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Deformation of Zircaloy-4 Tube with High Internal Pressure under Film Boiling of Water at Atmospheric Pressure

Van Toan Nguyen[a], Byoung Jae Kim[a*]
[a]*School of Mechanical Engineering, Chungnam National University,*
99 Daehak-ro, Yuseong-gu, Daejeon 34134, South Korea
[*]*Corresponding author: bjkim@cnu.ac.kr*

1. Introduction

Film boiling is a heat transfer mechanism, which is characterized by full cover of a vapor film on a heating surface. This may lead to the fact that the surface temperature rapidly rises due to the low thermal conductivity of the vapor film. As a result, the heating element can be deformed and failed. Therefore, studying behavior of the heating element under film boiling condition is important for safety of a thermal-fluid system such as of nuclear reactor system. Our study aims to numerically predict deformation of a Zircaloy–4 tube with an outer diameter of 9.5 mm and a length of 127.668 mm with high internal pressure (60 bar) under film boiling conditions of water at atmospheric pressure. The temperature distribution and deformation of the tube were obtained based on the thermal–fluid–structure interaction (TFSI) approach.

2. Numerical methods

To heat the tube input heat flux is applied on the inner surface of the tube which has thickness of 0.57 mm. This heat flux varies linearly along the tube axis and is expressed as follows

$$q = \begin{cases} 50000 + \dfrac{120000}{63.834}x, & x < 63.834\,mm \\ 290000 - \dfrac{120000}{63.834}x, & x \geq 63.834\,mm \end{cases} \qquad (1)$$

where x [mm] is x-coordinate axis coinciding with the tube axis, in which the origin is at the one end of the tube. The heat flux is highest at the middle of the tube and is lowest at two ends of the tube

Because of variation of the input heat flux on the tube, three-dimensional (3D) simulation must be considered. Figure 1 shows the 3D simulation domain of conjugate heat transfer problem of film boiling of water on the Zircaloy-4 tube. The domain size is 127.668×237.5×237.5 mm. A symmetry condition is applied on the sides of the domain, exception to the top side which is assigned as a pressure outlet condition. In addition, a no-slip wall boundary condition is applied on the tube surface.

Fluid is incompressible water at atmospheric pressure and saturated temperature, whereas, the water vapor is considered as ideal gas at low pressure and high temperature [1].

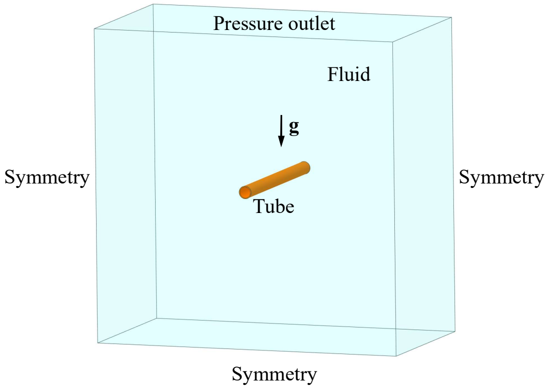

Fig. 1. Three-dimensional simulation domain of film boiling of water on tube.

Some properties of the water vapor such as thermal conductivity and viscosity are treated as temperature functions [2], others are taken at pressure of 1 bar and temperature of 100°C. Similarly, some properties of the Zircaloy–4 tube such as thermal conductivity, specific heat are set as a function of temperature [3].

The governing equations including continuity-, momentum- and energy equations are formed based on the single fluid concept. These equations are solved using ANSYS FLUENT program. On the other hand, the solid deformation is obtained using ANSYS MECHANICAL solver [4].

3. Results and discussion

The film boiling model was validated using the simulation domain as highlighted in Fig. 1. However, to consistent to experiment data [5], the tube diameter is changed to 12 mm and the domain size is changed to 130.65×300×300 mm. In addition, the surface temperature of the tube was kept constantly at 900°C. The time-space averaged heat transfer coefficient (HTC) on the heated surface then can be calculated and compared with the experiment data. Because the value of time-space averaged convection HTC obtained falls in range of experiment data of convection HTC, the considered film boiling model can be used for predicting the film boiling of saturated water on a large tube at atmospheric pressure.

By solving the time-independent governing equations the initial temperature profile for transient simulations was obtained first

$$T_0 = \begin{cases} 675 + 5.59x, & x < 63.834\,mm \\ 1389 - 5.59x, & x \geq 63.834\,mm \end{cases} \tag{2}$$

Next, the transient simulations were performed to obtain temperature distribution in the solid domain. This temperature distribution was then transferred to the mechanical simulation to get deformation of the tube. The new tube is used for conjugate heat transfer simulation of film boiling on the tube again. The process is repeated until the tube deformation to be high enough.

