Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 24-25, 2013

Cooling of Fuel Plates in an Accidental Drop of a Fuel Assembly

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1. Introduction

Many research reactors use plate type fuels whose coolant channels are narrow rectangular as shown in Figure 1. The channel gap is approximately 1.3 to 3 mm and the ratios of the width and the length of the channels to the gap are around 28 and 290, respectively. Because of the narrow gap and the high aspect ratios, cooling is a concern when a fuel assembly drops incidently during fuel transport and lies down on the pool bottom horizontally. This paper deals with an investigation into various heat transfer modes and cooling capability by natural circulation in case of an accidental drop of a fuel assemly.

2. Analysis of Heat Transfer

When a fuel assembly drops accidently and lies down horizontally, two cases are practically possible. One is that the side plate faces upward as shown in Figure 1 (hereafter called “case 1”) and the other is that the fuel plate faces upward. i.e., a 90-degree rotated shape of Figure 1 (hereafter called “case 2”). Namely the width of the flow channels can be placed vertically or horizontally.

Residual heat of the fuel plates is removed by two modes; the conduction through the side plates and the natural convection through the flow channels. The heat conducted to the side plates is transferred finally to the pool water by natural convection. The ratio of cooling capabilities by each heat transfer mode depends on the configuration of the fuel assembly placed on the floor.

The heat transfer through the side plates in case 1 would be less than that of case 2 because the side plate at the bottom side can not contribute to heat removal and because natural convection on horizontal plate is less than that on a vertical plate. Meanwhile, the heat transfer through the coolant channels is opposite to the side plate. It is obvious that natural convection is greater when the long side of narrow rectangular channel stands vertically than when it lies horizontally. Therefore, the heat transfer through the side plate in case 1 which is worse condition from the thermal hydraulic point of view was investigated. Additionally the heat transfer through the coolant channels was discussed in case 2.

2.1 Heat Transfer through the Side Plate

The heat transfer to the coolant in the channels was neglected for conservative calculation, and the heat transfer through the side plate at the top side was only considered. Then the maximum fuel temperature appears near the side plate at the bottom side as shown in Figure 1. The fuel temperature distribution at the fuel plate can be easily calculated from one dimensional conduction equation with uniform heat source as follows:

$$T_f(t) = \frac{q(t)}{2k_f}(L_f^2 - x^2) + T_{si}(t) \quad (1)$$

$$T_{si}(t) = \frac{q(t)L_f}{k_s} L_s + T_w(t) \quad (2)$$

where $q(t)$, L_f, and k_f are the heat per unit volume, the width, and the conductivity of the fuel plate, respectively. L_s and k_s are the thickness and the conductivity of the side plate, respectively. $T_{si}(t)$ and $T_w(t)$ are the interface temperature between the fuel plate and the side plate, and the surface temperature of the side plate, respectively. The surface temperature can be obtained from the heat flux and convective heat transfer correlations at a horizontal flat plate.

The correlation given in the reference [1] was used in single phase heat transfer condition. In nucleate boiling region the Rohsenow correlation with the coefficient given from Stephan & Abdelsalam was used [2]. The CHF was calculated from the Kandlikar’s model at an upward-facing flat plate [3].

2.2 Heat Transfer through the Coolant Channels

When the long side of narrow rectangular channel lies down horizontally, natural circulation between the heated coolant in the channels and the pool water plays an important role to remove the residual heat of the fuels. Heat transfer correlations developed at a horizontal channel with a narrow gap in vertical direction and a wide width and long length in horizontal direction are necessary for the safety analysis. Although a lot of researchers have studied boiling heat transfer in a narrow gap [3-8], unfortunately, there is no heat transfer correlation applicable to the horrizontal narrow rectangular channel heated at both sides of the upper and lower surfaces. Therefore, further studies are required to predict the cooling of the fuel by natural convection through the horizontal channels with a narrow gap, wide width, and long length.

