NATURAL CONVECTION HEAT TRANSFER CHARACTERISTICS OF KUR FUEL ASSEMBLY DURING LOSS OF COOLANT ACCIDENT

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ABSTRACT

The transient behavior of nuclear fuel during loss of coolant accident (LOCA) must be evaluated not only for power reactors but also for research plants. The safety of the plate-type fuels in the Kyoto University Research Reactor (KUR) has been studied by applying empirical correlations for natural convection of air and also by considering the averaged decay heat density so far. However, the applicability of such analysis to the KUR fuels, which have a curved plate shape, has not been examined and the transient behavior of the axial temperature profile along the fuel assembly should be evaluated under such severe accident conditions. In this study, the natural convection heat transfer characteristics were experimentally investigated with a simulated fuel assembly which has the same dimension with the KUR fuels. Furthermore, unsteady heat conduction analysis was performed by assuming the axial heat density distribution, and the cooling feature of the fuel plate during LOCA was discussed by estimating the time to the meltdown.

KEYWORDS
Natural convection, air, research reactor, LOCA, decay heat

1. INTRODUCTION

After the Fukushima Daiichi accident, a review of safety evaluation during the accident has been required not only for commercial nuclear power reactor but also research reactor. Although thermal power of the research reactor is significantly lower than the power reactor, the transient behavior of nuclear fuel during loss of coolant accident (LOCA) would affect the scenario of the severe accident. Therefore, the knowledge on LOCA should be accumulated for severe accident analysis. Kyoto University Research Reactor (KUR) is a light-water moderated tank-type reactor operated at the rated thermal power of 5 MW. KUR has been widely used for the experimental studies in neutron physics, radiation chemistry, nuclear engineering, medicine etc. The reactor core is placed at the bottom of the aluminum core tank which has 2 m in diameter and 8 m in depth. The core has plate-type fuels and the fuel assembly consists of the fuel plates arranged at regular intervals. As LOCA occurs in KUR, the fuel plates are cooled by the natural convection of air. Therefore, the natural convection heat transfer characteristics of the fuel assembly should be clarified to understand the fuel behavior during LOCA.

In the past, the natural convection phenomena from flat plates and in vertical ducts have been investigated by a lot of researchers and many empirical correlations have been proposed for heat transfer characteristics, because the natural convection appears in huge amount of the engineering applications. Elenbaas studied the natural convection in vertical channels with different cross-sectional shapes experimentally and the heat transfer correlations were derived for the natural convection between parallel plates [1] and in the duct with arbitrary shape [2]. Aihara et al. investigated numerically the laminar natural convection characteristics in the vertical channel [3]. They showed that their numerical results agreed with those of Elenbaas's experiments. The safety of the KUR fuel has been studied by applying such empirical correlation for natural convection so far. However, the applicability of the natural convection correlations to the reactor fuel assembly has not been studied and it should be made clear. In addition, the previous evaluation of the KUR fuel during LOCA has considered the decay heat density averaged over the fuel plate. However, the fuel element of the KUR in operation has an axial profile of the heat density. Therefore, the heat density distribution is very important for the evaluation of the fuel transient behavior and it should be taken into account.

In the present study, the applicability of the previous heat transfer correlation was investigated by the natural convection cooling experiments using a fuel assembly which simulates the KUR fuels. Furthermore, the unsteady heat conduction simulation was carried out to investigate transient temperature characteristics of the KUR fuel with the axial heat density profile.

