mass redistribution. In the coupled code, LHGR for current step provided by MARS-KS should be normalized when power shifting factor is activated. Therefore, LHGR in QT model to be implemented was normalized to preserve total power provided by system code.

2.3 Oxide/CRUD thermal barrier Model

Based on investigation of high burnup fuel, inner oxide, outer oxide and CRUD can be observed typically [7]. Under normal operation condition, pellet outer surface contacts with cladding inner surface when 10~20 MWd/kgU burnup reaches. Since contact occurs, bonding layer has been grown at the contact surface due to diffusion of oxygen from pellet. Also, oxide layer at outer surface has been created due to corrosion. In the case of CRUD, Fe and Ni ion could be solved in primary circuit of reactor. Those ions can be deposited on fuel surface which is relatively high power. The deposition on the fuel in reactor was investigated and can be defined as CRUD. As shown in Fig. 3, inner oxide, outer oxide and CRUD layer work as thermal barrier because thermal conductivities of those layers are considerably lower than that of bare clad.

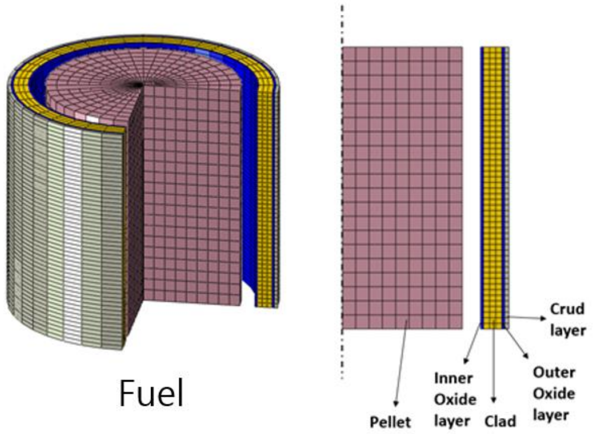

Fig. 3. Concept of oxide/CRUD thermal barrier of high burnup fuel

Those thermal barriers should be taken into account for temperature calculation of fuel. Under LOCA conditions the thermal barriers raise clad temperature rise which is figure of merit in terms of safety analysis. Therefore, thermal barrier model should be developed for safety analysis even though recent fuel module does not take into account thermal barrier model due to oxide and CRUD properly.

To consider thermal barrier in thermal calculation, thermal nodes for temperature calculation are added into the thermal solver as shown in Fig. 4. Whereas additional outer thermal node does not affect another fuel models, additional inner node influences gap conductance model because the deformed gap thickness can be reduced as much as additional inner oxide thickness. Here, it is assumed that the deformed gap thickness is maintained as long as additional inner oxide forms inside cladding.

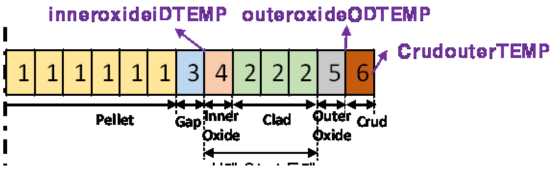

Fig. 4. Modification of thermal node for consideration of additional thermal barriers

In Fig. 4, number of each node represents thermal material properties; '1' is pellet; '3' is gap; '4' is inner oxide, '2' is clad, '5' is outer oxide, '6' is CRUD. Whereas thermal properties of oxide are clearly defined, the properties of CRUD need to be investigated more. For additional thermal nodes, FDM solver in the fuel module was updated and solved.

2.4 Verification

To simulate high burnup fuel behavior, two models have been developed and implemented into MARS-KS/FRAPTRAN coupled code. Verification approaches for two models are distinguished. Fuel relocation model (QT model) was already implemented in FRAPTRAN2.0P1. Therefore, it should be verified that the implemented model in the coupled code is identical to original model in FRAPTRAN2.0P1. For the verification of fuel relocation model, simple problem where fuel relocation occurs should be searched. With the problem, boundary conditions are set in coupled code and power conditions are also controlled. Fig. 5 demonstrates that temperature of FRAPTRAN2.0P1 and temperature of MARS-KS/FRAPTRAN are compared. The discrepancies of results are within numerical error. As a result, the implemented fuel relocation model is identical to original model.

To verify the developed thermal barrier model, simple problem was defined for comparison. In the problem, constant heat generation, bulk temperature and convective heat transfer coefficient are set. For verification of transient equation, bulk temperature is set for 10 seconds and raise for 10 seconds. For this scenario, 4 model sets are prepared as number of additional layers. Fig. 6 shows the verification of thermal barrier model for 4 cases. It is demonstrated that discrepancies for all cases are within numerical error. Therefore, the developed model in MARS-KS/FRAPTRAN is verified

