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Advancements in Transient Pool Boiling Heat Transfer During Rapid Cooling of an Alternate Accident-Tolerant Fuel Cladding Material

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Abstract - Quenching is critical for ensuring thermal safety in high-temperature systems, particularly in nuclear reactors. This study investigates the transient pool boiling heat transfer of FeCrAl alloy rods during rapid cooling in both distilled water and Gum Arabic (GA)-enhanced aqueous solutions at subcooling temperatures of 80°C, 85°C, 90°C, and 98°C. The experimental setup captures the evolution of boiling regimes and critical heat flux (CHF) under different coolant conditions. Results indicate that adding GA surfactant improves boiling heat transfer characteristics, most notably at intermediate subcooling (85°C), where the CHF increased by 13.6% compared to pure water. The minimum film boiling temperature (T_{min}) also rose to 34.2% with GA at 98°C, indicating delayed rewetting and enhanced surface stability. GA's presence promotes more effective bubble dynamics through surface tension reduction and improved wettability. This study offers quantitative validation of surfactant-based coolant strategies, contributing to the optimization of thermal management in accident-tolerant fuel systems and other high-performance cooling applications.

Keywords**:** Quenching, FeCrAl rods, surfactants, subcooling, transient pool boiling, nuclear safety.

1. Introduction

Quenching is a rapid cooling process of a hot object in a cool liquid. It involves several distinct heat transfer stages: film boiling, transition boiling, nucleate boiling, and single-phase free convection. At the Minimum Film Boiling (MFB) point, characterized by the Minimum Film Boiling Temperature (T_{min}) and Minimum Heat Flux (MHF), heat transfer shifts from film boiling to transition and nucleate boiling [1]. This phenomenon is crucial in various industrial applications, including nuclear reactor cooling, where it helps rapidly cool the reactor core during emergencies such as a loss of coolant accident (LOCA) [2], electronics cooling to prevent overheating [3], and the oil and gas industry to cool equipment exposed to high temperatures, particularly after welding or during drilling operations [4]. The quenching process is induced by several factors, such as the quenchant, fluid flow rate, temperature, and pressure of the quenchant, the design of the quench tank, and the characteristics of the parts being quenched [5].

Studies on pool boiling heat transfer during quenching have demonstrated the influence of operating conditions and material properties on cooling performance and boiling regimes. For example, experiments involving a plexiglass tank filled with water heated to subcooled temperatures showed that lower water temperatures significantly reduce cooling time. Similarly, heating test rods above T_{min} using a ceramic furnace revealed that increasing surface roughness enhances heat transfer. Additionally, higher subcooling temperatures improved the film boiling regime by facilitating more efficient heat transfer [6]. Further, the effects of liquid subcooling, material properties, and surface conditions on film pool boiling heat transfer were explored using stainless steel (SS), zirconium (Zr), and Inconel-600 rods. The results showed that Zr, with its lower thermal conductivity ($k\rho c_p$) and porous surface, exhibited a higher T_{min} than SS and Inconel-600. A generalized correlation was developed to predict T_{min}, considering liquid subcooling, surface roughness, and thermal properties, with a 1.5% average error and a 9.3% root-mean-square error [7]. Additionally, oxidation was found to have little effect on the T_{min} of SS, but it improved heat transfer for Zr. Higher liquid subcooling led to thinner vapor films, significantly enhancing cooling efficiency across all tested materials [8].

The role of surfactants in enhancing heat transfer has been studied, with findings demonstrating their significant impact on boiling heat transfer performance. Adding the cationic surfactant Habon G resulted in smaller, more numerous bubbles, which reduced the boiling excess temperature and improved heat transfer. Infrared thermography confirmed that surfactant solutions exhibited better heat transfer than pure water, with increased temperature fluctuations on the heated surface [9]. This finding aligns with studies on various surfactants (CTAC, SDBS, and APG), ethanol, and silicone oil, which showed that surfactant solutions enhanced heat transfer through bubble dynamics such as bubble jet and explosion phenomena [10].