2. NATURAL CONVECTION HEAT TRANSFER EXPERIMENTS

2.1. Experimental setup and method

The natural convection cooling experiments were performed using a simulated assembly of KUR fuels. The schematic view of the simulated fuel element is illustrated in Figure 1 and the cross section of this assembly is shown in Figure 2. The fuel element consists of 18 aluminum plates which has curved surface. Each plate has a thickness of 1.52 mm. The gap distance between the plates is 2.8 mm. The total length of the assembly is 600 mm. A ribbon heater was wrapped around the assembly and a thermal insulator which is made of a ceramic fiber was fixed outside of the heater. To measure the temperature of the fuel plate in the center part of the assembly cross-section, K-type thermocouples, which have a wire diameter of 0.1 mm and the accuracy is ±1.5 °C, were installed from the side face at three axial points, as shown in Figure 2. The inlet air temperature was also measured by a thermocouple placed underneath the assembly. In addition, the temperature at the outside of the insulator was measured to estimate the heat loss from the fuel assembly through the insulator. Furthermore, to increase the accuracy and the repeatability of the temperature measurement, the experiments were performed at the place without the effect of wind and large temperature fluctuation.

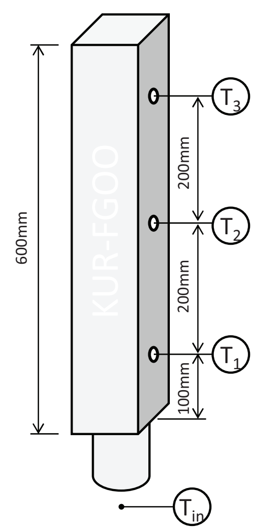

Figure 1. Overall view of the simulated KUR fuel assembly.

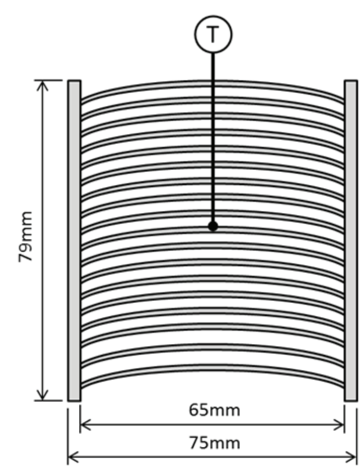

Figure 2. Cross sectional view of the fuel assembly.

In the experiment, the upper and lower sides of the simulated assembly were covered by an insulator and the assembly was heated by the wrapped heater. When the wall temperature reaches given temperature, the heater was turned off and the covers were removed. Then, the natural convection occurred between the plates and the temperature changes were measured. The sampling rate of the temperature was 1 Hz. The heat transfer coefficient of the natural convection from the fuel plates was estimated by a method presented in the next section.

2.2. Estimation of heat transfer coefficient using lumped capacitance model

The time-series signals of the measured wall temperatures were used to estimate the heat transfer coefficient by means of the lumped capacitance model. Assuming that the object has no temperature difference inside it and the steady temperature change is given, it can be treated as a lumped system of the thermal capacitance. In the case of the cooling of a flat plate, the high temperature plate is cooled by an ambient fluid (air) with a temperature T_f and the plate temperature T changes only dT during dt. Then, the heat balance in this case is given as follows,

$$\rho c_p \delta S \frac{dT}{dt} = 2hS\left(T - T_f\right) \tag{1}$$

where ρ, c_p, δ, S and h are the density, the specific heat, the plate thickness, the surface area of the plate and the heat transfer coefficient, respectively. Here, the integral constant is obtained using the initial condition and the following equation can be derived.

$$\theta = \frac{T(t) - T_f}{T(0) - T_f} = \exp\left(\frac{2h}{\rho c_p \delta} t\right) \tag{2}$$

where θ is the non-dimensional temperature. This non-dimensional temperatures estimated from the measured temperature change were plotted against the time, and then they were fitted by the exponential function. As a result, the heat transfer coefficient (h_{exp}) could be estimated, as follows.

$$h_{\exp} = \frac{1}{2} C \rho c_p \delta \tag{3}$$

where C is an exponential coefficient of the approximation. The density and the specific heat of the aluminum were given by taking into account the temperature dependence.

