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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Seokbin Seo, Charles P. Folsom, Colby B. Jensen, Robert J. Armstrong

**Idaho National Laboratory, 1955 N. Fremont Ave., Idaho Falls, ID 83415*
seokbin.seo@inl.gov

INTRODUCTION

The monitoring of the temperature of a heated surface commonly uses thermocouples, one of the most used temperature sensing technologies. The temperature that appears at the thermocouple junction is believed to represent the surface temperature when thermocouple wires are put directly on the surface. However, there are uncertainties in whether surface-mounted thermocouples can provide precise temperature detection [1]. This is especially true when thermocouple wires are exposed to a rapid change in thermal-hydraulic environment, like boiling of liquid, an inaccuracy in the temperature measurement can be exacerbated.

In the reactivity-initiated accident (RIA) scenario, right after the power burst with the occurrence of departure from nucleate boiling (DNB), the cladding temperature quickly reaches its maximum and is maintained in a steady film boiling regime. Then, under limited heat transfer performance of film boiling, the local cooling effect by the thermocouple wire may not be neglected [2,3]. The temperature of the wire will be impacted by the temperature of the surrounding vapor film, which will impact how much heat is transferred by conduction to the bead attached to the surface.

In this paper, we discuss the general characteristics of the cooling effect in vicinity of the surface-mounted thermocouple. We developed a computational model using a finite element method (FEM) technique for the multidimensional calculation of the heat transfer of cladding and thermocouples. We verified the solution against a benchmark problem and investigated its sensitivity to various key parameters.

MODEL DESCRIPTION

A finite element analysis with the Abaqus FEM program was carried out to demonstrate its feasibility against a benchmark problem. In 1984, T. Tsuruta and T. Fujishiro [4] derived an analytical model to describe the temperature drop caused by a thermocouple mounted at the heating surface. They developed heat conduction equation through the cladding embedding fin effect by thermocouple wires. They also calculated the convective heat transfer between the cladding and water vapor film while assuming the vapor film to be a flat and stationary layer. The model employed several inputs as key variables, including the thickness of vapor film, diameter of thermocouple, and coolant flow conditions. Since the analytical solution agreed well with the Nuclear Safety Research Reactor (NSRR) experimental data, we initially aimed to verify our numerical model against the analytical calculations.

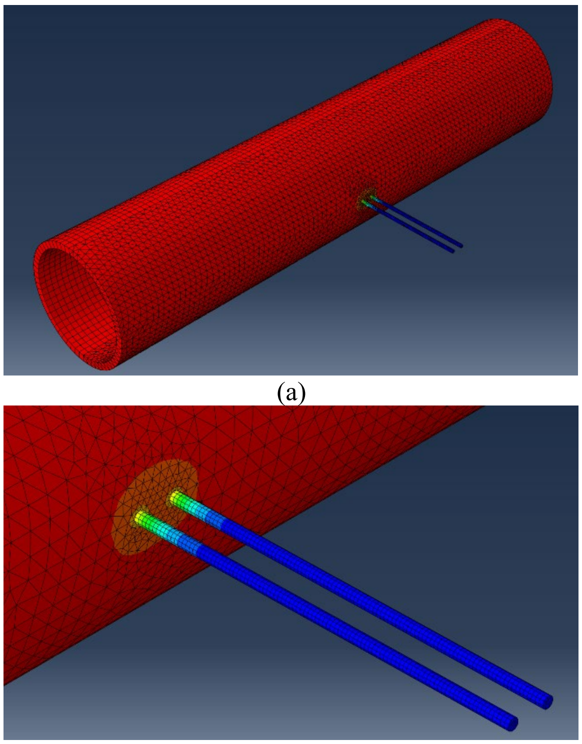
We constructed a model in Abaqus consisting of cylindrical cladding with two thermocouple wires mounted on the outer surface. The cladding is made of Zircaloy-4, and has a thickness of 0.62 mm, an outer diameter of 10.72 mm, and a height of 50 mm. The thermocouple wires are 10 mm-long with a diameter of 0.3 mm made of Pt and Pt-13% Rh, respectively. Pt-13% Rh thermocouple is attached at the midplane of the cladding and the other is located at upper position with an interval of 1 mm. We simplified the model by not including the fuel pellet, gas-gap, and surrounding water, instead, we applied an appropriate boundary condition to each interface to represent corresponding phenomenon.

