Numerical Simulation of Pool Film Boiling Heat Transfer during Quenching of Heated Cylindrical Rods

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Abstract This research investigates technical options to mitigate failure of a nuclear reactor, in which the coolant supply to the nuclear core has been compromised, known as Loss of Coolant Accident (LOCA). One possible way to decrease the severity of the incident is to quickly plunge the fuel rods in a coolant. The thermo-fluid-dynamics of the quenching process involves a very complex phenomenon due to the cooling mechanism. The aim of this research is to study the effects of the rod's surface material and the liquid subcooling on the quenching process particularly regarding the vapor film morphology around the surface of the rod. The initial temperature of the plunged rod is well above the minimum film boiling temperature (T_{min}) in order to sustain a stable vapor film around the test section. A mesh accuracy study was conducted. The model results for T_{min} were validated with the experimental data that was determined from an inverse heat conduction code. A 2D axisymmetric domain with heat transfer in fluid, phase change, and turbulent flow physical models were selected in COMSOL Multiphysics software to simulate 9.5 mm diameter and 25 cm length stainless steel (SS) and zirconium (Zr) rods plunged in water bath at various subcooling. Results show the dependency of T_{min} on liquid subcooling as well as the surface properties $(\boldsymbol{\rho k c_p})_{\boldsymbol{w}}$ of the heated rod. In addition, visualization results show the variation in vapor film thickness as the liquid temperature changes. Simulated T_{min} values were compared with the experimental results with a maximum error of 18.3% for pool boiling conditions explored in this study.

Keywords: Pool boiling, Film boiling, Minimum film boiling temperature (T_{min}), Quenching.

1. Introduction

Nuclear reactor is one of the significant applications in the field of two-phase heat transfer. Under normal operating conditions, the fuel rods experience high liquid temperatures. In the event of a Loss of Coolant Accident (LOCA), the rods may become temporarily uncovered before emergency coolant refloods the core. During this period of time, the rod cladding surface temperature is dramatically increased. In this case, film boiling becomes the prevalent mode of heat transfer. As the core is reflooded, the surface temperature of the cladding decreases and the rod is quenched. Understanding the transition from film boiling to enhanced modes of heat transfer during the quench process is important for reactor safety analysis.

The minimum film boiling temperature (T_{min}) is defined as the point at which the heat transfer transforms from film to transition boiling or vice versa. Surface material properties and conditions, liquid subcooling, coolant, system pressure, flow conditions, and initial surface temperature effects on T_{min} have been investigated in literature. Numerous experimental studies have been done in the field of pool film boiling heat transfer. Peterson and Bajorek [1] performed pool boiling experiments for vertical cylindrical rods made of stainless steel and zirconium. They studied the effect of high pressure and liquid subcooling on T_{min}. It was found that T_{min} value increases with the increase in liquid subcooling and system pressure. Stevens and Witte [2] observed a linear increase of T_{min} based on initial temperature of a moving sphere of uniform velocity in subcooled water. Baumeister et al. carried out experiments to investigate the effects of the thermal properties of the substrate materials [3]. They plunged heated aluminum, gold-plated copper, steel and pyrex glass in water and ethanol baths. It was concluded that surface materials with lower $\rho c_p k$ have higher T_{min}.

To the best of our knowledge, only few researches were performed in COMSOL Multiphysics software related to film boiling heat transfer due to the complexity of the cooling phenomenon. Passarella et al. [4] simulated the quenching process in COMSOL by submerging a spherical stainless steel workpiece in the water bath. Their model was based on the drift-flux mixture-model for multiphase flow. Results show the formation of the vapor blanket and the collapse around the workpiece. Their simulated results were compared with data from literature. A continued work by Passarella et al. studied not only the quenching process but also the metallurgical transformations, geometrical distortions and residual stresses at the end of the quenching process [5]. Cylindrical rods made of two different types of stainless steel were used as a test sample. The heat transfer coefficient was numerically calculated at different height of the quenched rod then compared with the typical correlation. They had to customize the equations in COMSOL software in order to model the two-phase heat transfer flow and to be able to generate the boiling curve.

