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Discussion on possibility of early film collapse for corium particles during FCI based on experimental results from unexpected collision between solid sphere and thermocouple

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1. Introduction

During a severe accident progression, fuel-coolant interaction (FCI) occurs in a lower head of reactor vessel or a pre-flooded cavity. Since the corium temperature is very high (~3000 K), film boiling regime is the main heat transfer mechanism during a FCI. This film boiling regime sustains until the corium reaches the minimum film boiling temperature. However, the heat transfer of some corium debris with the film boiling in a pre-flooded cavity would be influenced by the steam explosion. At the instant moment of the steam explosion, analysis codes apply the high heat transfer coefficient even though the corium particles are in the film boiling region in terms of the temperature: $5{\cdot}10^4$ W/m^{2}K in MC3D, ~10^6 W/m^{2}K for TEXAS-V [1]. After the steam explosion, the calculation of analysis codes returns to the normal boiling equation implemented in each code. This seems acceptable since some experiment showed that the specimen recovers the film boiling heat transfer right after the peak heat transfer resulted from the instant film collapse with the pressure shock [2]. However, the early collapse and the complete escape from the film boiling heat transfer was observed for the solid sphere with the water in experiments which we present here.

2. Method and results

2.1. Method

The experiment apparatus for the film boiling was set as shown in Fig. 1. This apparatus consists of the moving cylinder, the furnace, the support rod to hold the sphere, the acrylic water pool, and the high-speed camera [3]. Thermocouples are installed in a sphere specimen and the acrylic water pool. The sphere is made of SS316L and the diameter is 10 mm. The thermocouples are ungrounded sheathed K-type.

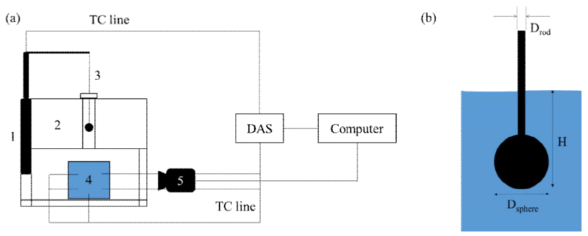

Fig. 1. (a) Diagram of the experiment system. (1 : pneumatic cylinder, 2 : furnace, 3 : support rod, 4 : water pool, 5 : high-speed camera) (b) Geometry of the specimen.

The original purpose of this experiment was measuring the heat transfer of the film boiling with the effect of the support rod [3]. When we performed the preliminary experiment, we obtained the results by the collision between the sphere and the thermocouple installed in the acrylic water pool. Unintentionally, we measured the effect of the collision during the film boiling. The experiment were performed as 15 times repeated with the same specimen.

The experimental heat flux was calculated as:

$$q''_{total} = \frac{Q_{total}}{\pi D_{sphere}^{2}} \tag{1}$$

$$Q_{total} = m_{sphere} c_p \frac{dT_{sphere}}{dt} \tag{2}$$

where q'' is the heat flux, Q is the heat, D_{sphere} is the diameter of the sphere, m is the mass, c_p is the specific heat, and t is time.

2.2. Results

The initial conditions and the quenching results are tabulated in Table I. The moving velocity of the sphere was approximately 0.25 m/s.

Table I. Experiment conditions and quenching results

Test #	Initial sphere temperature (C)	Initial water temperature (C)	Quenching mode
1	946.25	25.8	Fast
2	936.72	28.6	Slow
3	927.35	30.8	Slow
4	929.19	32.5	Fast
5	933.94	34.1	Fast
6	919.47	35.5	Fast
7	922.06	36.9	Slow
8	926.62	37.8	Slow
9	918.86	38.7	Slow
10	926.08	39.5	Slow
11	930.02	40.2	Slow
12	927.15	40.8	Slow
13	926.19	41.4	Fast
14	927.40	41.9	Slow
15	921.13	42.6	Fast

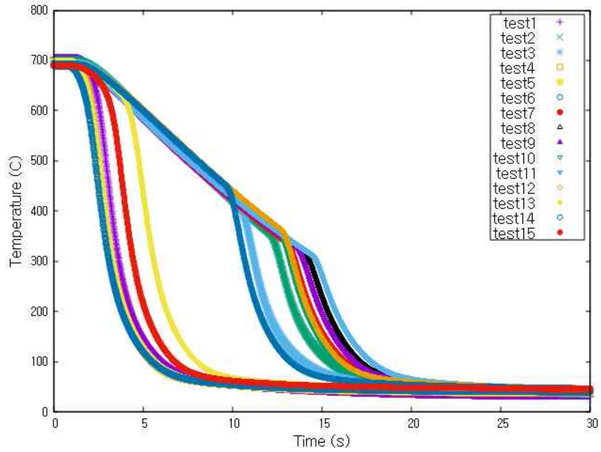

Fig. 2. Time vs. temperature.

