Effect of Fouling on Quenching of Simulated Fuel Rods

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INTRODUCTION

Mineral deposits on fuel rods in subcooled flow boiling are a common occurrence and can significantly impact the power distribution in the bundle as well as the anticipated neutron flux [1–3]. These corrosion deposits typically have a nickel iron-ferrite composition and can have a profound effect on the heat transfer mechanisms. Oxide growth on steel and zircaloy clad rods is a porous, non-uniform layer on an otherwise smooth, flat surface. In nuclear plants, safe operations require oxide layers not exceed a certain thickness in relation to the base fuel rod material, which houses the uranium pellets. There are limitations on oxide growth because it compromises the structural integrity of the rod, which may lead to failure of the material.

In 2010, oscillatory reflood experiments were performed at the NRC/PSU RBHT facility that varied the magnitude and frequency of flow rate oscillations [4]. After processing the data, noticeable corrosion and silicon dioxide deposits were observed on the heater rods. Once recognized, the rods with fouling and corrosion were replaced and stationary components were power-washed. The bundle was rebuilt and ready for testing again in 2013. Since then, oscillatory reflood experiments have been repeated in the clean bundle to identify the effect of fouling on rod bundle thermal-hydraulics.

Multiple characterization techniques including X-ray diffraction (XRD), scanning electron microscopy (SEM) associated with Energy-dispersive X-ray spectroscopy (EDS), and field emission scanning electron microcopy (FESEM) were used to identify the phases, chemical composition, and surface microstructure of the Iconel600 rods before and after use in the NRC/PSU RBHT facility [5]. Micro- and nanoparticles composed of NiO, Cr_2O_3, and Fe_2O_3 were observed on the surface of the fouled heater rods. The oxide layer has been characterized as porous with a maximum thickness of 2µm. The water contact angle is found to decrease overtime for the fouled surfaces, indicating an increase in the surface wettability and liquid spreading. Owing to the thin oxide layer, the variation in the analyzed surface roughness of the clean and fouled surfaces is negligible. The porous microstructure coupled with the increase in surface wettability play a significant role in the enhancement of film boiling heat transfer.

EXPERIMENTAL SETUP

The NRC/PSU RBHT test facility has a full-length 7×7 electrically heated rod bundle that simulates a portion of a 17×17 PWR reactor fuel assembly. The test section consists of a full-length rod bundle arranged in a rectangular array housing structure in a square channel of 90.2 mm (3.55 in) [4, 6]. The flow housing is connected to the lower and upper plenums, see Fig.1. The flow housing is made of Inconel 600, which has a wall thickness of 6.4 mm so that it can withstand higher temperature and pressures. The flow housing has 23 pressure taps at different elevations through which DP (differential pressure) cells are connected to measure pressure drop. There are 45 full-length heater rods and four unheated corner rods in the bundle. The diameter of the heater rods is 9.5 mm, the heated length is 3.657 m and the pitch is 12.6 mm. Four corner rods provide structural support to the bundle and accommodate the wiring for the grid thermocouples.

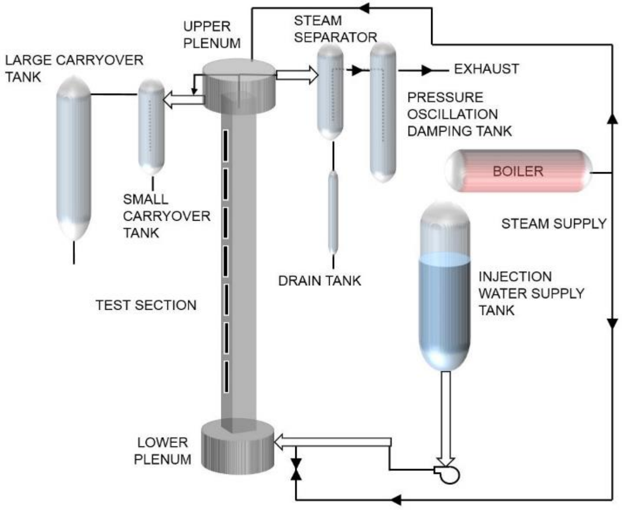

Fig. 1. NRC/PSU RBHT Facility.

RESULTS AND DISCUSSION

Oxidation can be likened to a surface roughness, and the added porosity is known to enhance heat transfer due to capillary forces, which disperse, and breakup liquid films faster than a clean, bare surface [7]. For these reasons, it is expected that the fouled bundle would quench faster than the clean bundle, as seen in Fig. 2. When comparing the minimum film boiling temperature, or Tmin, from the fouled bundle, the effect of oxidation is apparent. Test conditions for clean and fouled bundle experiments are shown in Table I. For the clean bundle (Exp. 7184), it was found that Tmin ≈ 895 K and for the fouled bundle (Exp. 5231), Tmin ≈ 940 K. Oxidation acts to break up the vapor film in film boiling faster and by so-doing, the minimum film boiling temperature increases with oxidation and decreases the quench time.The experimental uncertainty associated with the thermocouple is +/- 1.11 K [8]. In terms of experimental repeatability, the largest variation in a temperature and time measurement is 13 K and 16 s, respectively [9].

In addition to quenching behavior, thermal-hydraulic parameters are shown in Fig. 3. of the inner 3×3 with bundle fouling. Hollow and filled shapes represent oscillatory and constant reflood experiments, respectfully. Experiments No.s in the 5000s are fouled and those in the 7000/8000s are clean. A decrease in the bundle quench time occurs, regardless of oscillatory reflood, when there is bundle fouling. This is expected due to enhanced entrainment which occurs when there is oscillatory reflood in the bundle.

