Development and Various Nuclear Fuel Applications Status of Accident Tolerant Fuel Pellet Technology with Enhanced Thermal Conductivity

Dong-Joo Kim*, Dong Seok Kim, Jae Ho Yang, Heung Soo Lee, Ji-Hae Yoon, Ji-Hwan Lee, Hyun-Gil Kim

Korea Atomic Energy Research Institute, 111, Daedeok-daero 989Beon-gil, Yuseong-gu, Daejeon, 34057, Korea

**Corresponding author: djkim@kaeri.re.kr*

1. Introduction

KAERI has been developing the ATF (Accident Tolerant Fuel) pellet technologies with enhanced thermal conductivity [1-5]. The high thermal conductive fuel can enhance the performance and safety of LWR fuels under transient and accident conditions [6-7] as well as during normal operations through higher thermal conductivity and lower temperature of fuel pellet. The high thermal conductive fuel technologies are also expected to apply to SMR fuels, especially water-cooled type SMRs.

The high thermal conductive UO_2 fuel can remarkably reduce the FGR (Fission Gas Release) and RIP (Rod Internal Pressure) which are the major aspects of the fuel performance and safety. And it can reduce not only the diffusivity and mobility of FP (Fission Products) but also the fuel pellet thermal stress by decreasing the fuel pellet temperature and temperature gradient.

The lower temperature fuel can decrease the radial deformation of fuel pellet under operational power transient conditions due to the decreased thermal expansion. In addition, because the ductility of metallic phase in the developed pellet is high compared to that of UO_2, a soft and ductile thin metal wall facilitates the faster creep deformation of the fuel pellets, thereby reducing the mechanical loading of the fuel cladding. These are expected to make the beneficial effects on the PCMI (Pellet-to-Cladding Mechanical Interaction) under operational power transient conditions.

Under LOCA conditions [6], the high thermal conductive fuel can make a lower PCT (Peak Cladding Temperature) of fuel performance. In the lower temperature fuel, the fuel safety margin under accident conditions can be remarkably increased due to the decrease of a stored energy in the fuel. In terms of the power-to-melt, the high thermal conductive fuel pellet can make the great beneficial effects.

In this presentation, it is intended to report the development status of ATF pellet technologies with enhanced thermal conductivity and the various nuclear fuel application status.

2. Development of ATF pellet technologies

2.1. Metallic microcell and microplate fuel pellet

The metallic microcell and microplate UO_2 fuel pellets are being developed as ATF pellet at KAERI.

Concept of metallic microcell UO_2 fuel pellet is that metallic microcell-walls envelope UO_2 granules in UO_2 pellet, and increase thermal conductivity and enhance retention capability of FPs of UO_2 pellet. The metallic walls, which has high thermal conductivity, make a thermally connected network and effectively enhance the thermal conductivity of the UO_2 pellet.

Fabrication technologies of metallic microcell fuel pellet have been developed, and the technologies associated with commercial UO_2 pellet manufacturing process has been considering [4, 8]. The measurements of thermophysical and mechanical properties of metallic microcell fuel pellet have been carried out. The out-of-pile performance test, evaluation and computational analysis of microcell fuel pellet have been performed under various conditions and circumstances [9-13]. In addition, in-reactor fuel performance data (in-situ online measured data of fuel centerline temperature and rod internal pressure) of metallic microcell fuel pellet were obtained and verified by the irradiation test at Halden research reactor in Norway [14]. Recently, it has been making efforts to establish the quality assurance system of lab-scale fabrication process and out-of-pile performance test of microcell fuel pellet, and to perform

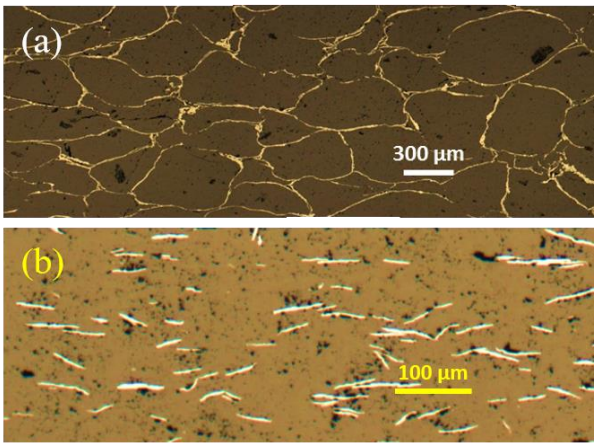

Fig. 1. Microstructure image of (a) metallic microcell fuel and (b) metallic microplate fuel (bright lines are the Mo metal phase).

the further studies of analysis and modelling using the in-reactor fuel performance data.

