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Thermal Behavior of a Single Spent Fuel in Water Pool Storage Under Partially Uncovered Condition

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1. Introduction

The standard of nuclear safety has been required to be improved after Fukushima accident. Not only for the safety of nuclear reactor core, many attentions are given to the spent fuel pool(SFP). Among possible accidents in SFP, loss of coolant accident (LOCA) is mostly highlighted. LOCA in SFP can be led by a partial drain-down or a boil off scenario. In order to predict the response and consequence in such case, exact model on the partially uncovered SFP has to be established.

Most studies on accidents in SFP have been done by safety analysis codes such as ATHLET-CD, ASTEC, MAAP, and MELCOR.[1, 2] However, an experimental investigation has not been conducted so far. Schultz et al.(2014) studied experimentally the response of air cooled BWR fuel assembly which is blocked at lower side fluid path.[3]

In this study, we experimentally investigated the thermal response of a partially uncovered single nuclear fuel rod (SNFR) in the SFP. The SNFR was 1/4 scaled down in axial length. 1-dimensional numerical analysis model was developed and compared with the result of experiment.

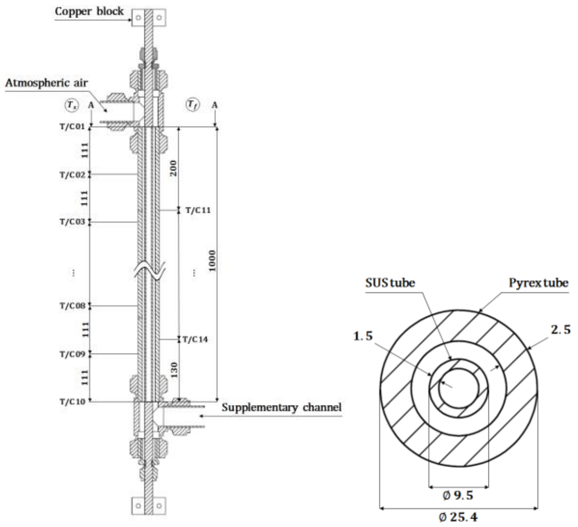
2. Experimental Setup

2.1 Test section

The test section was modeled on the nuclear fuel of PWR (17×17 assembly). The original SNFR have length of 3.66 m, diameter of 9.5 mm, and thickness of 0.57 mm [4]. In this study, we used scaled down test section by about 1/4 in length. The outer diameter of the SNFR was conserved to 9.5 mm, however, the thickness of the tube was increased to 1.55 mm.

The original material of nuclear fuel rod cladding is Zircaloy, but stainless steel (SUS 316) was used in this experimental study. To simulate submerged SNFR, Pyrex tube was used as the outer tube. The single round SUS tube was surrounded by round Pyrex tube so they composed a concentric annular channel. The gap between SUS tube and Pyrex tube was determined as 2.7 mm for having an equivalent hydraulic diameter of an original fuel assembly.

As shown in Fig.1, surface temperatures of SUS tube were measured at axially 10 different points. Fluid temperatures were measured at axially 4 different points and they were horizontally centered positions between surface of SUS tube and Pyrex tube. For temperature measurements, K-type thermocouples were used. Agilent 34972A were used for the data acquisition.



(a) (b)

Fig. 1. Experimental facility (vertical (a) and horizontal (b) cross section of the test section)

2.2 Experimental facility and procedure

To simulate the decay heat of nuclear fuel rod, direct heating method was applied. Upper and lower sides of the SUS tube were welded with SUS rods. The SUS rods were connected to direct current (DC) power supply of which has maximum capacity of 6.6 kW (20 V × 330 A).

The input power was controlled to generate 40W which can generate peak temperature over than 200℃ and less than 300℃ which is the limitation of the material of experiment component. This heat input is corresponding to the steady state heat flux 1340W/m^2 at the tube surface. Because there were large radiation heat loss in this experiment, the amount of power input was determined higher than the decay heat of normal SNFR. If we use the scaling law of natural circulation, 40W generation from a 1m rod is corresponding to 1280W generation from a 4m rod[5]. For example, Wu et al.(2014) calculated that 7 days after the shutdown accident, the decay heat from a PWR(CPR 1000) fuel assembly of the last core discharged batches was 50.37kW. Because fuel rods per assembly of CPR 1000 is 264, the decay heat from the SNFR of a fuel assembly which generates 50.37kW is 190W[6]. It is much more less than 1280W of this study.

