An Experimental Visualization Study of the Reflood Heat Transfer on Single Heater Rod with CRUD Layer

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1. Introduction

During normal operation of a nuclear power plant, corrosion byproducts contained in the primary coolant are deposited on the surface of the nuclear fuel cladding, forming a deposit layer with a thickness of several tens of micrometers by subcooled nucleated boiling. This is called CRUD, which stands for Chalk River Unidentified Deposits.[1]

CRUD is a porous deposit layer primarily composed of metal oxides, characterized by low thermal conductivity, which consequently serves as a thermal resistance. This can potentially reduce the efficiency of core heat transfer during normal operation, subsequently raising the temperature of both the nuclear fuel and its cladding.[2] Additionally, the elevated temperatures by the nuclear fuel and cladding can impact the dispersion of heat within the core. [1,3]

Recently, in contrast to CRUD's typical thermal resistance effect, certain studies focusing on boiling and quenching heat transfer on surfaces exhibiting similar characteristics to CRUD have indicated an enhanced heat transfer effect.[4] The improved heat transfer properties of CRUD counteract the thermal resistance effects it typically presents. This is achieved by enhancing the heat transfer process during the cooling of nuclear fuel rods through reflooding in Loss of Coolant Accidents (LOCAs).

To validate the enhanced heat transfer effect of CRUD, this study carried out reflooding experiments on a single heated rod with CRUD layer.

2. Reflooding Experiment

Fig. 1 depicts a schematic diagram of the experimental setup for reflooding, comprising three primary segments as illustrated. The setup consists of three key components: the test section, which facilitates visualization for simulating the reflooding process; the coolant supply system designed for introducing cooling water during reflooding; and the steam supply system responsible for establishing initial conditions within the test section. The specimen used in this study is a single heated rod with an outer diameter of 9.5 mm, mirroring the outer diameter of nuclear fuel cladding. This identical specimen was used for conducting CRUD deposition experiments (conducted at UNIST). These deposition experiments were conducted under conditions of the primary coolant of PWR– with parameters of 15.5 MPa pressure, 320℃ temperature, and ion concentrations of Ni: 25 ppm and Fe: 12.5 ppm. The resulting CRUD-deposited specimen was verified to possess porous and hydrophilic surface characteristics. (Fig.2 & Table. 1)

