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Research Paper

# Parametric investigation of film boiling heat transfer on the quenching of vertical rods in water pool

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## HIGHLIGHTS

- The effects of liquid subcooling, thermophysical properties, and surface conditions on $T_{min}$ were experimentally investigated.
- Surface characterization analyses were performed to obtain essential information needed to identify the effects of surface condition on $T_{min}$.
- The quenching behavior for various surfaces was captured sing a high-speed camera.
- Substrate materials with lower thermophysical properties and higher porosity were observed to quench faster.
- A new generalized correlation to predict $T_{min}$ was developed based on the experimental data.

## ARTICLE INFO

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Surface characterization
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## ABSTRACT

The present study explores the effects of liquid subcooling, material properties and surface conditions on the film pool boiling heat transfer using stainless steel (SS), zirconium (Zr), and Inconel-600 rods. Vertical quenching experiments were performed in subcooled and saturated distilled water pool at atmospheric pressure. Surface characterization results (microscope images, surface roughness, and water contact angle) were obtained to characterize the morphology of the substrate surface of the test samples. A visualization study was carried out using a high-speed camera to observe the phenomenon of quench front axial propagation in addition to the instability of the vapor-liquid interface. Embedded thermocouples are used to measure the change in temperature of the test samples with time. An inverse heat conduction code was used to determine the surface temperature and the corresponding heat flux curves. The effects of liquid subcooling, thermal properties of the substrate, and surface conditions on the minimum film boiling temperature ($T_{min}$) were investigated. The lower $k\rho c_p$ and the porous surface of the Zr test sample disturb the flow of the vapor during film boiling. This along with the lower contact angle of the Zr surface resulted in a higher $T_{min}$ value compared to the other two test samples. A generalized correlation was developed and compared to various existing correlations. The effects of liquid subcooling, surface roughness, and thermal properties of the substrate materials were taken into account in developing the correlation. The average error estimated for the generalized correlation is 1.5% and the root-mean-square error is 9.3%.

## 1. Introduction

Film boiling is invariably encountered in many applications such as refrigeration, nuclear reactor safety analysis, quenching of metals, and regenerative cooling of rockets [1]. It is the mode of heat transfer that occurs when a sufficiently hot surface is submerged in subcooled or saturated liquid. Once film boiling is established, a stable vapor film completely surrounds the heated surface and prevents it from being in direct contact with the coolant [2]. The formation of the vapor blanket around the heated surface leads to a significant reduction in the cooling performance due to its low thermal conductivity [3,4]. For example, in a postulated large break loss of coolant accident (LOCA) of a nuclear reactor, the temperature of the fuel rods might exceed 1200 °C. This could be higher than the melting temperature of the cladding material. Therefore, it is significant to study the parameters that affects the wetting temperature to mitigate failure of a nuclear reactor. The minimum film boiling temperature ($T_{min}$) is defined as the minimum temperature that maintains a stable vapor film around the heated surface. $T_{min}$ has been widely investigated in terms of material property, surface conditions and oxidation, liquid subcooling, liquid properties,

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**Nomenclature**

| | |
|---|---|
| fps | frame per second |
| $c_p$ | specific heat [J (kg K)$^{-1}$] |
| $h_{fg}$ | latent heat of vaporization [kJ kg$^{-1}$] |
| $k$ | thermal conductivity [W (m K)$^{-2}$] |
| LOCA | loss-of-coolant accident |
| $q_{CHF}$ | critical heat flux [W m$^{-2}$] |
| r | radius of the test sample [m] |
| $R_a$ | average surface roughness [m] |
| $R_{ref}$ | reference surface roughness [m] |
| SS | stainless steel |
| t | time [s] |
| T | temperature [K] |
| $\rho$ | density [kg m$^{-3}$] |
| $\mu$ | dynamic viscosity [N s m$^{-2}$] |

*Subscripts*

| | |
|---|---|
| sub | subcooled |
| sat | saturated |
| $w$ | wall/surface of the heated substrate |
| $f$ | fluid |

system pressure, flow condition, and initial surface temperature [5,6].