Further research on stainless steel samples revealed that surfactants stabilize the vapor layer in the film boiling regime, prolonging cooling time while enhancing nucleate boiling. Compared to deionized water, surfactant solutions exhibited higher heat transfer rates, with cooling times increasing by 43% and heat transfer coefficients and heat fluxes rising by 25-31% [11]. The impact of SDS surfactant and liquid subcooling on the MFB point showed that surfactants reduce T_{min} and MHF, prolonging the film boiling duration. In contrast, higher subcooling accelerates the transition to nucleate boiling [1]. Experiments with alkylbenzene sulfonate surfactant further demonstrated that increasing liquid subcooling raises the transition temperature (T_{tr}) for nickel, stainless steel, and zirconium materials. Surfactant solutions resulted in lower T_{tr} than pure water, likely due to reduced surface tension. Moreover, surface conditions such as oxidation and contamination were found to influence the quenching process significantly, underscoring the importance of surface characteristics in determining heat transfer performance [12].

While extensive research has been conducted on the effects of quenching on various materials, such as stainless steel, zirconium, and nickel, there is a notable gap in the literature regarding the impact of quenching on FeCrAl alloys. To address this gap, this study investigates the quenching behavior of FeCrAl using distilled water and distilled water with GA surfactant at different subcooling temperatures of 80°C, 85°C, 90°C, and 98°C. This research aims to provide insights into the boiling heat transfer performance and its dependence on surfactant addition and subcooling levels for this specific alloy.

2. Experimental Method

2.1. Preparation Method

Two types of quenchant were used: distilled water and the mixture of Gum Arabic (GA) surfactant and distilled water at a concentration of 1000 mg/L. The required amount of surfactant was dissolved in water using an ultrasonic probe sonicator (Ultrasonic Horn, Misonix Company, USA), with the dissolution process taking 15 minutes to ensure complete dissolution.

2.2. Experimental Method

Figure 1 shows the components of the quenching experiment that consist of: stainless-steel cylindrical rod (SS), tube furnace, two immersion heaters, quartz glass tank, K-Type thermocouple, an immersion thermocouple, computer, data acquisition system (DAQ).

The vertical tube furnace (EVA12/300B, Carbolite Gero) is used to heat the cylindrical tube rod before quenching it in the coolant fluid, and its heating capacity can reach a maximum of 1200 ℃. The cylindrical tube rod that made of SS with a diameter of 10 mm and a length of 5 cm is heated in a tube furnace to an initial temperature of 600 ℃. When heated, the SS rod is connected to a 1m long stainless-steel tube to hold the sample. An embedded K-type thermocouple is used to measure the temperature of the rod. This thermocouple is installed in the steel rod through a 1mm hole at the center of the rod.

Furthermore, a quartz glass tank to hold the coolant fluid is used for visualization. The tank has a glass sheet top to prevent the test sample from exposure to the steam produced from the liquid pool during the heating process as well as to avoid additional oxidation on the surface. A surface heater heats the coolant fluid to specify the coolant temperature, and the temperature of the coolant fluid before and during the quenching process is measured by the immersion K-type thermocouple. In addition, the data acquisition system (DAQ) monitors the transient temperature before and during the quenching process. A computer is used to record the temperature-time histories of the thermocouples connected to DAQ and to the computer by using LabVIEW software during the experiment [13].

