Numerical Study on Fluid-Thermal-Structure Interaction for a Solid Wire under Film Boiling

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1. Introduction

Film boiling heat transfer is a phenomenon which is broadly studied because of its importance in many fields, especially in nuclear safety field. However, researchers mainly focus on the prediction of the heat transfer rate. Meanwhile, film boiling usually occurs at high temperature, at which temperature a heating element can be deformed and failed. Therefore, understanding and predicting behavior of the heating element is important to avoid unsafety in nuclear reactor systems. In this study numerical simulations of a nichrome wire of 2 mm diameter under different film boiling conditions of water at atmospheric pressure were performed. The temperature distribution and deformations of the wire were obtained based on the fluid-thermal-structure interaction (FTSI) approach.

2. Numerical methods

Figure 1 shows the two-dimensional simulation domain including fluid and a heating solid element. The diameter of the solid wire is 2 mm and the domain size is 40×40 mm. The solid wire is located in the middle of the simulation domain. A translation periodic condition was applied on the left and right side of the domain.

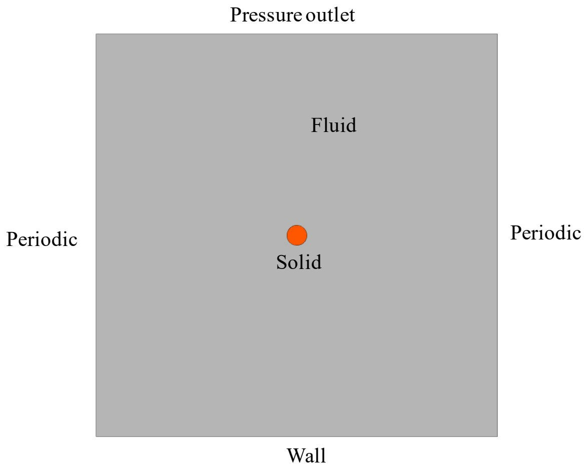

Fig. 1. Simulation domain.

Fluid is saturated water at atmospheric pressure and saturated temperature. The water vapor is treatment as ideal gas because the density varies largely [1]. The thermal conductivity and viscosity of vapor were set a function of temperature [2]. Other properties of water and vapor were calculated at a pressure of 0.1013 MPa and a temperature of 100°C. Similarly, the properties of the nichrome wire (Ni80Cr20) such as thermal conductivity, thermal expansion and stress-strain curves were set as a function of temperature [3–5].

The conjugate heat transfer simulations were performed using the ANSYS FLUENT solver. The continuity, momentum and energy equations are solved throughout the domain based on the single-fluid concept. The ANSYS MECHANICAL solver was used to obtain the solid deformation [6].

3. Results and discussion

The film boiling model was validated using a simulation without the solid domain with a surface temperature of 700°C. The result of the wall heat flux is 250735 W/m^2, which is similar to an experiment value of 229005 W/m^2 [7]. The relative error is about 9.5%.

The volumetric heat generation rates for simulations were determined based on the properties of Ni80Cr20 as: 250×10^6, 350×10^6 and 450×10^6 W/m^3.

The steady-state temperatures of the solid wire were obtained by solving the time-independent constitutive equations. These values are shown in Table I.

Table I: Temperature of solid wire when different heat generations applied

Case number	Heat generation, q (W/m^3)	Temperature, T (K)
1	250,000,000	779
2	350,000,000	896
3	450,000,000	1055

The transient simulations were conducted to get temperature distribution in the solid domain.

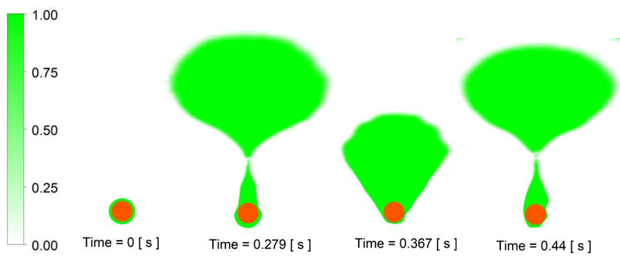

Fig. 2. Bubble generation for $q = 4.5\times10^8$ W/m^3

Figure 2 shows initial vapor, second and third vapor bubble generations at times of 0.279 s and 0.44 s, respectively when the volumetric heat generation is 4.5×10^8 W/m^3. Because of the periodic behavior of film boiling regime and the similarity of the second and third vapor bubble shapes generated the solid deformation was considered only on this time range.