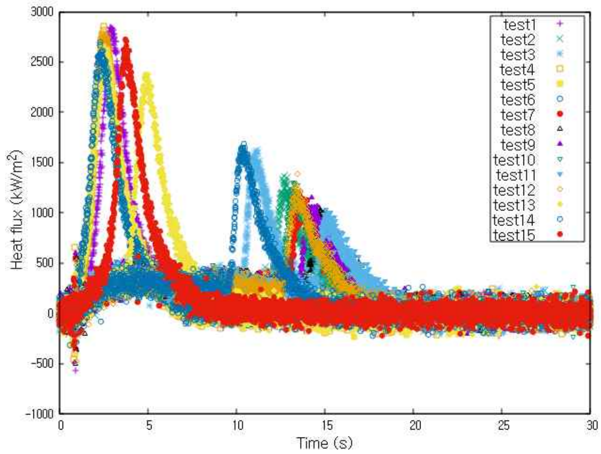

Fig. 3. Heat flux vs. temperature.

As shown in Fig. 2, the early collapse of the film boiling resulted in the rapid temperature decrease at the high temperature with 6 out of 15 cases. In detail, test 1, 4, 5, 6, 13, 15 showed the fast quenching from the temperatures of 833~927 °C within a few seconds, and others showed the regime change at the temperatures of 396~572 °C within a tens of seconds. As shown in Fig. 3, it showed the definite difference between the fast and the slow quenching.

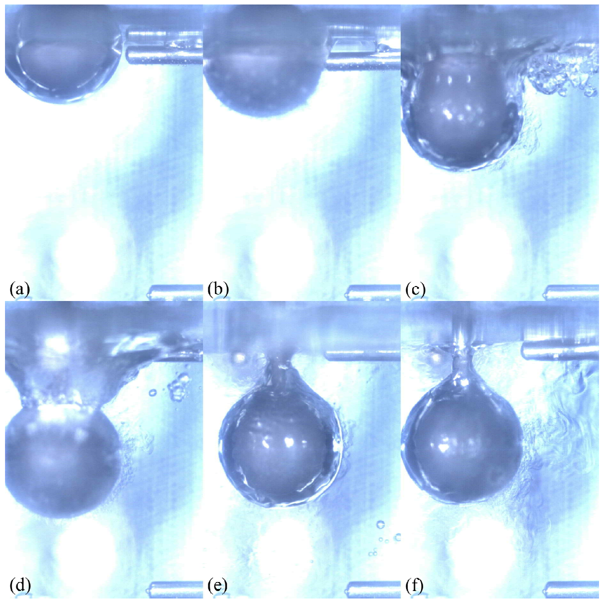

Fig. 4. Photographs of Test 15 (Fast quenching case).

There are some photographic results as shown in Fig. 4. The first one (Fig. 4. (a)) showed the moment before the collision of the sphere and the thermocouple in the water pool. We could see that the film boiling is formed in the lower hemisphere of the specimen. At Fig. 4. (b), the film boiling instantly breaks up. However, the heat flux did not show the particular behavior. The film boiling state recovered as shown in Fig. 4. (c), right after Fig. 4. (c). When the sphere reached to the lowest position as observed in Fig. 4. (d), the film boiling was instantly broken again. Note that this kind of the film breakup at the lowest position was not observed every fast quenching case, while the slow quenching case (Test 11) showed the behavior as Fig. 4. (d). When the sphere bounces back to the upper position, it seems the film boiling recovers (Fig. 4. (e)). It sustained the film boiling state about 1.36 s. This film boiling began to break down from its bottom and it propagated to the whole geometry.

For the case of Test 13, which showed the fast quenching, no sign of the instant film breakup was visually observed. However, as described in Fig. 2 and Fig. 3, Test 13 showed the fast quenching.

Since these experiment were just unexpected and preliminary cases, no further investigation was done for this issue. Considering these results, we would state that the fast quenching for the corium particles could occur randomly during FCI in such situations: 1) solidified corium particle contacting to the bottom of the cavity, 2) solidified corium particle interacting with the pressure wave generated by the steam explosion. For those situations, the heat transfer should be overestimated comparing to the current analysis of severe accident codes. It also leads to the low initial temperature of MCCI and the better coolability for ex-vessel corium debris. Thus the further investigations for this topic are recommended to clarify the observed phenomenon and to attain the realistic evaluation of the heat transfer during FCI or after the steam explosion.

3. Conclusions

We introduce the experimental results that showed the early collapse of the film boiling when the unexpected collision occurred. This kind of collision could happen with a solid state of corium particles during FCI: 1) the corium meets with the cavity bottom, 2) the corium interacts with the pressure wave generated by steam explosion. If this occurs in reality, the heat removal from the corium would be enhanced during FCI rather than expected heat transfer.

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