A convective heat transfer with gas-filled gap at 1440 °C was assumed at the inner surface of cladding with the gap heat transfer coefficient of 5.43 kW/m^2-K. A heat transfer coefficient of 1.18 kW/m^2-K and a bulk temperature of 100 °C were used at the outer cladding surface and bottom part of thermocouples to represent the film boiling heat transfer to vapor layer. In the same manner, 10.63 kW/m^2-K and 25 °C were used at the upper part of thermocouples to calculate the convective heat transfer to the bulk liquid water. Key thermophysical properties of materials utilized in this study were retrieved from the reference [4].

RESULTS AND DISCUSSION

Figure 1(a) presents an example of temperature profile in the system. While Abaqus predicted the temperature profile as physically expected, the contour clearly indicates the temperature drop caused by the thermocouple, as shown in zoomed region where the upper thermocouple is attached in Figure 1(b). Note that the temperature is the highest for the red color and it decreases as the color changes to blue.

For further demonstration of problem, we compared the temperature profile along the axial direction against the benchmark problem with respect to the distance from the thermocouple, as shown in Figure 2. The temperature values along the cladding surface predicted by Abaqus deviates slightly from the reference analytical solution. This is because the present study applied convective heat transfer from the gas-gap temperature field to the inner cladding surface while a fixed temperature for the outer cladding surface was applied in the reference problem. The temperature profile along the axial direction, however, is in agreement with the reference case, and the temperature drop due to the fin effect of thermocouples appears to be same. For both problems, near the thermocouple, the surface temperature of cladding was up to ~ 180 °C less than the temperature at the surface far from the thermocouples. As a result, we verified that the Abaqus model was well developed to represent the heat transfer behavior near surface-mounted thermocouples.



(a)

(b)

Fig. 1. (a) Typical temperature profile predicted by Abaqus, (b) Zoomed temperature field along the cladding surface-mounted thermocouples.

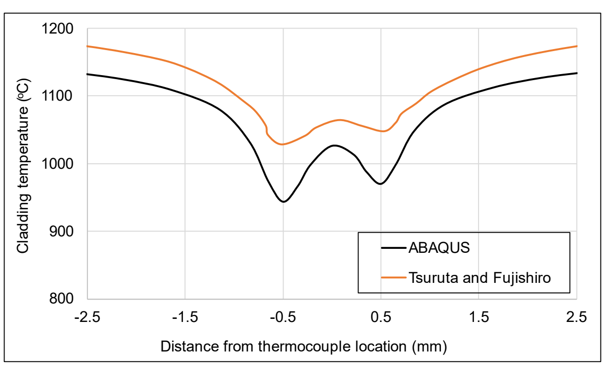


Fig. 2. Surface temperature profiles predicted from the Abaqus simulation and the reference [4] along the axial direction in the cladding.

We conducted a series of studies to investigate the sensitivity of the temperature drop to key parameters: the thickness of vapor film layer, thermocouple wire diameter, and the film boiling heat transfer coefficient between the cladding and vapor film layer. Figure 3 shows the effect of vapor film thickness on the temperature profile near thermocouples. The temperature drop increases as the vapor film thickness decreases, and its effect becomes significant for the vapor film layer of 1 mm or less thickness. Near the thermocouples, the heat conduction from the cladding surface to the thermocouples is the dominant heat transfer mechanism due to high thermal resistance of vapor layer. Furthermore, along the thermocouple wire, the heat transfer to the liquid coolant makes up the majority of the heat flow. Hence, the decrease of vapor layer thickness enhances the heat flow through the wire, because it increases the surface area for the heat transfer to the bulk liquid from the wire.