The surface characteristics of the heated surface such as the surface roughness, surface oxidation and surface wettability are among those parameters having important influence on $T_{min}$ [7]. A recent study investigates the cooling behavior for heated surfaces possessing different water wettability degrees. Different diameter stainless steel spheres were quenched in saturated and subcooled water. It was concluded that the vapor film around the sphere destabilizes for smaller contact angles, $\theta < 30$ °C, than larger contact angles such as $\theta > 100$ °C [8]. Lee et al. [9] has recently investigated the effect of surface coating and oxidation on the quenching curve behavior for five test materials. The quenching curve was shifted to the right using the oxidized and coated surfaces, indicating faster collapse of the vapor film. A flaky feather-like structure was formed on the oxidized copper sample for two hours. This structure was able to disturb the vapor film and cause a quicker quenching than the as-received sample. Moreover, $T_{min}$ was found to increase as the surface roughness increases. Kang et al. [10] investigated the effect of surface roughness and contact angle on $T_{min}$ using completely wetting, rough, and smooth zircaloy rods. The capillary-wicking into the nano-scale needle shaped structure caused the surface to be completely wettable. Thus, it provides a higher $T_{min}$ compared to the smooth and rough surfaces. Moreover, the visualization study showed an unstable liquid-vapor interface due to a dramatic cooling during intermediate liquid–solid contact regions.

Hsu et al. compared $T_{min}$ values for vertically quenched stainless steel and zircaloy spheres in de-ionized and natural sea water [11]. The quenching curves as well as the results of visualization showed that the stable vapor film was sustained in the de-ionized pool. In addition, the vapor film collapses at a higher $T_{min}$ when the sphere was quenched in a sea water pool. For both pools, it was concluded that the material property of the spheres has a significant impact on $T_{min}$. Similar research was conducted by Lee et al. [9] showing that for the same sample size and liquid subcooling condition, the quenched stainless steel and zirconium exhibited the longest and shortest quenching time, respectively. That is due to the lower heat capacity of the zircaloy compared to the stainless steel. Peterson and Bajorek experimentally studied the effect of material properties on $T_{min}$ by quenching stainless steel, carbon steel, and zircaloy at elevated pressures [12]. They concluded that $T_{min}$ increases as liquid subcooling increases, for the same pressure and test sample. The effects of surface oxidation and material properties were also carried out in their research. It was found that the oxide surface and lower thermal properties of the substrate material increase $T_{min}$ values.

Research on film boiling and $T_{min}$ are abundant in literature, while $T_{min}$ empirical correlations are limited. Berenson [13] and Henry [14] correlations are most widely used in predicting $T_{min}$ values. Berenson developed a $T_{min}$ correlation based on Zuber's correlation for the minimum heat flux and including Taylor-Helmholtz hydrodynamic instability [15]. His correlation is used to predict $T_{min}$ only for an ideal isothermal surface. An extended study was conducted by Henry to improve Berenson's correlation by including the effects of liquid subcooling and the surface thermal properties of the test sample. Both correlations were developed using experimental data from horizontal heated surfaces. Experiments by Henry [14], Adler [16], Mori [17], Dhir [18], Lauer [19], and Ohnishi [20] showed the linear relation of $T_{min}$ with liquid subcooling. Since the liquid subcooling is not the only significant factor that affects $T_{min}$, a more general correlation needs to be developed to accurately predict $T_{min}$.

The objective of the present work is to further investigate the effects of liquid subcooling, surface conditions and thermal properties of the substrate material on $T_{min}$. A test facility was designed and built to conduct quenching experiments for three cylindrical samples made of 316-stainless steel (SS), zirconium-702 (Zr), and Inconel-600. Surface characterization including microscopic images of the surface, water contact angle, and surface roughness was performed and their effects on film boiling were studied. Boiling curves were determined using an inverse heat conduction code [21,22] from the temperature transients recorded by thermocouples embedded in the test samples. Visualization of the film boiling process was performed using a high-speed camera to understand the mechanism of film breakup for each test sample. A generalized correlation was developed accounting for the effects of liquid subcooling, surface roughness, and thermal properties of the substrate materials observed in this study.

## 2. Experimental method

### 2.1. Experimental facility

Fig. 1 shows the experimental set-up for the quenching experiments. It consists of a cylindrical test sample, quenching bath, radiant heater, Olympus i-Speed 3, and a data acquisition system NI 9213. Three types of metallic cylinders made of 316-stainless steel (SS), zirconium-702 (Zr), and Inconel-600 were used in this study. A cylindrical ceramic heater is capable of operating at a maximum temperature of 1100 °C. It is used to preheat the test sample to the desired temperature before plunging it in the liquid bath. Ceramic fiber spun blanket is used to minimize the heat loss to the surrounding environment while allowing rapid heat-up of the test sample. A transparent chromatography jar is filled with distilled water to facilitate visualization and record the boiling phenomenon that occurs on the surface of the test sample during quenching. A side-mounted immersion heater is used to bring the water bath to the prescribed temperature before performing the experiment. During the experiment, the pool temperature is adjusted using the immersion heaters thermostat controller and is monitored using an immersion thermocouple probe. An acrylic sheet is used to cover the water tank during heating to block the steam from reaching the test sample.

### 2.2. Experimental conditions and procedure

The test sample was preheated by a radiant heater with an 870 W power supply to an initial temperature of 550 °C. This temperature was