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Natural convection cooling characteristics in a plate type fuel assembly of Kyoto University Research Reactor during loss of coolant accident

Daisuke Ito *, Yasushi Saito

Research Reactor Institute, Kyoto University, 2-1010 Asashiro-nishi, Kumatori-cho, Sennnan-gun, Osaka 590-0494, Japan

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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 reactors. Kyoto University Research Reactor (KUR) is a light-water moderated tank-type reactor operated at the rated thermal power of 5 MW and has been widely utilized for a lot of scientific researches. The safety of the plate-type fuels in the KUR has been studied by a reactor coolant system analysis code. However, for the accurate prediction of the natural convection phenomena of air during LOCA, the empirical correlation for natural convection should be selected properly and an experimental validation should be performed. In this study, the natural convection heat transfer characteristics were experimentally investigated using a simulated fuel assembly which has the same dimension with the KUR fuels. Furthermore, a simplified unsteady heat conduction simulation was performed by taking the axial heat density distribution into account, and the cooling feature of the fuel plate during LOCA was discussed by estimating the time to the meltdown.

1. Introduction

After the Fukushima Daiichi accident, a review of safety evaluation during the accident has been required not only for commercial nuclear power reactors but also research reactors in Japan. Generally, the amount of the nuclear fuel in the research reactor core is small and thermal power of the research reactor is significantly lower than that of the power reactor. So the potential safety of the research reactor is higher than the power reactor. However, severe accident analysis is important for the research reactors as well as the power reactor to prove the reactor safety and to understand the accident scenario. Especially, 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 for the research reactor. A system code (e.g. RELAP5) has been applied to simulate the thermal hydraulic behavior in the research reactor (Hamidouche et al., 2004). In addition, some simulations using RELAP5 have been carried out to analyze thermal hydraulic phenomena during LOCA in pool-type research reactor with plate type fuels (Chatzidakis and Ikonomopoulos, 2013; Hamidouche and Si-Ahmed, 2011; Hedayat et al., 2007; Karimpour and Esteki, 2015; Soares et al., 2011). They simulated the transient reactor behavior after LOCA and the possibility of the fuel damage was investigated by estimating the temperature of the fuel elements. From these studies, the availability of such system code to simulate the transient accident situation in the research reactor has been represented. On the other hand, focusing on the fuel damage, the thermal behavior of the fuel during LOCA is dominated by the natural convection heat transfer. However there is no study that is focused on the natural convection in between the plate-type fuels during LOCA. So the natural convection characteristics in the flow channel between the fuel plates would be an important factor to clarify the transient behavior of the fuel during LOCA and also to enhance the accuracy of the simulation using the thermal–hydraulic system code.

In the past, the natural convection phenomena in vertical ducts have been investigated by a lot of researchers (Elenbaas, 1942a, 1942b; Aihara et al., 1986; Sparrow and Bahrami, 1980; Bar-Cohen and Rohsenow, 1984; Lee, 1999; Morini and Spiga, 2001; Ali, 2009) and many empirical correlations have been proposed for the 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 (Elenbaas, 1942a) and in the duct with arbitrary shape (Elenbaas, 1942b). Aihara et al. (1986) investigated numerically the laminar natural convection characteristics in the vertical

* Corresponding author.
E-mail addresses: itod@rri.kyoto-u.ac.jp (D. Ito), ysaito@rri.kyoto-u.ac.jp (Y. Saito).

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Nomenclature

A	area, m^2
b	gap distance, m
C	coefficient
c_p	specific heat, J/(kg K)
d	thickness, m
g	gravity, m/s^2
Gr_ξ	modified Grashof number
h	heat transfer coefficient, W/(m^2 K)
l	length, m
Nu_ξ	modified Nusselt number
P	thermal power, W
Pr	Prandtl number
Q	quality of heat, W
Q_w	decay heat, W
S	surface area, m^2
T	temperature, °C
t	time, s
u	velocity, m/s
Ra_ξ	modified Rayleigh number

Greek letters

β	volume coefficient of expansion, 1/K
δ	thickness, m
θ	non-dimensional temperature
λ	thermal conductivity, W/(m K)
ν	kinematic viscosity, m^2/s
ξ	characteristic size, m
ρ	density, kg/m^3

Subscripts

in	inlet
out	outside
p	plate
f	fluid
ins	insulator
exp	experiment
nc	natural convection

channel. They showed that their numerical results agreed with those of Elenbaas's experiments.

Kyoto University Research Reactor (KUR) is a light-water moderated tank-type reactor operated at the rated thermal power of 5 MW. The KUR has been widely used for the experimental studies in neutron physics, radiation chemistry, nuclear engineering, medicine etc. The sectional view is illustrated in Fig. 1. 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. The KUR fuel plates have a curved surface in order to increase the plate surface area. The fuels are cooled by the light water convection during the reactor operation. However, the natural convection of air might occur between the fuel plates during LOCA in the KUR. The safety of the KUR fuel during LOCA has been proved by a reactor coolant system analysis code THYDE-W (Shen et al., 2010). For the accurate prediction of the natural convection phenomena of air during LOCA, the empirical correlation should be selected properly and an experimental validation should be performed. Therefore, in the present study, the applicability of the previous natural convection heat transfer correlation was investigated by the natural convection cooling experiments. The natural convection heat transfer characteristics depend on the geometric configuration of the channel. So a fuel assembly which is made of aluminum and simulates the actual KUR fuel geometry was used. In addition, the transient temperature behavior of the KUR fuel with the axial heat density profile was investigated numerically. Generally, the system analysis code like RELAP5 is very useful for the transient studies. However, in this study, a simplified unsteady heat conduction simulation was presented and applied to the KUR fuels in order to study the applicability of the natural convection empirical correlation. Finally, the possibility of the meltdown of the fuel plate was discussed.

2. Natural convection heat transfer experiments

2.1. Experimental setup and method

The natural convection cooling experiments were performed using a test assembly which simulates the KUR fuels. The schematic diagram of the experimental setup is illustrated in Fig. 2 and the cross section of this assembly is shown in Fig. 3. The simulated fuel plates of the test assembly are made entirely of aluminum, and the shape and configuration are exactly the same as the actual KUR fuel assembly. The fuel element consists of 18 plates which has the 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 with a heating capacity of 1 kW 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, as shown in Fig. 3. The inlet temperature was also measured by a K-type 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. These temperatures were acquired by a thermocouple input module (National Instruments Corp., NI 9211) with a sampling rate of 1 Hz. Furthermore, to increase the accuracy and the repeatability of the temperature measurement, the experiments were performed at the place without the influence of large temperature fluctuation. As a result, the variation of the inlet temperature during the experiment was within 2 °C.

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. The heat input was controlled by a variable transformer and it was set at 500 W. When the wall temperature reaches given temperature which is an initial temperature of the cooling experiments, 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 heat transfer coefficient of the natural convection from the fuel plates was estimated by a method presented in the next section. The heat up temperature of the assembly was varied at a range from 70 to 300 °C.

2.2. Estimation of heat transfer coefficient

The time-series signals of the measured wall temperatures were used to estimate the heat transfer coefficient by means of the