2.3. Evaluation of heat loss

The natural convection heat transfer coefficient can be calculated by above method for ideal channel geometry. However, the actual setup of the simulated assembly would contain the influence of the heat loss. The heat release from the thermal insulator covering the test section should be considered because the heat flux due to the natural convection is very small. Therefore, it is expected that the heat transfer coefficient estimated in the previous section has larger value than the actual natural convection heat transfer. Thus, the heat loss from the insulator was estimated from the temperature measured outside the insulator (T_{out}). From the heat balance of the simulated fuel assembly, the actual natural convection heat transfer was given by subtracting the quantity of the heat conduction to the insulator from that of the heat transfer obtained in the experiment, as follows,

$$Q_{nc} = Q_{exp} - Q_{loss} = h_{exp} A_{plate} \left(T_p - T_f\right) - \frac{\lambda_{ins}}{d_{ins}} A_{out} \left(T_p - T_{out}\right) \tag{4}$$

where A_{plate} and A_{out} are the plate surface area inside the assembly and the outer surface area of the assembly, respectively. λ_{ins} and d_{ins} are the thermal conductivity and thickness of the covered insulator. In this experiment, d_{ins} = 45 mm. Finally, the natural convection heat transfer coefficient could be calculated as follows,

$$h = \frac{Q_{nc}}{A_{plate}\left(T_p - T_f\right)} \tag{5}$$

2.4. Comaprison of natural convection heat transfer characteristics with previous correlations

The averaged heat transfer characteristics in the vertical duct [2] are expressed for the laminar natural convection at a constant wall temperature condition, as follows.

$$Ra_\xi \to \infty : \ \overline{N}u_\xi = 0.795 \left(\frac{Pr}{1 + 2\sqrt{Pr} + 2Pr} \right)^{0.25} Ra_\xi^{0.25} \tag{6}$$

$$Ra_\xi \to 0 : \ \overline{N}u_\xi = Ra_\xi \tag{7}$$

where Ra_ξ and Nu_ξ are defined as

$$Ra_\xi = PrGr_\xi \frac{\xi}{l} = Pr \frac{g\beta\left(T_p - T_f\right)\xi^3}{\nu^2} \frac{\xi}{l} \tag{8}$$

$$Nu_\xi = \frac{h\xi}{\lambda_a} \tag{9}$$

where Pr is the Prandtl number. The fluid properties were estimated by using the wall temperature. l is the axial length of the fuel plates. The channel gap distance between the plates is b and the characteristic size is given $\xi = 0.347b$ for the rectangular channel with an infinite width [3]. λ_a is the thermal conductivity of the fluid. In the simulated assembly, the ratio of the gap to the channel length was considerably small. Therefore, Ra_ξ was given as extremely small value and so it was calculated by Eq.(7).

The heat transfer characteristics of the natural convection in the simulated fuel assembly are shown in Figure 3. The solid line represents the result of Eq.(7). The measured results of the simulated assembly agree within 15% with the natural convection characteristics for the rectangular duct. The difference might be caused by radiation in the channel. However, data at more different temperature conditions should be accumulated to check the effect of the radiation in future. Also, the effect of the curved surface of the KUR fuel assembly should be investigated. In this study, Eq.(7) is applied to estimate the heat transfer characteristics in the simplified simulations.