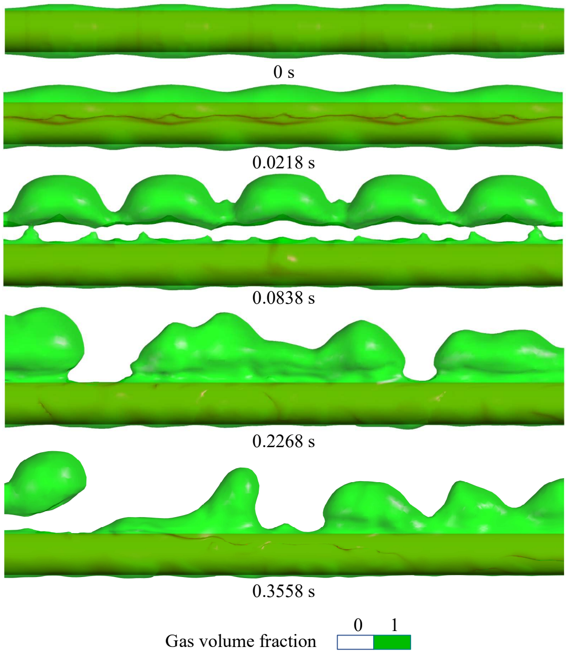

Fig. 2. Bubble generation on undeformed tube.

Figure 2 shows bubble generation on the undeformed tube. The length of the tube was chosen as five times of the most dangerous wave length. At the initial stage five bubbles were separately generated, however, when time goes up the bubbles can be merged to get larger bubble before detaching. The bubble shapes are irregular, they can be a shape of a mushroom or wave. Although the input heat fluxes are different along with the tube axis, the bubble behavior are not much different, the different is only the bubble generation rate. According to that, the bubble generation at the middle is faster than at the ends of the tube.

During film boiling process, the temperature of the tube periodically changes and the period time is small compared to the deformation time. Therefore, the time-average temperature distribution was used as body temperature in Mechanical solver. This body temperature is shown in Fig. 3. The temperature is highest at the middle and is lower at the ends of the tube because the input heat flux is highest at the middle and is lower at the ends of the tube, respectively. Moreover, at a same cross-section, the temperature on the top portion is higher than on the low portion because the vapor film tends to be thicker at the top than at the bottom of the tube.

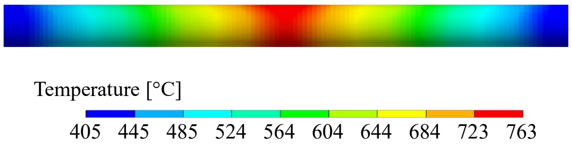

Fig. 3. Time average temperature distribution in undeformed tube.

Under high internal pressure, the tube was deformed as illustrated in Fig. 4. The deformation mainly occurs at the top-middle portion of the tube, wherein the temperature is highest. Thus, the deformation is not uniform as in almost studies [6,7]. In those studied, the deformation of the cladding tube is called by ballooning phenomenon.

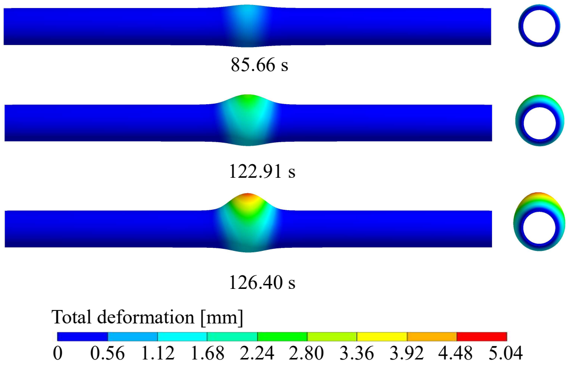

Fig. 4. Tube shape at different deformation time.

During creep deformation, the maximum deformation increases when creep time increases and the deformation becomes very high when the creep time reaches to 126 s. This is a sign of the failure of the tube.

4. Conclusions

This paper has presented the numerical simulation to determine the ballooning phenomenon of the Zircaloy-4 tube with high internal pressure under film boiling of water at atmospheric pressure. When the input heat flux increases the temperature and deformation also increases. The temperature distribution is not uniform in the tube and therefore, the deformation is not uniform. The deformation is highest at the top-middle of the tube, in which the temperature is highest. The highest deformation increases when the creep time increases and the tube can be failed at 126 s.

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