Three different water levels were tested. The three uncovered ratios were 75 %, and 100 %. They represented water levels of 50 cm, 25 cm, and 0 cm, respectively. Remaining volume in the annular channel was filled with air and the channel was open to the atmosphere.

The experimental procedures were as follows. The distilled water was poured into the gap. The initial air temperature was 25℃ room temperature. The water of which temperature was about 90℃ was poured into the gap. The power was started to flow into the tube and the tube was heated up. During the heating process, the water level was kept consistently by water supplement.

Temperatures of 10 designated points were measured periodically with time step of 5 sec. During the experiment, quasi steady state was determined as if every points indicated the temperature increase less than 1 K/hr.

3. Numerical model for prediction

1-dimensional numerical model was developed for prediction of temperature transition during the SNFR experiment. Finite difference method was used. Implicit method was used for the spatial calculation.

For the axial temperature profile of SUS tube $T_s\,(z,t)$ was modeled by following energy conservation equation.

$$q''' + k_s \frac{\partial^2 T_s(z,t)}{\partial z^2} - \frac{q''_{conv}}{x_1} = \rho_s c_{ps} \frac{\partial T_s(z,t)}{\partial t} \tag{1}$$

where q''' is uniform power generation rate of SUS tube by direct heating. k_s, ρ_s, and c_{ps} are thermal conductivity, density, and specific heat of solid, respectively (i.e. SUS tube). Likewise, axial temperature of fluid $T_F\,(z,t)$ was also calculated as equation (2).

$$-\rho_f c_{pf} v \frac{\partial T_f(z,t)}{\partial z} + k_f \frac{\partial^2 T_f(z,t)}{\partial z^2} + \frac{q''_{conv}}{x_2} = \rho_f c_{pf} \frac{\partial T_f(z,t)}{\partial t} \tag{2}$$

where v is air velocity. Every time step, the convective heat flux q''_{conv} was calculated as equation (3).

$$q''_{Conv} = h\left(T_S(z,t) - T_F(z,t)\right) \tag{3}$$

Properties of solid and fluid, convective heat transfer coefficient, and air velocity were assumed to be constants. Based on the experimental result of Pyrex tube temperature, radiation heat loss was also calculated.

In case of 100% uncovered tube, correlation for forced convection in a circular tube annulus was used for the h. In this case, heat is transferred at the inner tube and the outer tube is insulated [7].

$$Nu = 3.657 + 1.2\left(d_i / d_o\right)^{0.8} = 5.869 \tag{4}$$

where Nu is $h(d_o - d_i)/k$. Following the equation (4), h was assumed to be 32.30 W/m^{2}K. In order to calculate v, approximated solution which stands for the average velocity in a vertical heating channel with constant temperature was used as equation (5) [8].

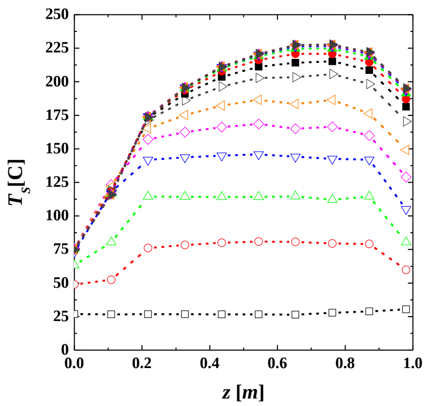
$$v = \frac{g\beta\left(d_o - d_i\right)^2\left(T_0 - T_\infty\right)}{16\nu} \tag{5}$$

where T_0 is steady state temperature of the heating wall.

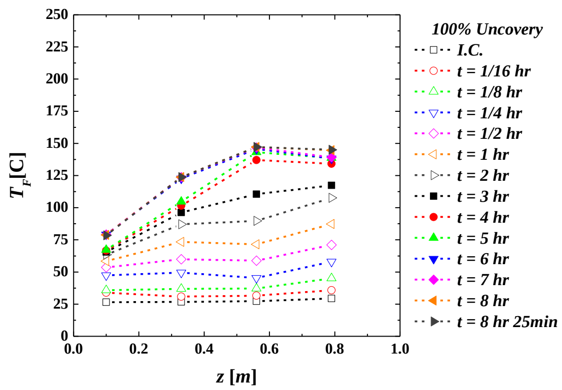
In the case of partially uncovered tube, h was assumed to be 4.5 W/m^{2}K [1]. The velocity of water was assumed to be 0.