In addition, steam temperatures are shown for the two experimental sets in Fig.'s 4 and 5. For the clean bundle experiments in Set A (Fig. 4), the steam temperature for the oscillatory reflood experiment is approximately 200 K lower than for the constant reflood experiment, confirming enhanced entrainment. However, for the fouled bundle experiment, the trend in the steam temperatures is not as clear. Both temperatures in Fig. 5 are the same at the start of the experiment, however, the constant reflood experiment appears to wet sooner than the oscillatory reflood test. The peak temperatures for the fouled bundle experiments were approximately 200 K lower than the clean bundle tests, see Fig. 5. This significant difference in surface conditions may have contributed to the observed steam temperatures for these tests. Additionally, it can be concluded from Fig.'s 4 and 5 that the effect of fouling dominates the effect of oscillatory reflood when comparing the steam temperatures.

CONCLUSIONS

In conclusion, the effect of fouling decreases bundle quench time, and decreases the steam temperatures when compared to clean bundle experiments. The effect of oscillation period serves to increase the required bundle quench time and decreases the steam temperatures for the clean bundle tests. The effect of fouling dominates the effect of oscillatory reflood when comparing the steam temperatures.

TABLE I. EXPERIMENTAL CONDITIONS

Set	Exp. No.	Flow velocity (m/s)	Oscillation period (s)
A	8069	0.0254±0	∞
	7184	0.0254±1	4
B	5238	0.0254±0	∞
	5231	0.0254±1	4

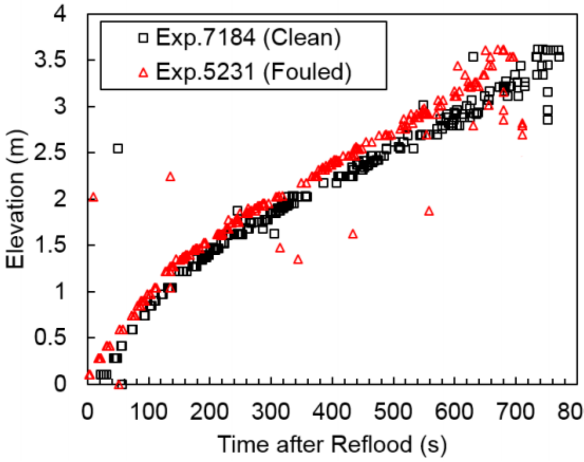

Fig. 2. Quench front profiles with and without fouling for oscillatory reflood experiments.

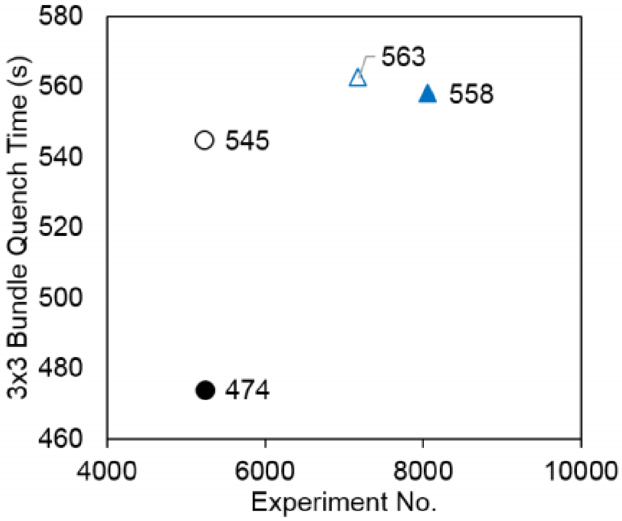

Fig. 3. Quench time of clean and fouled bundle experiments. Hollow and filled shapes represent oscillatory and constant reflood experiments, respectively. Experiments No.s in the 5000s are fouled and those in the 7000/8000s are clean.

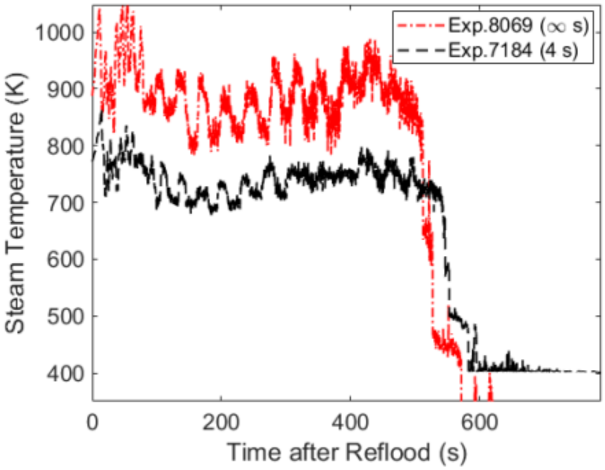

Fig. 4. Steam temperatures for clean bundle tests.

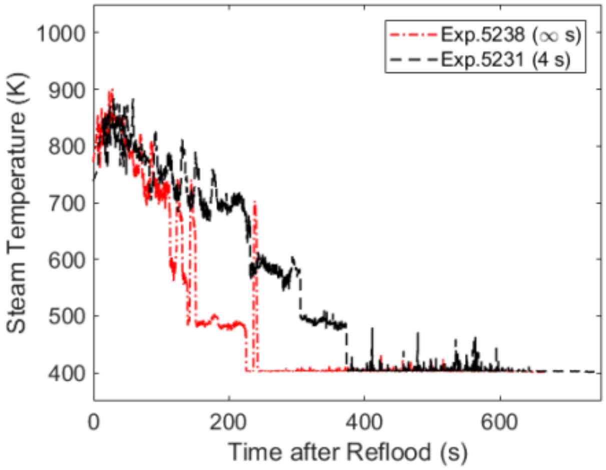

Fig. 5. Steam temperatures for fouled bundle tests.

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