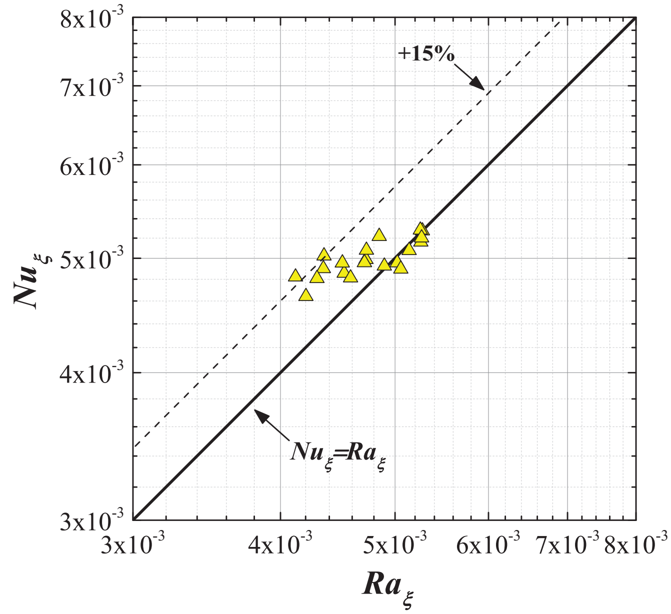

Figure 3. Natural convection heat transfer characteristics of simulated fuel assembly.

3. EVALUATION OF TEMPERATURE PROFILE USING NUMERICAL SIMULATION

3.1. Simulation model and method

To predict the fuel temperature transient phenomena due to the decay heat in the actual KUR fuel assembly, the natural convection heat transfer characteristics were evaluated by the unsteady numerical simulation. In the simplified simulation model shown in Figure 4, the one-dimensional energy equations for both the fuel plate and the ambient fluid were solved and the transient temperature change was estimated. First, the energy equation for the ambient fluid (air) is obtained by ignoring the air temperature fluctuation and the heat conduction in the air, as follows,

$$\rho_a c_{p,a} u \frac{\partial T_a}{\partial z} = \frac{2h}{d_a}(T_p - T_a) \tag{10}$$

where the subscripts p and a denote the physical properties of the wall material and the air, respectively. The fluid flow of the natural convection in the duct would be affected by some factors like pressure drop and wall friction of the channel. Here, it is assumed that only the buoyancy force dominates the magnitude of the fluid velocity. So, the fluid velocity is estimated from the equation of motion for the air, as follows,

$$u \approx \sqrt{g\beta(T_p - T_a)z} \tag{11}$$

where g is the gravity acceleration, β is the volume coefficient of expansion and z is the axial position from the inlet. Next, the energy equation in the fuel plate was formulated by considering the heat conduction in the plate and heat transfer to the air.

$$\rho_p c_{p,p} \frac{\partial T_p}{\partial t} = \lambda_p \frac{\partial^2 T_p}{\partial z^2} - \frac{2h}{d_p}(T_p - T_a) + Q_w \tag{12}$$

where Q_w is the heat density due to the decay heat and λ_p is the heat conduction coefficient. Here, the temperature distribution in the plate thickness was ignored. The heat transfer coefficient in Eq.(10) and Eq.(12) was estimated by Eqs.(7)-(9) for the natural convection heat transfer in the rectangular duct, as follows,

$$h = Pr \frac{\lambda_a g \beta \left(T_p - T_f\right) \xi^2}{\nu^2} \frac{\xi}{l} \tag{13}$$

Above equations were solved numerically by Euler's explicit scheme. Then, the transient behavior of the wall temperature profile was obtained.

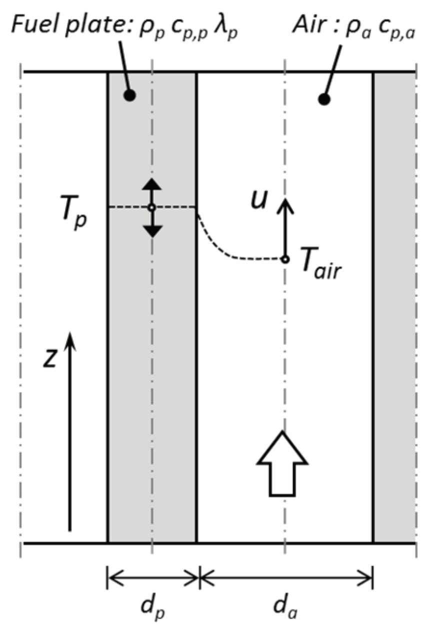

Figure 4. Simplified model for numerical simulation.