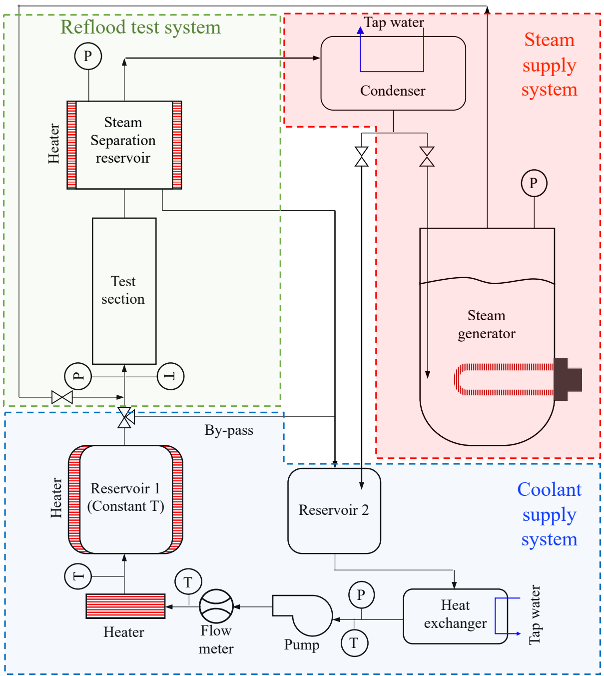

Fig. 1 Schematic diagram of reflooding experimental facility

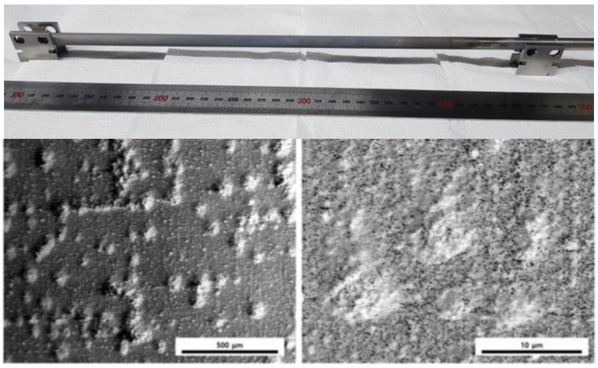

Fig. 2 CRUD sample and SEM images

Table 1 Experimental condition of the reflood test

Parameters	Value
Contact angle	23.4 °
Thickness of CRUD	10 – 15 μm
Avg. surface roughness	0.78 μm

The experiment was carried out with a reflooding rate of 50 mm/s and an inlet subcooling temperature of 10 K(Table. 2). Throughout the experiment, a high-speed camera was used to visualize the various two-phase flow regimes. Furthermore, temperature data from an embedded thermocouple within the specimen were collected.

Table 2 Experimental condition of the reflood test

Parameters	Value
Outlet pressure	0.1 MPa
Inlet subcooling	10 K
Reflood rate	50 mm/s
Linear heat generation	2 kW
Initial wall temperature	700℃

3. Experimental results

In initial stages of reflooding visualization results, it was observed that the film boiling heat transfer regime on a bare surface specimen persisted for a longer duration after coolant injection compared to the CRUD-deposited specimen. (Fig.3 & 4-(1)) In both specimens, the flow regime exhibited similar characteristics, including disturbances at the interface and liquid entrainment subsequent to the collapse of the vapor film. The most significant difference between the two visualization results was the point at which the vapor film collapsed. (Fig.3 & 4-(2))

In the case of the CRUD-deposited specimen, it is presumed that the cooling performance improved due to the rapid collapse of the vapor film and subsequent interface disturbances, leading to direct contact between the cooling water and the specimen surface. Additionally, the significant liquid entrainment generated further contributed to the enhanced cooling performance compared to the bare surface specimen.

Both the bare surface specimen and the CRUD-deposited specimen exhibited significant disruption of the vapor-liquid interface, initiating quenching and the formation of quench front. However, the visualization results indicated that the CRUD-deposited specimen prompted the initiation of quenching more rapidly than the bare surface specimen, resulting in an earlier formation and higher speed of the quench front. (Fig.3 & 4-(3), (3-1))

Subsequently, as cooling water continued to be injected, the water level rose, and the formation of reverse annular flow was observed due to the steam generated at the quench front. (Fig.3 & 4-(4))