3. Results

In this work a spent fuel assembly discharged after power operation of 5 MW was considered. The maximum heat flux was assumed as 3 times the average heat flux. The residual heat of the spent fuel as a function of decay time given from ANSI/ANS-5.1 [9] was used to assess the adequate time that the spent fuel integrity was ensured even in the worst case of an accidental drop of a fuel assembly. The cooling capability of the fuel plates with decay time following the reactor shutdown was assessed by assuming that the side plate of the fuel assembly faces upward and the heat transfer through only upper side plate was available.

Figure 2 shows the maximum fuel temperature with decay time. By calculating from the Kandlikar's model critical boiling occurs on the side plate up to 27 seconds following reactor shutdown. The CHF is around 844.8 kW/m^2 and the fuel plates must be failed. After 27 seconds nucleate boiling is expected on the side plate. At the decay time of 2 hours the maximum fuel temperature reaches the blistering temperature of 400℃. The maximum fuel temperature gradually decreases with decay time due to the decrease of residual heat of the fuel. This means that fuel transport operation is allowed after 2 hours at least following the reactor shutdown. When the decay time of the fuel reaches around 24 hours, nucleate boiling is expected to disappear. At this time the heat flux at the side plate becomes to be equivalent to the maximum heat flux which can be removed by single phase natural convection. This heat flux is around 102 kW/m^2 calculated from the correlation in the reference [1] with the saturation temperature at the side plate surface and the pool water temperature of 45℃.

In case a fuel assembly after power operation of 10 MW accidently drops during fuel transport, it is calculated that the maximum fuel temperature decreases below the blistering temperature after the decay time of 24 hours.

4. Conclusions

When a plate type fuel assembly was accidently dropped during fuel transport and was laid down horizontally, the cooling capability of the fuel plates were predicted with decay time of the fuel after reactor shutdown. The minimum decay time to avoid fuel failure was studied in assuming that the residual heat of the fuel was only transferred to the upper side plate and removed to the pool water finally. Consequently the very conservative calculations give the minimum decay times of 2 hours for 5 MW operation and 24 hours for 10 MW, respectively, to avoid fuel failure even in the worst case of a fuel assembly drop accident. If the heat transfer through the coolant channels is taken into consideration in the accident, the cooling capability of the fuel plates would increase and the minimum decay time would decrease.

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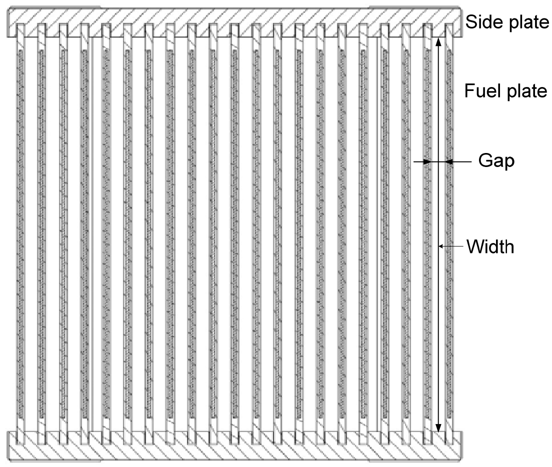

Fig.1. Plate type fuel assembly

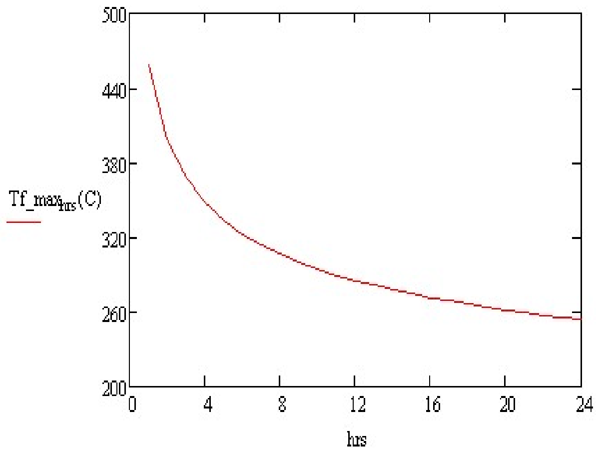

Fig.2. Maximum fuel temperature with decay time