4. Result and Discussion

4.1 Transient response



(a) tube surface temperature

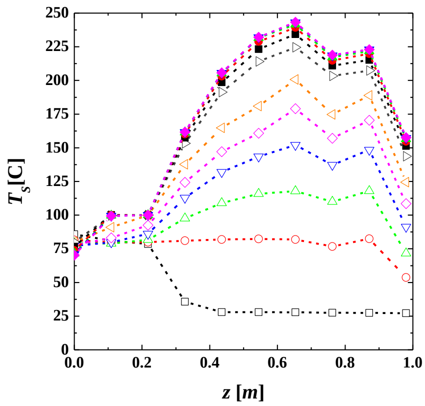


(b) fluid temperature

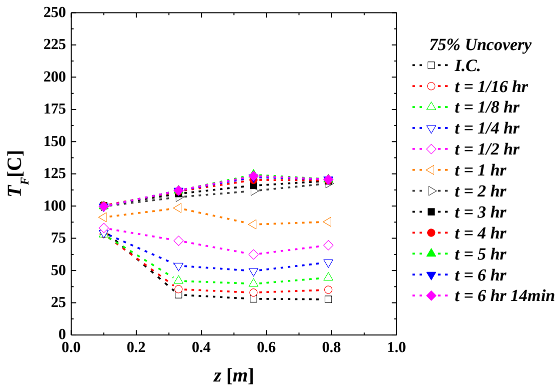
Fig. 2. Transient response of 100% uncovered tube.

The transient temperature profile of 100 % uncovered tube is presented in Fig.2. Temperature decrease of upper region(> 0.8m) is assumed to be due to the heat loss through the SUS rod. In early period(< 1/2 hr), the temperature gradient was made at lower part only. As time passes, the gradient spread to upper part also. Around 2 hours after the heat up, peak temperature became over 200 ℃.

In the case of 75 % uncovered tube (Fig.3), it took an hour for the peak temperature to be increased more than 200 ℃ after starting heat up. The peak value of steady state air temperatures was 124 ℃. This value was 25 K lower than that of 100% uncovered case. Comparing with 100 % uncovered case, it meant that the convective heat transfer is diminished.



(a) tube surface temperature



(b) fluid temperature

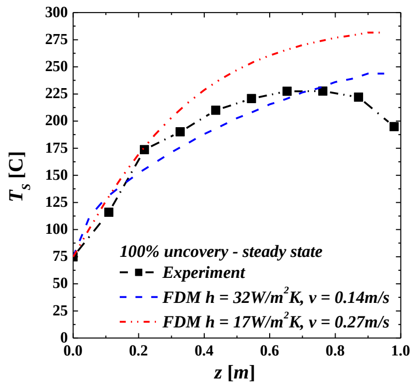
Fig. 3. Transient response of 75% uncovered tube.

4.2 Comparison between experimental result and numerical simulation

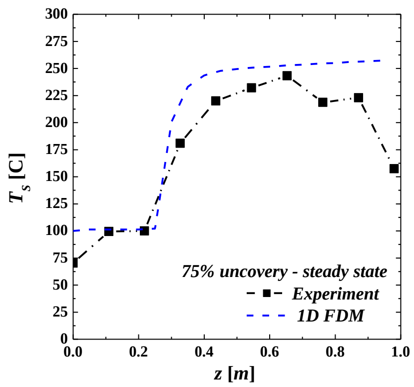
Fig. 4 shows temperature profiles of steady state in the case of 100 % and 75 % uncovered tube. In this study, transient results showed large differences because steady h and v were assumed. However, for both cases, overall temperature trends of steady state were well reconstructed by simulation.

In case of Fig.4 (a), there were some discrepancies between experimental results and simulation results, but the region where the curvature of the temperature profile changes was similar. In case of Fig.4 (b), simulation results of air temperature had slightly higher values than those of experimental results.

The numerical results were varied sensitively by changes of radiation heat loss modeling, heat transfer coefficient, and air velocity.



(a)



(b)

Fig. 4. Comparison between steady state experimental and numerical results(a: 100% uncover, b: 75% uncover)

4. Conclusions

An experimental study was conducted for obtaining transient temperature profile data of a modeled single nuclear fuel rod in heating condition under partially uncovered condition. Numerical prediction model was developed also and the prediction result was compared with the experimental result.

Acknowledgements

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