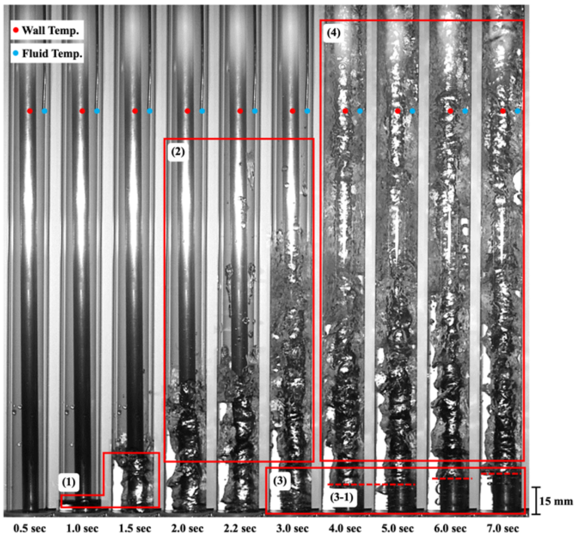

Fig. 3 Visualization results of Bare surface during reflooding experiment

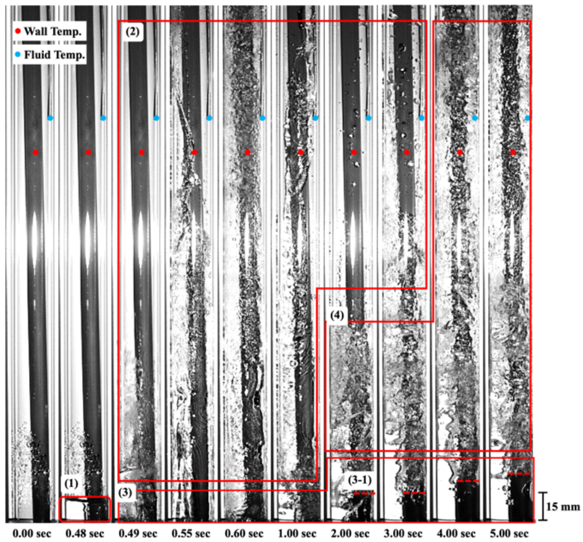

Fig. 4 Visualization results of CRUD surface during reflooding experiment

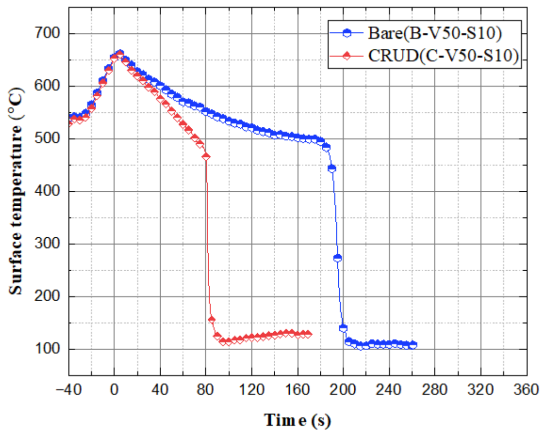

Fig. 5 Measurement results of surface temperature history during reflooding experiment

Furthermore, based on the visualization results, the propagation speed of quench front was measured and compared. It was observed that the propagation speed of quench front on the CRUD-deposited surface (~2.098 mm/s) was more than twice as fast as that on the bare surface (~0.978 mm/s).

Fig. 5 shows the temperature history result at the temperature measurement positions on the specimens after the injection of cooling water for both specimens. For the bare surface specimen, following the injection of cooling water at 0 seconds, a gradual cooling due to the film boiling heat transfer occurred. Then, quenching started shortly thereafter, and around 180 seconds, a quenching caused a sharp drop in specimen temperature.

On the other hand, for the CRUD-deposited specimen, compared to the bare surface specimen, the cooling time due to film boiling heat transfer was shorter than that of the bare surface specimen, but the magnitude of temperature drop was observed to be greater. This can be attributed to the rapid collapse of the vapor film generated by film boiling on the lower section of the specimen. This collapse triggers disruptions at the vapor-liquid interface and subsequently affects the direct contact between cooling water and the specimen's surface, as well as the cooling due to the generated liquid entrainment. Furthermore, it was noted that quenching initiated approximately 80 seconds after the cooling water injection, aligning closely with the propagation speed of the quench front as determined from the visualization results.

4. Conclusions

Through this experimental study, it was confirmed via visualization and measured temperature history that the CRUD-deposited specimen exhibited approximately half the time required for specimen quenching compared to the bare surface specimen. Furthermore, it is deduced that the increased propagation speed of the quench front in the CRUD-deposited specimen, approximately 100% higher than in the bare specimen, contributed to the reduction in quenching time.

Through this experimental study, it has been confirmed that heat transfer can be enhanced due to CRUD deposition. However, due to the challenges in creating CRUD-deposited specimens and the limited number of experiment cases, it is considered difficult to get the generalized conclusions regarding the effect of CRUD on reflooding and quenching heat transfer phenomena. Therefore, it is considered necessary for future research to involve the fabrication of CRUD-deposited specimens with diverse configurations and the performing of reflooding experiments under various conditions.

Acknowledgments

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