The focus of this paper is to investigate the effects of surface materials and liquid subcooling on quenching of vertical cylindrical stainless steel (SS) and zirconium (Zr) rods submerged in a quiescent water bath. The main parameter to be considered is T_{min} which is an important parameter that contributes to the safety of a nuclear reactor. A 2D axisymmetric domain with heat transfer in fluid, phase change, and turbulent flow physical models were selected in COMSOL Multiphysics software. This shows the ability of the software to model the two-phase quenching problem without customizing the software's equations. The results show the dependency of T_{min} on both liquid subcooling and material properties. The thickness of the vapor film for various liquid subcooling is also presented.

2. Modeling Methodology

2.1 Model Geometry

The model simulates a solid cylindrical test section with 9.5 mm diameter and 25 cm length submerged in 30 cm diameter and 50 cm height water bath. The dimensions of the rod simulate the actual size of the fuel rods used in the nuclear reactors. The simulated model presents the lower section of the experimental facility shown in Figure 1 after the test sample is being plunged in the water bath.

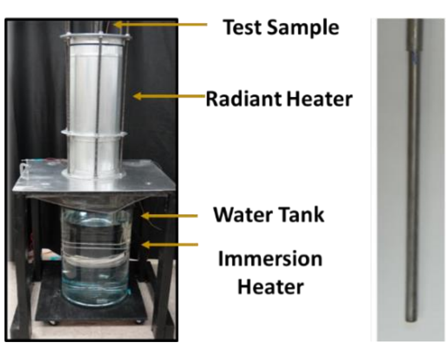

Figure 1. Experimental Facility and Test Sample

2.2 Mathematical Model

Figure 2 illustrates the geometry of the solid rod in the water pool. An axial symmetry axis is chosen to save memory and computational time. The initial temperature was specified to 550ºC for both rods. The gravity force was added to the water to involve the buoyancy force. At the top of the water tank, a convective heat transfer and an open boundary were specified since the tank is open to the atmospheric air during the experiment. The water domain was selected as a phase change material under the heat transfer in the fluid model. The latent heat of vaporization is given (2264.76 kJ/kg).

An initial step prior to modeling the problem is to determine the flow condition. Since the flow is pool boiling, naturally occurred; the flow condition can be determined by calculating Rayleigh number. It is defined as:

$$\boldsymbol{Ra = Gr.Pr} \tag{1}$$

$$\boldsymbol{Gr = \frac{\beta g \Delta T L^3}{v^2}} \tag{2}$$

where Ra is the Rayleigh number, Gr is the Grashof number, Pr is the Prandtl number, $\boldsymbol{\beta}$ is the thermal expansion of the vapor film, g is the gravitational acceleration constant, $\boldsymbol{\Delta T}$ is the temperature difference between the heated surface and the liquid temperatures, L is the characteristic length of the rod, and $\boldsymbol{v}$ is the kinematic viscosity of the vapor film. All the vapor properties are evaluated at the film temperature which is the average temperature between the heated surface and liquid temperatures.

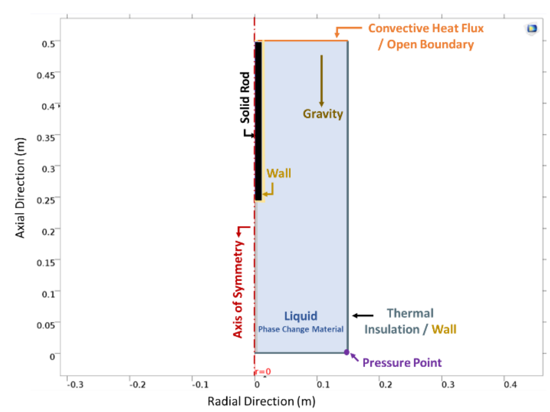

Figure 2. Model geometry and boundary conditions

The calculated Ra at an initial temperature of 550ºC and saturated liquid equals to $2.7\text{x}10^{11}$. The critical Ra from transition to turbulent in a vertical natural flow is approximately equal to 10^9 [6]. Thus, the model is selected to be turbulent ($\boldsymbol{k-\omega}$). The continuity, momentum and energy governing equations have been solved by COMSOL.

2.3 Thermal Properties of the Test Samples

The test samples are made of stainless steel (SS) and zirconium (Zr) cylindrical shape. These metals were commonly used in the cladding of the fuel rod used in the nuclear reactors. Table 1 presents the thermal properties of the test samples used in the model [7].