3.2. Comparison with experimental results

In order to validate the present simulation method, the cooling characteristics measured with the simulated fuel assembly were compared with the simulation result. The local temperature change was simulated without the heat generation term in Eq.(12) The experiments were performed by the same procedure described in section 2.1. A typical comparison result is shown in Figure 5. The initial temperature is set at 200°C and the plate is cooled gradually by the natural convection. Although the difference between the experimental and numerical results increases slightly with time, they were in good agreement. The error ratio was 3.3 % at t =180 min. This comparison showed that the present simulation method could predict the natural convection heat transfer in the KUR fuel assembly geometry.

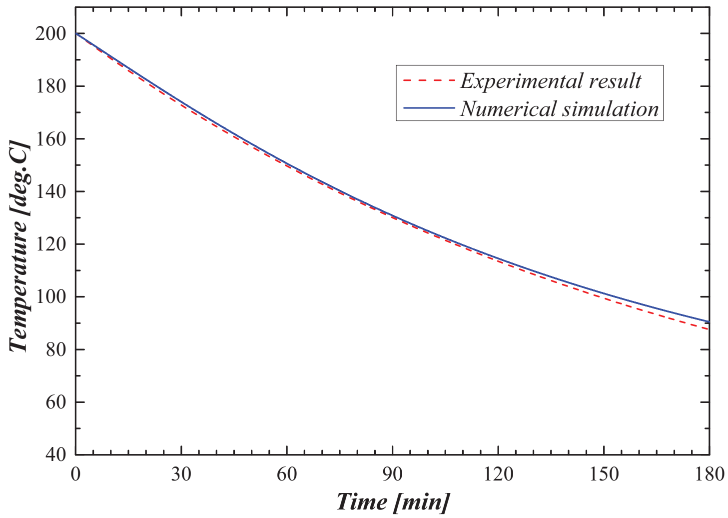

Figure 5. Comparison of cooling characteristics between experiment and simulation

3.3. Estimation of decay heat profile along fuel assembly

As the reactor operates continuously at the power (P_0) during t_0 days, thermal power (P) after the cooling for t_c days is given by the Way-Wigner equation [4], as follows,

$$\frac{P}{P_0} = 0.0061\left\{t_c^{-0.2} - \left(t_0 + t_c\right)^{-0.2}\right\} \tag{14}$$

Generally, KUR operates 3 days in a week of which early 2 days have 1 MW thermal power and the rest has 5 MW power. However, in this study, the fuel behavior of the reactor which operates at 5 MW for 155 days was investigated to evaluate the most severe case. The estimated values of the decay heat and the heat density are shown in Table I. The heat density decreases with an increase of the cooling period. The typical heat density profile along the fuel is shown in Figure 6. This represents the axial profile when the control rods are withdrawn. The middle part of the fuel rod has higher heat density than the averaged one.

Table I. Averaged decay heat from fuel plate after 155 days operation at 5 MW thermal power.

Cooling Period [day]	Decay heat [kW]	Decay heat per fuel assembly [kW]	Decay heat per fuel plate [kW]	Heat density [kW/m^3]
10^{-5}	293.9	11.8	0.653	10426.5
1	19.4	0.78	0.043	688.0
3	13.4	0.54	0.030	475.5
7	9.64	0.39	0.021	342.1
14	7.06	0.28	0.016	250.5

