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Preliminary Study of the Onset of Nucleate Boiling (ONB) for the Thermal-hydraulic Design of HANARO Irradiation non-instrumented Capsule during the Natural Convection

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1. Introduction

The low power research reactors were built around the world and there are now about 775 research reactors in the world [1]. In Korea, 5 research reactors exist now including the KJRR which is being constructed. In the early 1980s, as the Korean nuclear power program started and the HANARO was designed by the KAERI for research and development of neutron science and its applications.

The HANARO reactor is an open-tank-in-pool type for easy access, and the capsules are being utilized for the irradiation test of materials and nuclear fuel in HANARO. The concept of the capsule is the direct contact with the coolant to cool the temperature of specimen down. The capsule is formed the reactor coolant to pass through the bottom guide as shown in Figure 1. To successfully accomplish the irradiation test, it is essential that the capsule should be designed considering the thermal margin such as the margin to Onset of Nucleate Boiling (ONB), the margin to Departure from Nucleate Boiling (DNB). In this paper, the preliminary study was performed by focusing on the ONB and the capsule design will be performed using the heat flux and temperature at ONB condition calculated in this paper.

Fig. 1. The Instrumented Capsule for irradiation test in research reactor.

2. Heat transfer models and calculation

A non-instrumented capsule is utilized in studies on the irradiation characteristics of a nuclear fuel in the OR hole (Irradiation hole) of HANARO. To design the non-instrumented capsule, many problems require the knowledge of the temperature distribution and heat flux. Temperature distribution is an important phenomenon which influences the fuel behavior and integrity during the test time. This information is required to assess the safety margins in fuel plates. The ONB, boiling of the coolant, pulsed boiling, and DNB are usually regarded as the thermal-hydraulic phenomena which the safety limits should be evaluated based on them. Especially, The ONB is a heat transfer regime which should be determined for accurate thermos-hydraulic evaluations, i.e., single-phase flow versus two-phase flow. To determine the heat flux under ONB condition, it is assumed that the fuel is plate-type and the geometry has 2X35X130 mm. The values for calculation are presented in Table I. The simplified geometry is shown in Figure 2.

Table I: Assumed value for thermal design of fuel capsule

Variable	Value
Length	35 mm
width	2 mm
Height	130 mm
Fuel type	Plate
Coolant Tem.	35°C

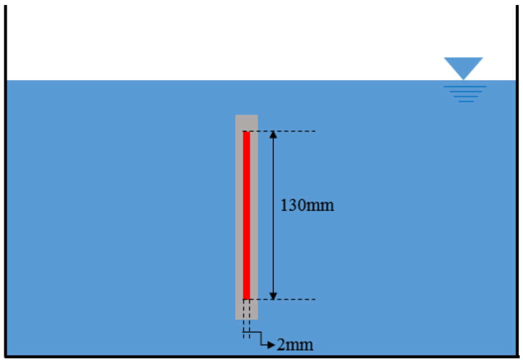

Fig. 2. Simplified geometry for the natural convection cooling test of plate-type fuel capsule

2.1 Heat transfer Model

For the conservative assumption, it is only cooled by the natural convection in pool. Pool boiling is defined as boiling from a heated surface submerged in a large volume of stagnant coolant. Assuming the natural convection, it can be calculated that the onset of subcooled nucleate boiling is on the interaction point between fully developed boiling curve and single-phase heat transfer curve as shown in Figure 3.

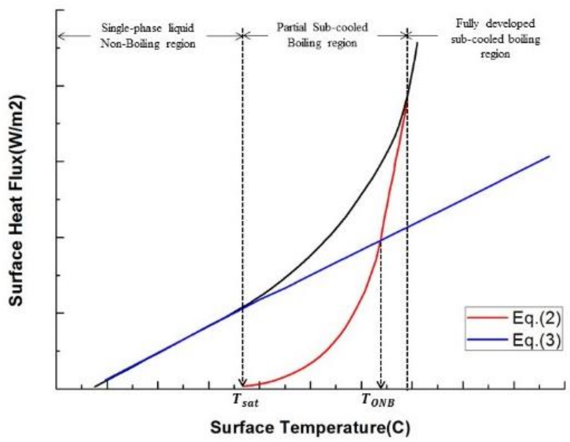

Fig. 3. The interaction point on boiling curve

According to the guide book for research reactor, the IAEA recommends the Bergles-Rohsenow correlation and Ricque-Siboul correlation [2]. Under ONB conditions, the clad surface temperature over which nucleate boiling will occur for a given local coolant pressure and surface heat flux can be expressed by the correlation developed by Bergles and Rohsenow.