The metallic microplate UO_2 fuel pellet which is another concept of high thermal conductive fuel can effectively enhance the thermal conductivity of the UO_2 pellet. A large number of metallic micro-sized thin plate were homogeneously dispersed in a UO_2 pellet, and arranged in the radial direction of the pellet. Heat transfer in the fuel pellet can be efficiently enhanced by the radially arranged metallic microplates. It is expected that we can provide various options for enhancing thermal conductivity of fuel pellets by using metallic microcell and microplate UO_2 fuel pellets.

2.2. Combined accident tolerant fuel pellet

KAERI has been developing the combined ATF pellet with high thermal conductivity and FP retention capability through a cooperation with KEPCO NF. The concept of the combined ATF pellet is a combination of the advantages of high thermal conductive fuel (metallic microcell or microplate fuel pellet concept) and high FP retention capable and fast creep deformable fuel (ceramic microcell or PCI-remedy fuel pellet concept). The fabrication technology development and out-of-pile performance test of the combined ATF pellet have been conducted. The verification test for commercial mass production process compatibility and the commercial fuel design analysis are being carried out by KEPCO NF. Recently, the irradiation testing is being planned and will be performed through a cooperation with KEPCO NF and KAERI.

2.3. High thermal conductive burnable absorber fuel

Gd_2O_3 containing UO_2 fuel pellet is typically used as burnable absorber fuel pellet (burnable poison rod) to control reactivity, especially excess reactivity control in beginning of cycle. However, with increasing the Gd_2O_3 added content, the decrease of thermal conductivity of burnable absorber UO_2 fuel pellet is inevitable. The decreased thermal conductivity of fuel pellet results in the fuel temperature increase, fuel rod power peaking, etc. For this reason, in the Gd_2O_3 containing burnable absorber fuel pellet, the much lower uranium enrichment must be applied compared to that of UO_2 fuel pellet.

KAERI has been developing the high thermal conductive burnable absorber UO_2 fuel pellet that the metallic microcell or microplate fuel pellet technology is applied to the integrated burnable absorber fuel pellet [15]. It is possible to apply a higher uranium enrichment to the burnable absorber fuel pellet, and it is also expected to be used as a useful technology in the higher content Gd_2O_3 applications.

3. Summary

As the ATF pellet, the metallic microcell and the metallic microplate UO_2 fuel pellets which are the high thermal conductive fuel to enhance the accident tolerance of nuclear fuels under transient and accident conditions as well as the fuel performance during normal operations. The fuel concept and material design, fabrication technology development, mass production process compatibility test, out-of-pile and in-reactor test of the higher thermal conductive fuel have been carried out. In addition, various nuclear fuel applications (the combined ATF pellet, the high thermal conductive burnable absorber fuel pellet, etc.) of higher thermal conductive fuel technologies are being actively performed through a cooperation with nuclear fuel industry, utility and universities.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2022-00144289).

REFERENCES

[1] Y.H. Koo, J.H. Yang, J.Y. Park, K.S. Kim, H.G. Kim, D.J. Kim, Y.I. Jung and K.W. Song, KAERI's Development of LWR Accident-tolerant Fuel, Journal of Nuclear Technology, Vol.186, p.295, 2014.

[2] H.G. Kim, J.H. Yang, W.J. Kim, Y.H. Koo, Development Status of Accident-tolerant Fuel for Light Water Reactors in Korea, Nuclear Engineering and Technology, Vol.48 [1], p.1, 2016.