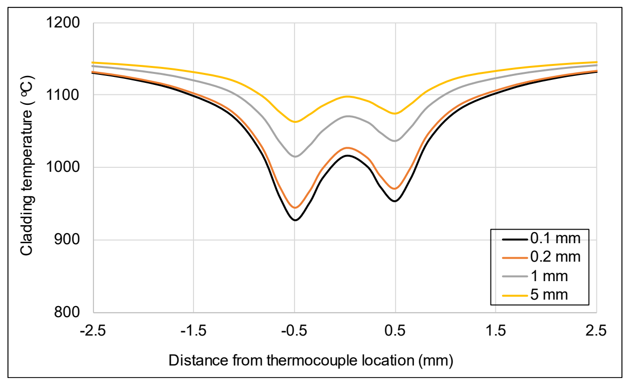


Fig. 3. Surface temperature profile along the cladding with respect to different vapor film layer thickness.

The impact of the diameter of thermocouple on the fin effect is indicated in Figure 4. As the thermocouple becomes thicker, the local cooling effect of the thermocouple is enhanced. It is reasonable to conclude that the increase in thermocouple diameter results in larger surface area for the heat sink on the cladding because of a larger cross section for heat conduction.

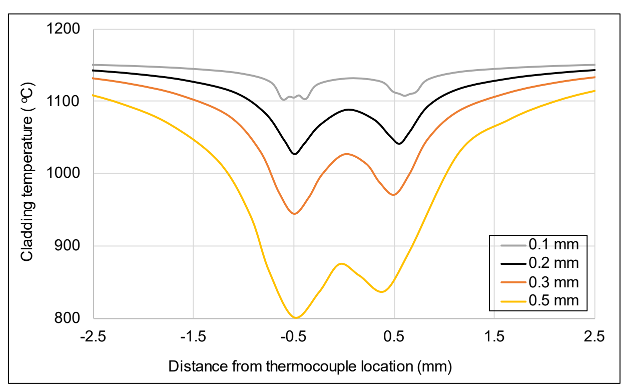


Fig. 4. Surface temperature profile along the cladding with respect to different thermocouple diameter.

Lastly, the influence of the film boiling heat transfer coefficient on the thermocouple fin effect is investigated, and the results are shown in Figure 5. Over the examined film boiling heat transfer coefficient range of 0.5 to 10 kW/m^2-K, the temperature of cladding surface does not change significantly. Although the increase in film boiling heat transfer coefficient allows more heat to be transferred to surrounding vapor film layer, the heat conduction to the wire still dominates the overall heat transfer phenomena near thermocouples.

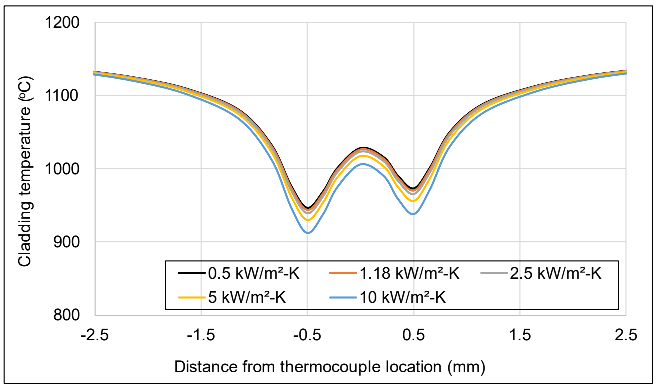


Fig. 5. Surface temperature profile along the cladding with respect to different film boiling heat transfer coefficient.

CONCLUSION

A computational model is developed to estimate the local cooling effect of the thermocouple wire mounted on the cladding surface under film boiling condition. The model predicts the temperature profile along the cladding surface as physically expected and is verified against the benchmark problem. Sensitivity studies reveal the significant effects of the thickness of vapor film layer and the diameter of thermocouple on the temperature drop near the thermocouple, for they increase the heat transfer area to the liquid water region. The impact of film boiling heat transfer coefficient, however, is not significant, as the primary heat transfer mechanism near the thermocouple is the heat conduction to the wire. Future studies will include the contribution of radiative heat transfer between the cladding surface and the vapor film layer, as well as a transient power history which represents an actual RIA scenario.

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