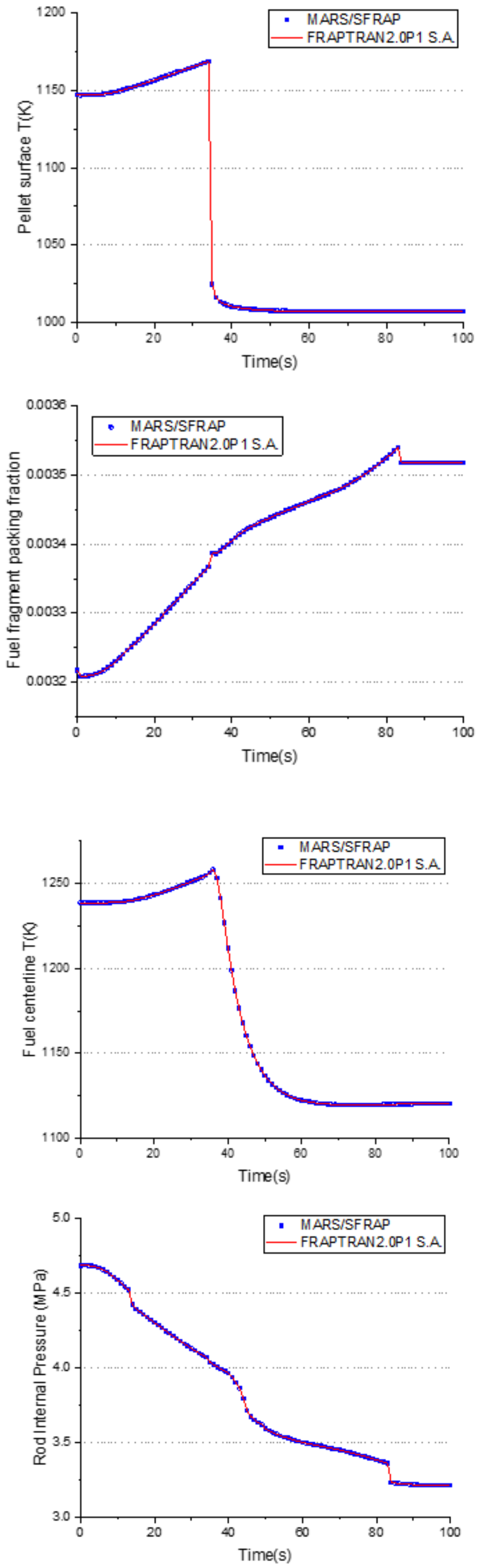

Fig. 5. Comparison between results of MARS/FRAP and FRAPTRAN2.0P1

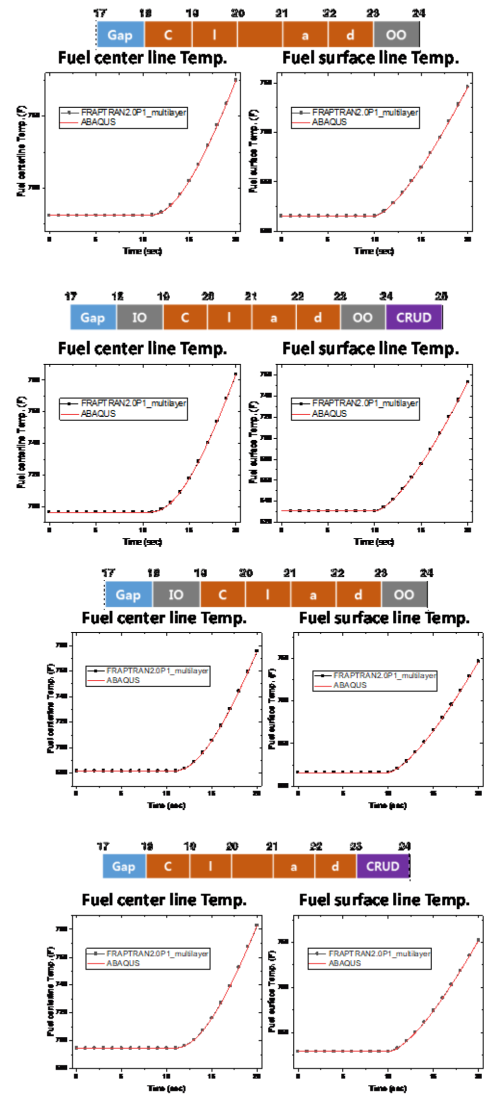

Fig. 6. Verification of thermal barrier model of MARS-KS/FRAPTRAN

3. Conclusions

Since ECCS acceptance criteria will be revised to take into account high burnup fuel behavior, MARS-KS/FRAPTRAN fully coupled code has been updated with implementation of fuel relocation model and development of oxide/CRUD thermal barrier model. Fuel relocation model was determined as QT model which was already implemented in FRAPTRAN2.0P1. QT model has been implemented into current MARS-KS/FRAPTRAN code. The implemented model was verified by comparison between the coupled code and original model with identical boundary conditions. Thermal barrier model has been developed by adding thermal node in temperature solver. For verification, the solution by FEM solver is compared with the solution by the developed solver. Consequently, coupled code is able to take into account high burnup fuel characteristics which affect clad temperature during LOCA. For the future, the coupled code will be validated against multi-physics experiments. Validated code can perform safety analysis with consideration of high burnup fuel behavior.

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