[3] D.J. Kim, Y.W. Rhee, J.H. Kim, K.S. Kim, J.S. Oh, J.H. Yang, Y.H. Koo and K.W. Song, Fabrication of Micro-cell UO_2-Mo Pellet with Enhanced Thermal Conductivity, Journal of Nuclear Materials, Vol.462, p.289, 2015.

[4] D.J. Kim, K.S. Kim, D.S. Kim, J.S. Oh, J.H. Kim, J.H. Yang, Y.H. Koo, Development status of microcell UO_2 pellet for accident-tolerant fuel, Nuclear Engineering and Technology, Vol.50, p.253, 2018.

[5] H.S. Lee, D.J. Kim, J.H. Yang, D.R. Kim, Numerical and experimental investigation on thermal expansion of UO_2-5 vol% Mo microcell pellet for qualitative comparison to UO_2 pellet, Journal of Nuclear Materials, Vol.518, p.342, 2019.

[6] K.A. Terrani, D. Wang, L.J. Ott, and R.O. Montgomery, The Effect of Fuel Thermal Conductivity on The Behavior of LWR Cores during Loss-of-coolant Accidents, Journal of Nuclear Materials, Vol.448, p.512, 2014.

[7] N.R. Brown, A.J. Wysocki, K.A. Terrani, K.G. Xu, and D.M. Wachs, The Potential Impact of Enhanced Accident Tolerant Cladding Materials on Reactivity Initiated Accidents in Light Water Reactors, Annals of Nuclear Energy, Vol.99, p.353, 2017.

[8] D.S. Kim, D.J. Kim, J.H. Yang, J.H. Yoon, H.S. Lee, H.G. Kim, Development of Mo microplate aligned UO_2 pellets for accident tolerant fuel, Korean Nuclear Society Virtual Spring Meeting, 2020.

[9] J.H. Yang, K.W. Song, D.S. Kim, D.J. Kim, H.S. Lee, J.H. Yoon, Y.H. Koo, Thermodynamic evaluation of equilibrium oxygen composition of UO_2-Mo nuclear fuel pellet under high temperature steam, Frontiers in Energy Research, Vol.9, p.667911, 2021.

[10] J.H. Yang, D.S. Kim, H.S. Lee, D.J. Kim, J.H. Yoon, Effect of molybdenum melting on the UO_2-Mo composite pellet integrity, Korean Nuclear Society Autumn Meeting, Changwon, Korea, 2021.
[11] H.S. Lee, D.J. Kim, D.S. Kim, D.R. Kim, Numerical investigation of thermal conductivity in UO_2-5 vol% Mo fuel pellet with Mo configuration of radial direction, Korean Nuclear Society Spring Meeting, Jeju, Korea, 2020.
[12] H.S. Lee, D.S. Kim, D.J. Kim, J.H. Yang, J.H. Yoon, Y.H. Koo, K.W. Song, Numerical investigation of the thermal conductivity of UO_2-Mo microplate fuel pellets to realize enhanced heat transfer in the fuel radial direction, Journal of Nuclear Materials, Vol.554, p.153075, 2021.
[13] Y.H. Koo, J.H. Yang, D.S. Kim, D.J. Kim, C.H. Shin, H.S. Lee, H.G. Kim, Analysis of pellet-to-cladding gap closure for a metallic micro-cell pellet under normal operating conditions, Journal of Nuclear Materials, Vol.556, p.153186, 2021.
[14] K.I. Björk, J.F. Kelly, C. Vitanza, S.S. Drera, S. Holcombe, T. Tverberg, H. Tuomisto, J. Wright, M. Sarsfield, T. Blench, J.H. Yang, H.G. Kim, D.J. Kim, C.W. Lau, Irradiation testing of enhanced uranium oxide fuels, Annals of Nuclear Energy, Vol.125, p.99-106, 2019.
[15] D.S. Kim, D.J. Kim, J.H. Yang, J.H. Yoon, H.S. Lee, Fabrication of integrated burnable absorber fuel pellets with enhanced thermal conductivity, Korean Nuclear Society Autumn Meeting, Changwon, Korea, 2022.