Table 1: Thermal Properties of the Test Samples

Material	Density (m^3/s)	Thermal Conductivity (W/m.K)	Heat Capacity (J/kg.K)
SS-316	8238	13.4	468
Zr-702	6570	22.7	278
In-600	8470	22.7	443.8

2.4 Mesh Study

The mesh study was performed for 4600, 8083, 16039, 42243, and 78669 elements. The last two provides the closest results to the experimental data. In order to save memory and computational time, the grid 42243 are considered in this study.

The wall-lifts-off was checked as seen in Figure 3 due to its effect on the accuracy of the results in turbulent model. The recommended wall-lifts-off on most of the walls is 11.06 [8]. The wall-lifts-off was found to be 11.06 on all the walls as shown in Figure 3. Wall-lifts-off is defined as a non-dimensional distance measured from the wall to the wall adjacent grid point. It is recommended to be equal to 11.06 according to COMSOL 4.2 manuals.

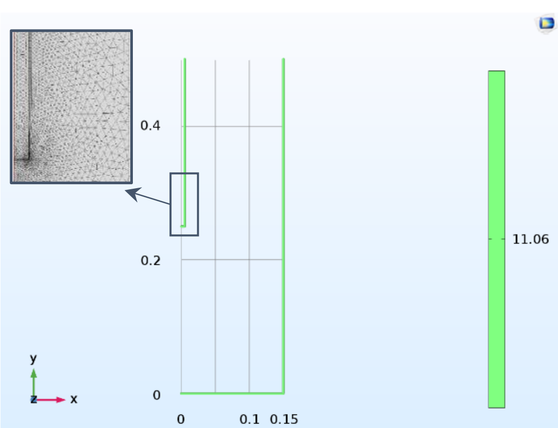

Figure 3. Wall-lift-off

Results and Discussion

In this section, the results of the visualization study, the effect of subcooling and the substrate material, and the validation of the model are presented.

3.1 Visualization Results

Figure 4 shows the simulated vapor film thickness for different time periods for SS sample plunged in a water bath at 98°C with rod initial temperature of 550°C for the lower three inches of the rod. When the heated rod is plunged in two degrees of liquid subcooling bath, small bubbles are being generated at the wall then being merged to form a continues and a stable vapor film. The vapor film completely covers the solid surface and prevents it from being in a direct contact with the heated surface. This regime is called film boiling regime. The vapor-liquid interface is found to be wavy as seen in Figure 4a. The thickness of the vapor film decreases as the temperature of the rod decreases. Figure 4d shows the thin vapor film at the bottom of the rod. This indicates that the cooling rate decrease. When the vapor film collapses, the liquid touches the rod's surface at T_{min}.

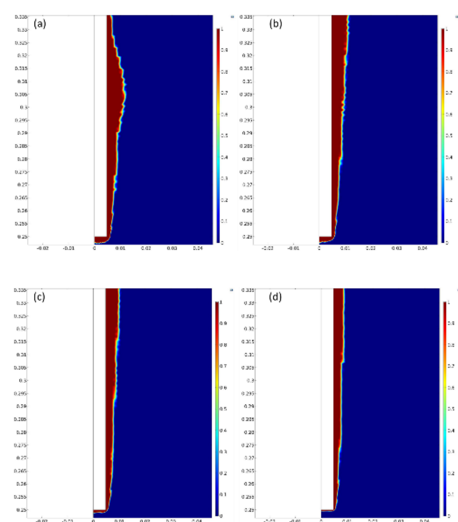

Figure 4. Simulated vapor film plunged in a liquid bath with two degrees of subcooling at various time; (a) 5 sec, (b) 15 sec, (c) 25 sec, and (d) 35 sec

Figure 5 shows the simulated vapor film thickness plunged in ten degrees of liquid subcooling bath with the same initial temperature and substrate material. The vapor film is thinner in this case. This is due to the smaller difference between the bulk temperature of the liquid and the surface temperature of the heated surface. The vapor film in the case of higher subcooling collapses faster since the liquid rapidly cools the heated surface.

