

Evaluation of Temperature Non-Uniformity in CRUD-Mimicking Layers of Varying Thickness Using a Fiber-Optic Sensor

SeHyeon Park ^a, UngJin Na^b, Jihun Kim^b, Euijae Kim^c, Sungjin Kwon^d, HangJin Jo ^{a, b*}

^a Division of Advanced Nuclear Engineering, POSTECH, Pohang, Republic of Korea

^b Department of Mechanical Engineering, POSTECH, Pohang, Republic of Korea

^c KEPCO Nuclear Fuel Co., Ltd., Daejeon, 34057, Republic of Korea

^d Korea Institute of Fusion Energy, Daejeon, 34133, Republic of Korea

*Corresponding author: jhj04@postech.ac.kr

***Keywords :** Pool boiling, Fiber-optic sensor, Temperature distribution, Metal oxide porous layer with chimney structure

1. Introduction

CRUD (Chalk River Unidentified Deposits) is a porous deposit formed on nuclear fuel cladding by the deposition of metal oxides generated by corrosion of components in the reactor primary system. The composition and morphology of CRUD vary with the operating conditions and coolant chemistry of nuclear power plants. Chimney structures, which provide pathways for liquid supply and vapor escape, have been observed in some CRUD deposits. A CRUD layer can act as an additional thermal resistance between the cladding and the coolant. Its effective heat transfer characteristics can also vary with boiling and liquid-vapor transport within the layer [1].

The thickness of the CRUD layer is an important parameter affecting liquid supply, vapor escape and thermal resistance. A spatially non-uniform distribution of liquid and vapor within the porous layer may cause local variations in effective thermal resistance and heat removal, leading to a non-uniform temperature distribution on the surface. In addition, the formation of local dry spots and rewetting failure at high heat flux have been reported to play an important role in the occurrence of critical heat flux (CHF) [2,3]. Therefore, both the surface-averaged temperature and the local temperature distribution should be considered when evaluating the thermal integrity of fuel cladding with CRUD deposits.

Total reflection and infrared thermography have been used to investigate the liquid-vapor distribution and local thermal behavior on surfaces. However, these techniques generally require a transparent heater or an optically accessible measurement configuration, which limits their direct application to opaque metal oxide porous layers. In contrast, an optical frequency-domain reflectometry (OFDR)-based fiber-optic sensor can provide distributed temperature measurements with high spatial resolution along the optical fiber [4].

In this study, the local surface temperatures of CRUD-mimicking layers with different thicknesses were measured using a fiber-optic temperature sensor in the nucleate boiling regime. The effects of layer thickness

and heat flux on surface temperature non-uniformity were evaluated.

2. Experiments

CRUD-mimicking layers with a chimney structure were fabricated by sintering method. The layer thicknesses were 70, 100, and 120 μm . To isolate the effect of layer thickness, the same particle size, sintering conditions, and chimney geometry were used for all samples. A sample without a CRUD-mimicking layer, denoted the plain sample, was also tested as a reference.

Pool boiling experiments were conducted in saturated water at atmospheric pressure using a conduction-heated test section. A schematic of the experimental apparatus is shown in Fig. 1. Heat was supplied to the boiling surface using cartridge heaters inserted into a copper block. At each heat flux, the temperature was measured after steady-state conditions were reached, and the heat flux was then increased stepwise.

To measure the local temperature distribution, a fiber-optic sensor was placed along nine grooves machined beneath the boiling surface of the copper block, as shown in Fig. 1. The spatial resolutions in the x- and y-directions were 2.6 and 3.0 mm, respectively. At each heat flux condition, the temperature distribution was measured for 10 s after steady-state conditions were reached.

The spectral shift measured by the OFDR-based fiber-optic sensor is affected by temperature and strain. It can be expressed as follows:

$$-\Delta\nu = C_T\Delta T + C_\varepsilon\varepsilon \quad (1)$$

where $\Delta\nu$ is the spectral frequency shift, ΔT is the temperature change, and ε is the strain. C_T and C_ε are the sensitivity coefficients for temperature and strain, respectively. To minimize external mechanical strain in the optical fiber, the fiber was installed inside a SUS304 capillary tube. The frequency shift was converted to temperature using the calibration results obtained over the experimental temperature range.

(c)

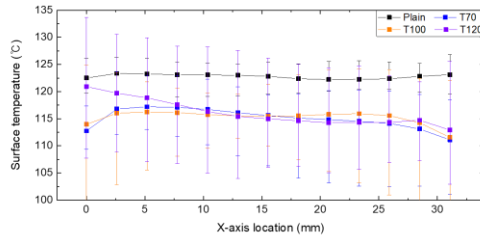


Figure 3. Average surface temperatures at heat fluxes of (a) 300, (b) 600, and (c) 850 kW/m². Error bars show the minimum-to-maximum range measured along Lines 1–9 over 10 s.

4. Conclusions

In this study, local surface temperature distributions of CRUD-mimicking layers with different thicknesses were measured using an OFDR-based fiber-optic temperature sensor. The samples with CRUD-mimicking layers exhibited higher CHF values than the plain sample. Within the investigated range, CHF tended to increase with increasing layer thickness.

The surface temperature range increased with heat flux. At the same heat flux, thicker CRUD-mimicking layers exhibited wider temperature ranges, indicating larger differences between the observed high and low local temperatures.

These results suggest that both the surface-averaged temperature and the local temperature distribution, including the non-uniformity associated with CRUD layer thickness, should be considered when evaluating the thermal behavior of CRUD layers

5. Acknowledgement

This research was supported by an internal project (development of critical heat flux measurement technique using optical fiber temperature sensor) grant funded by KEPCO Nuclear Fuel Co., Ltd., Republic of Korea, and by the National Research Council of Science & Technology (NST) grant funded by the Korea government (MSIT) (No. GTL25031-000).

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