$$q_i = 15.6P^{1.156}\Delta T_s^{(2.3P^{-0.0234})} \quad (1)$$

Where, P is system pressure (psia), T_S is the degree of super heat (°F) (the surface temperature minus the saturation temperature), and q_i is the incipient heat flux $(BTU/hr - ft^2)$ to cause nucleation at a wall superheat. This equation can be rearranged for the wall temperature at ONB condition, which is given as

$$T_{ONB} = T_{sat} + (5/9)(9.23q_i/P^{1.156})^{P^{0.0234}/2.16} \quad (2)$$

Where, T_{ONB} is wall surface temperature at ONB condition, and T_{sat} is saturated temperature of water. The Bergles and Rohsenow correlation has been validated for thin rectangular channels by conducting boiling experiments on the Oak Ridge research reactor and experimental study on narrow rectangular channels with low pressure (1.05 to 1.60 bar). It was observed that this correlation closely predicts the experimentally determined ONB heat flux when the flow is turbulent.

The single-phase heat transfer equation is determined by the newton cooling equation.

$$q_i = h(T_{ONB} - T_b) \quad (3)$$

Where, T_b is bulk temperature of water. For single-phase convection, this correlational approach has been recommended by Churchill and Chu. [3] This correlation provide the heat transfer coefficient for natural convection adjacent to a vertical plane, both for laminar and turbulent flow.

$$\overline{Nu}_L = \frac{k}{L}\left(0.825 + \frac{0.387Ra_L^{1/6}}{(1+(0.492/Pr)^{9/16})^{8/27}}\right)^2 \quad (4)$$

$$\overline{Nu}_L = \frac{k}{L}\left(0.68 + \frac{0.67Ra_L^{1/4}}{(1+(0.492/Pr)^{9/16})^{4/9}}\right) \quad (5)$$

Where, k is thermal conductivity, Ra_L is the Rayleigh number, and Pr is the Prandtl number. When the $Ra_L < 10^{12}$, the equation (4) can be used. For laminar flows, the equation (5) is slightly more accurate. It is observed that a transition from a laminar to a turbulent boundary occurs when Ra_L exceeds around 10^9. These values such as k, Ra_L, and Pr is calculated at mean liquid temperature T_f.

$$T_f = (T_{ONB} + T_b)/2 \quad (6)$$

To find the wall temperature at ONB condition, the bulk temperature of water T_b is assumed the degree of 35℃.

2.2 Calculation

To find temperature and heat flux under ONB condition, iteration method is used. First, the initial heat transfer rate and heat flux. Then, the ONB temperature calculate using the Eq. (2) and (3). The heat transfer rate is estimated by using Eq. (3). This value should be same as assumed value of heat transfer rate. If the temperature calculated by Eq. (2) and (3) are almost same in this condition, the iteration process will be done.

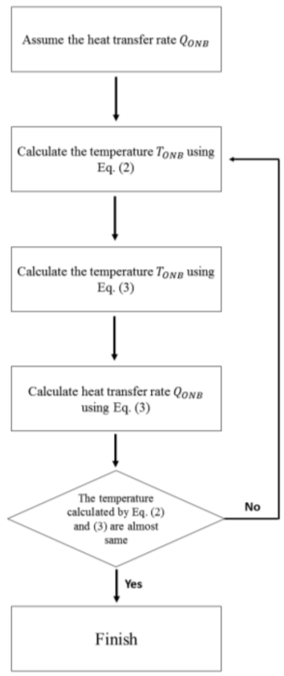

Fig. 4. Iteration process

The iteration performed using this method and result is estimated as shown in Table I. when the ONB temperature is about 104.7 °C and heat flux at ONB condition is 11.32 W/cm^2, the iteration result converge. Additionally, the Rayleigh number is about 1.3×10^3, Nu is 318.56, and heat transfer coefficient h is 1625 W/m^{2}k.

Table I: Iteration results

Iteration	Q_{ONB} (W)	q''_{ONB} (W/cm^2)	T_(2)	T_(3)	ΔT
1	1000	10.246	104.54	98.1	6.4
2	1100	11.27	104.74	104.365	0.4
3	1105	11.32	104.75	104.68	0.08
4	1110	11.37	104.76	104.99	0.23

3. Conclusions

In this paper, the temperature and heat flux under ONB condition are simply calculated for the thermal design of fuel capsule for irradiation test. These values will be considered to design the non-instrumented capsule for natural circulation. To confirm the calculated value, detailed calculation will be performed using the one dimensional and multi-dimensional codes. These results will be compared and the final heat source for irradiation test will be estimated.

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