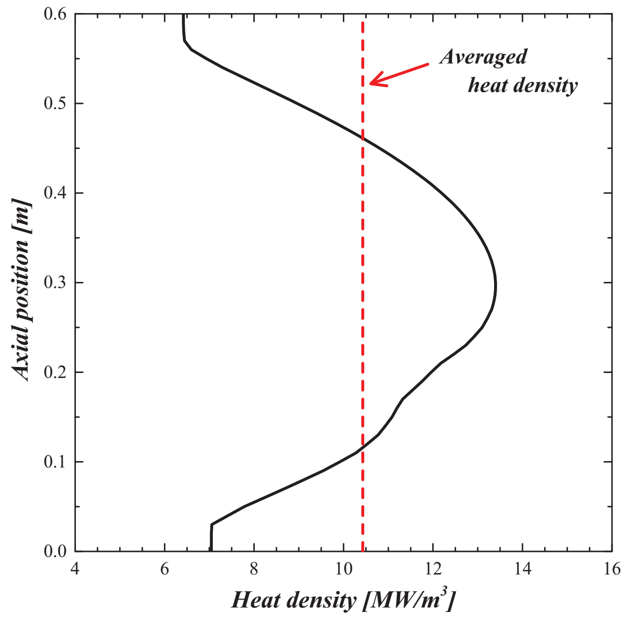

Figure 6. Heat density profile after cooling period of 10^{-5} days.

3.4. Thermal properties of actual fuel plate in KUR

In the KUR fuel plate, a fuel meat part which has a thickness of 0.5 mm is sandwiched in between two aluminum plates with 0.51 mm thickness, as illustrated in Figure 7. It has a structure that U_3Si_2 particles are dispersed in the aluminum. The density, the specific heat and the thermal conductivity of the fuel plate were calculated from the volume fraction of the fuel meat part and the aluminum cladding [5]. The composition of the fuel meat part is shown in Table II. Here, the melting point of the aluminum is 660 °C and the wall temperature was calculated until the temperature exceeds the melting point. In this simulation, the instant heat generation density averaged over the fuel plate was calculated by Eq.(14). The axial profile was estimated from the profile shown in Figure 6 by assuming that the profile shape remains regardless of the heat density change.

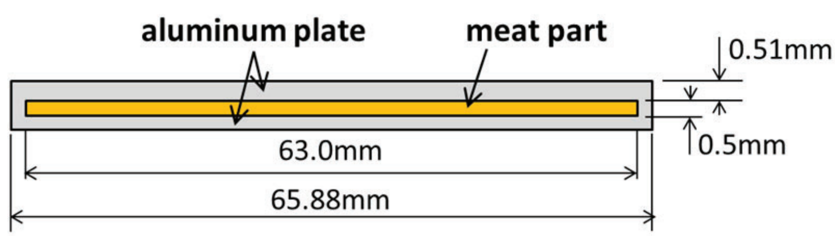

Figure 7. Cross-sectional view of the actual KUR fuel plate which consists of fuel meat part and aluminum plates

Table II. Composition in meat part of KUR fuel

	Nuclide	Number density [/cm^3 × 10^{24}]	Weight fraction
U	^{234}U	1.1842×10^{-5}	79.7 %
	^{235}U	1.6189×10^{-3}	
	^{236}U	8.8628×10^{-6}	
	^{238}U	6.4551×10^{-3}	
Si	^{28}Si	5.1331×10^{-3}	18.8 %
	^{29}Si	2.5991×10^{-4}	
	^{30}Si	1.7253×10^{-4}	
Al	^{27}Al	4.2044×10^{-2}	1.5 %

3.5. Transient behavior of temperature profile along fuel assembly

Temperature transient of the KUR fuel plate after the loss of coolant was calculated numerically. The transient change of the axial temperature profile as the coolant is lost just after the operation (10^{-5} day) is shown in Figure 8. The solid lines in the figure represent the temperature profiles after the loss of coolant. The initial temperature was 50 °C. It was shown that the temperature profile moves to high temperature side because of the heat density profile. After 10 minutes, the fuel temperature increases rapidly more than 200 °C. However, the heat generation due to the decay heat decreases with time, as Eq.(14). So the temperature increasing rate becomes smaller with time, too. In this condition, the fuel plate is not cooled by the natural convection and the meltdown might occur at the middle part of the fuel.