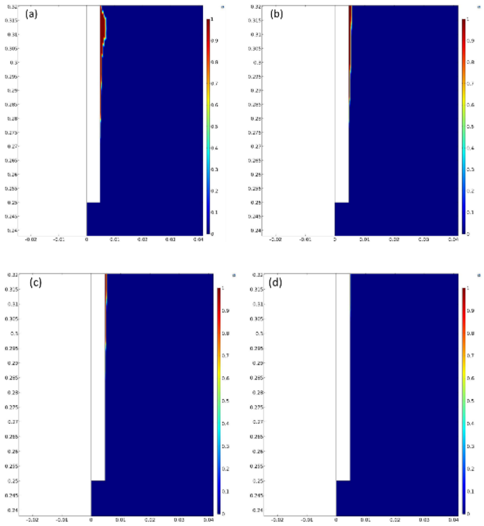

Figure 5. Simulated vapor film plunged in aliquid bath with ten degrees of subcooling at various time; (a) 5 sec, (b) 15 sec, (c) 25 sec, and (d) 35 sec

A high-speed camera was used during the experiments to record videos at 750 frames/sec displaying the boiling behavior. Figure 6 represents the experimental vapor film for SS rod quenched in various temperature baths with an initial rod temperature of 550ºC. The simulated vapor film displays a similar behavior as experimental vapor film. As the liquid subcooling increases, the vapor film thickness decreases as shown in Figures 6a and 6b. Moreover, the vapor film collapses faster, thus the rod dramatically cools in the case with higher subcooling. In the case of higher subcooling, the bubbles forming at the heated surface condense at the vapor-liquid interface before forming thicker vapor film.

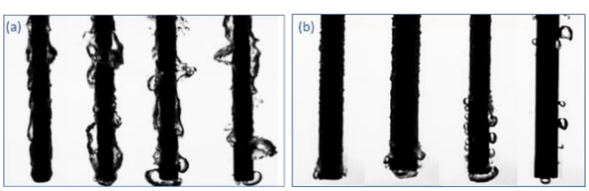

Figure 6. Experimental vapor film for SS sample at various time in liquid subcooling bath; (a) two degrees and (b) ten degrees

Figure 7 shows the three-dimensional plot for the submerged rod in the water bath at two degrees of liquid subcooling for various time interval. The SS rod was heated to 550ºC as an initial temperature. The simulated results present the cooling process of the rod. The rod starts to cool at top section (top quench) where the liquid is open to the atmosphere. The effect of axial conduction is clearly recognized. The liquid contact with the surface is established initially at the top and bottom of the rod as seen in Figure 7d when the temperature of the rod is in a thermal equilibrium with the water bath.

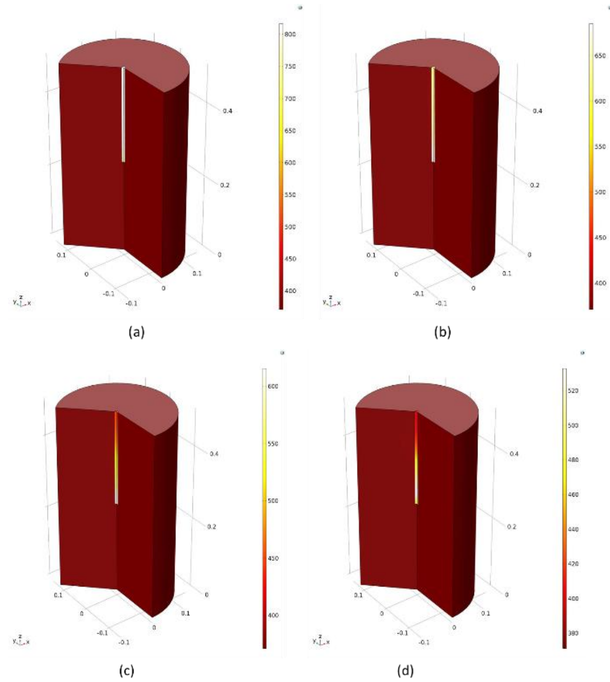

Figure 7. Three-dimension temperature variations for SS Rod; (a) 5 sec, (b) 15 sec, (c) 25 sec, and (d) 35 sec