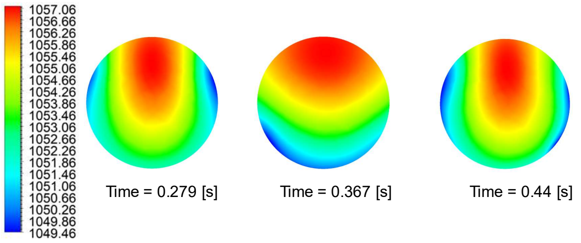

Fig. 3. Temperature distribution in solid domain for $q = 4.5\times10^8$ W/m^3.

The temperature distribution in the solid wire under film boiling is not uniform as shown in Figure 3. Temperature difference is about 7.6°C. The surface temperature at the top of the wire where the vapor is thickest is highest. The temperature is not always the lowest at the bottom surface of the wire. The lowest temperature is tightly related to the local vapor film thickness.

Figure 4 illustrates the total deformation (mm) of the solid wire at times of 0.279, 0.367 and 0.44 s, respectively. The minimum deformation is at center of the wire and the maximum deformation is at the surface of the wire. Because the absolute deformation value is small one-way FSI approach is appropriate.

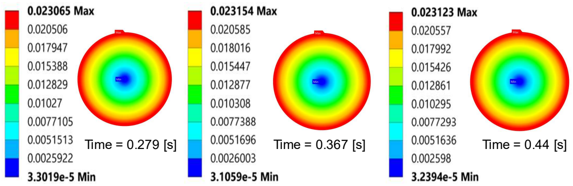

Fig. 4. Total deformation of the solid wire for $q = 4.5\times10^8$ W/m^3.

The surface deformation of the solid wire over time is depicted in Figure 5. As heat generation is increased, the deformation is increased. The top surface of the wire has the greatest deformation. During film boiling, the deformation changes by time according to the periodic behavior of the stable film boiling.

4. Conclusions

This paper has presented the numerical simulation to determine the deformation of the Nichrome wire under film boiling condition. The thermal deformation of the wire strongly depends on the volumetric heat generation. The deformation increases as the heat generation increases. The temperature distribution and radial deformation are not uniform throughout the solid domain. In the future, the three-dimensional deformation will be investigated.

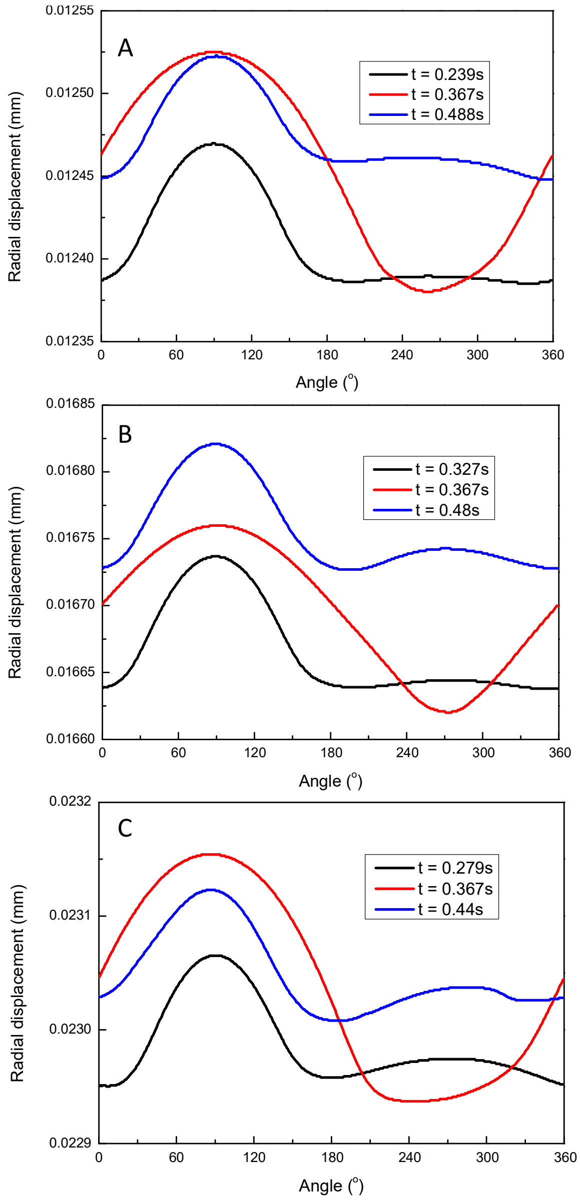

Fig. 5. Radial deformation of the solid surface for $q = 2.5\times10^8$ W/m^3 (A), 3.5×10^8 W/m^3 (B), 4.5×10^8 W/m^3 (C)

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