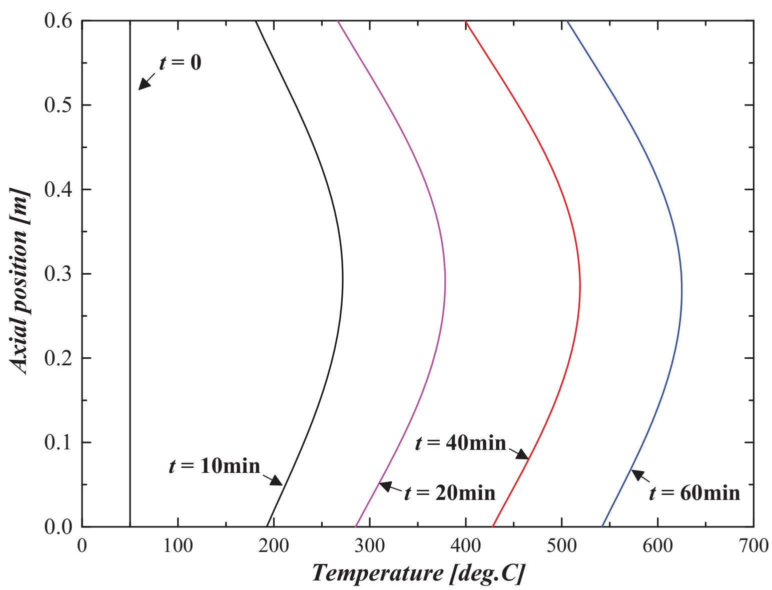

Figure 8. Typical profiles of temperature transient after loss of coolant (t_c = 10^{-5} days).

The time to the fuel melting was estimated by comparing the maximum temperature of the fuel and the melting point. The estimated results are shown in Table III. The cooling period after the reactor shutdown was varied. It was found that the meltdown takes about one hour even for the loss of coolant just after the operation. Thus, the appropriate measures such as the coolant injection to the reactor core have to be taken within an hour. If one week cooling period was given, the reactor has the capacity of about a day. In addition, the possibility of the fuel self-cooling (without the meltdown) was represented by taking more than 2 weeks.

Table III. Calculated results

Cooling period [day]	**Initial heat density [kW/m^3]**	t_{melt} or T_{max}
10^{-5}	10426.5	1h7m22s
0.042 (1 hour)	1648.6	1h49m11s
0.5 (12 hours)	848.6	3h49m7s
1	688.0	5h6m43s
3	475.5	9h29m4s
7	342.1	23h19m31s
14	250.5	$T_{max} \approx 450$ °C
21	203.9	$T_{max} \approx 350$ °C
28	174.0	$T_{max} \approx 300$ °C

4. CONCLUSIONS

To investigate the transient behavior of the KUR plate-type fuel during LOCA, the applicability of the previous heat transfer correlation were represented by the natural convection cooling experiments of the simulated fuel assembly. In addition, the fuel temperature transient was calculated by the unsteady heat conduction simulation and the time to meltdown of the fuel plate after the loss of coolant was estimated. As the results, the following conclusions were obtained.

- From the experiments with the simulated assembly of the KUR fuel, it was shown that the previous correlation for the natural convection in a vertical duct could evaluate the natural convection heat transfer characteristics in the KUR fuel assembly.

- As a result of the comparison of the cooling curve between the experiment and the simulation using the simplified model, the adequacy of the present simulation method was represented

- The transient change of the fuel temperature profile was estimated by this simulation method which considers the axial profile of the decay heat. Further, the time to meltdown was estimated and the possibility of the melting was discussed.

- The possibility of the meltdown would be reduced by providing a spray cooling system or other additional cooling system.

This study applied very simplified models for estimating the heat transfer characteristics and simulating the transient behavior. Therefore, some unrealistic things were assumed. To enhance the prediction accuracy of the temperature transient, the models should be modified and further validations with the experiments have to be done. However, rough tendency to understand the fuel cooling characteristics during LOCA in KUR could be estimated in the present study. In addition, these findings would be applicable to other research reactors with similar core configuration.

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