3.2 Boiling Curves

The pool boiling curve for saturated water is shown in Figure 8. The y-axis represents the surface heat flux in the logarithmic scale. The x-axis represents the excess temperature which is the difference between the wall temperature of the solid surface and the saturation temperature of water in logarithmic scale. From the pool boiling curve, region I represents the natural convection regime that occurs when the excess temperature is less than 5ºC, no bubbles form. Region II represents the beginning of nucleate boiling when the excess temperature is between 5 to 10ºC, isolated bubbles form. Between points A and B, the bubble grows to a specific diameter and detaches from the solid surface without any interaction between the bubbles. Region III represents the fully nucleate boiling, slugs and vapor columns grow at the surface. The maximum or critical heat flux (CHF) at the surface occurs at point C, bigger bubbles grow at the surface. Following that, transition boiling regime occurs (region IV), some of the bigger bubbles merge at the surface when its temperature lies between 30 and 320ºC [7]. Point D is named T_{min}; it is the temperature that corresponds to the minimum surface heat flux. At temperature above T_{min}, the heated surface and the bulk liquid are completely separated by a stable vapor blanket. This region V is denoted by the film boiling regime.

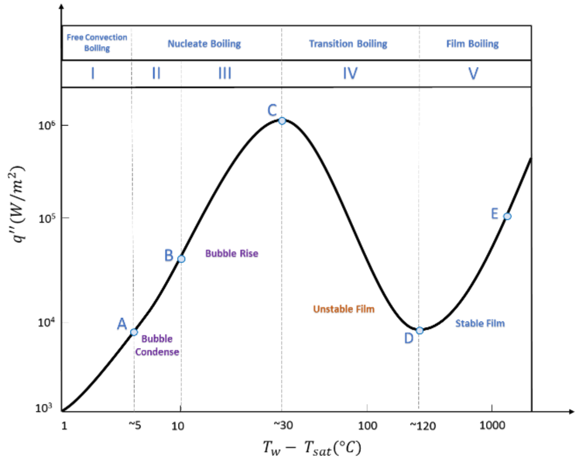

Figure 8. Water boiling curve

3.2.1 Effect of Liquid Subcooling

The effect of liquid subcooling is presented in this section by comparing the results of the SS rod plunged in two different degrees of liquid subcooling. Figure 9 confirms the visualization results. As the liquid subcooling increases, T_{min} increases. This is due to the difference between the surface temperature and the liquid bulk temperature of the water bath. T_{min} values for the SS rod plunged in two and ten degrees of liquid subcooling are approximately equal to 367 and 420ºC, respectively.

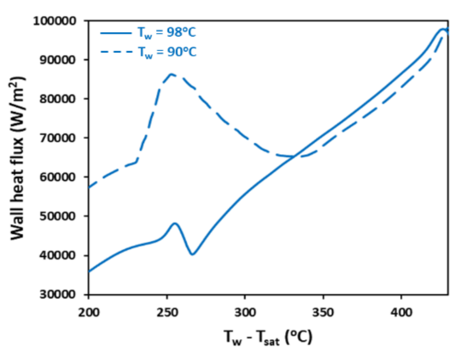

Figure 9. Simulated boiling curves for SS rod at various degrees of liquid subcooling

3.2.2 Effect of Substrate Material

The effect of substrate material is discussed in this section by comparing SS and Zr rods that are plunged in two degrees of liquid subcooling bath. Figure 10 shows the simulated boiling curve for the two substrate materials. It is noticed that the surface material has a significant impact on T_{min} as well as the liquid subcooling. As the thermal properties $(\rho k c_p)_w$ of the substrate material increases, T_{min} decreases.

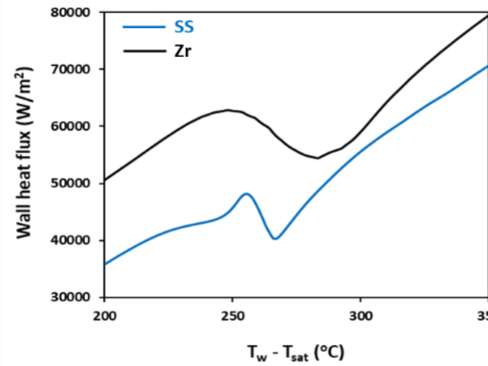

Figure 10. Simulated boiling curves for SS and Zr rods at two degrees of liquid subcooling

3.3 Model Validation

The results from the simulated model are validated with the experimental results by comparing T_{min} values from the experimental and simulated boiling curves. The test facility and the SS test sample are shown in Figure 1. The test sample has three embedded thermocouple inside the test sample that are connected to the data acquisition system to measure the temperature. An inverse heat conduction code (DATARH) was used to calculate the surface temperature and the corresponding heat flux at the surface. T_{min} is determined from the experimental boiling curves shown in Figures 11 and 12. The comparison between the experimental and simulated T_{min} is listed in Table 2. The maximum and minimum errors are 18.3 and 1.0% for the SS rod plunged in ten degrees of liquid subcooling and Zr rod plunged in two degrees of liquid subcooling, respectively.

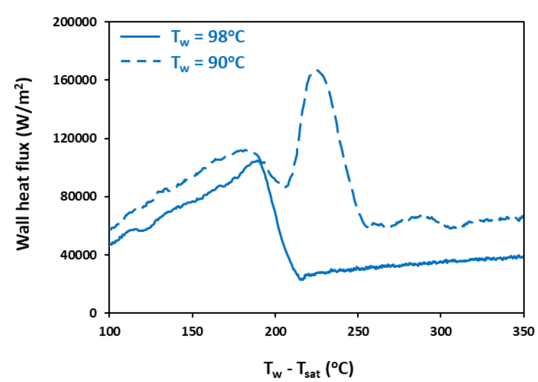

Figure 11. Experimental boiling curves for SS rod at various degrees of liquid subcooling

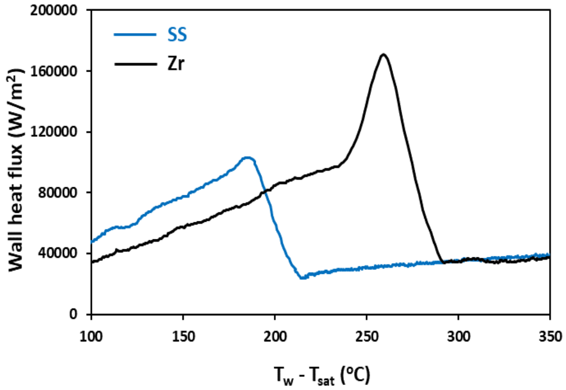

Figure 12. Experimental comparison between the boiling curves for SS and Zr rods at two degrees of liquid subcooling

Table 2: Experimental and Simulated T_{min} Values

Substrate	Experimental (°C)	Simulated (°C)	Error %
Stainless Steel $\Delta T_{sub} = 10°C$	355	420	18.3
Stainless Steel $\Delta T_{sub} = 2°C$	320	367	14.6
Zirconium $\Delta T_{sub} = 2°C$	389	393	1.0

4. Conclusions

This study explores on the quenching behavior of stainless steel and zirconium rods in a water bath at different temperatures. Since the Ra > 10^9 in the vapor film flow, turbulent flow ($k - \omega$) combined with heat transfer in fluid and phase change models were selected to simulate the model. Continuity, momentum and energy governing equations have been solved by COMSOL Multiphysics software. Mesh independency examination was conducted to confirm that it does not affect the results accuracy. The model was validated with the inverse heat conduction code results from the experimental data with a maximum error of 18.3% indicating a good agreement with the experimental data. This shows the capability of COMSOL software in modeling complex two-phase flow problems.

The simulated and experimental results conclude that as liquid subcooling increases, T_{min} increases. Additionally, as the thermal properties of the substrate increases, T_{min} decrease. Therefore, it is important for engineers to select the cladding material carefully in quenching applications. Visualization results show the vapor film thickness for various degrees of liquid subcooling. The vapor film is continuous and stable in film boiling regime. Moreover, the vapor film is thicker and it takes longer time to collapse in a bath with lower subcooling due to the temperature difference between the hot surface and the bulk temperature of the water.

5. Future Work

T_{min} is one of the most important parameters in the safety of the nuclear reactors, especially in the case of loss of coolant accident. Therefore, more simulation need to be done to evaluate T_{min} for various degrees of liquid subcooling, initial rod temperatures, porous surface rods, and substrate materials. Numerical correlations need to be developed for T_{min} and compared with the experimental data and literature.

6. References

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