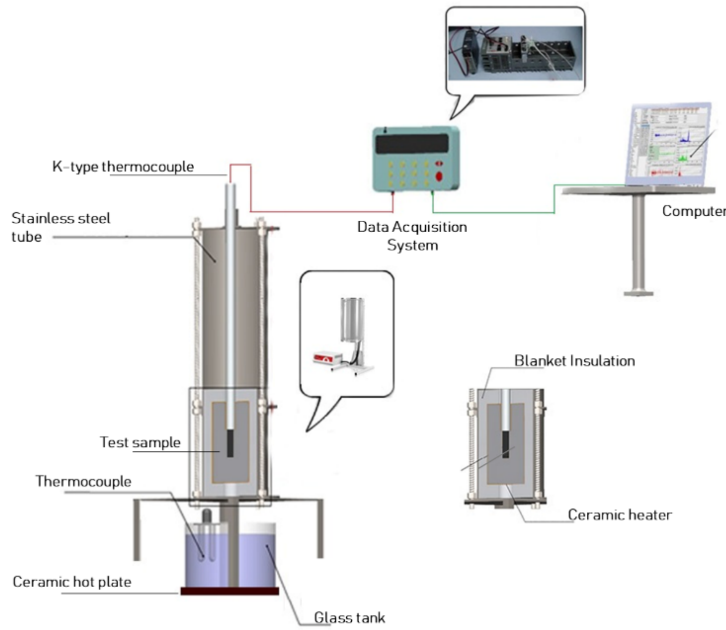


Fig. 1: Schematic Diagram of the Quenching Setup at Kuwait University.

2.3. Experimental Procedure

Roughly 1 L of liquid is prepared as the coolant for this experiment. The base fluid (distilled water) and water with GA are prepared at 1000 mg/L. By quenching in pools of various temperatures and at atmospheric pressure, transitory pool boiling during quenching is studied. The vertical tube furnace is initially used to heat the rod to 600 °C. To guarantee the occurrence of the film boiling heat transfer regime, this starting temperature is kept above the expected T_{min} for FeCrAl. In the current investigation, a surface heater is used to heat the liquid coolants in a glass tank until they reach close to saturation temperature, and each iteration will have a different temperature, such as 80, 85, 90, and 98 °C.

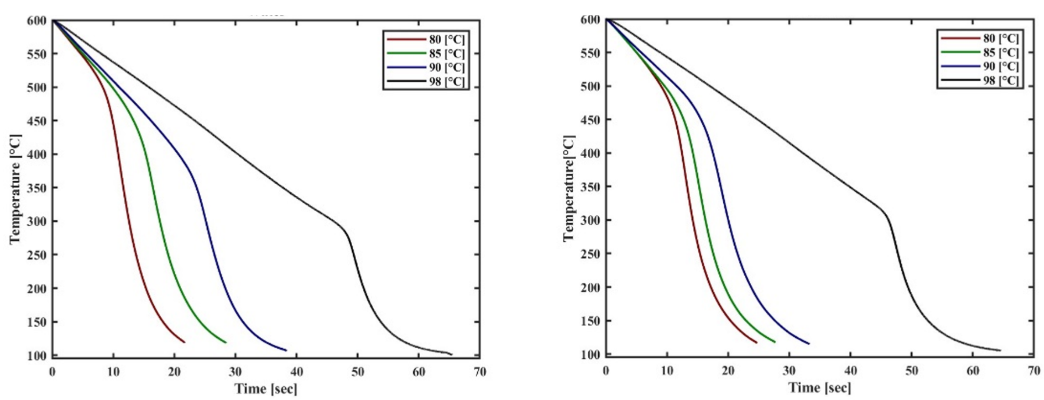
Furthermore, the thermocouples on the stainless-steel rod and the coolant fluid are connected to measure the change in temperature to both the rod and the liquid used in this experiment, respectively. The heaters were switched off once the initial temperatures for the solid rod and the coolant liquid had been reached. The shaft collars are loosened as soon as the specimen and the liquid pool achieve the required temperatures, enabling the sample to be quenched entirely into the liquid coolant. The duration will be measured from the time of initial submersion until thermal equilibrium is reached. This duration will be measured and compared for each of the nine mentioned coolants used in this experiment, at the four cases of initial fluid temperature for each coolant. As such, the effect of different coolants on the process of thermal heat transfer will be measured to identify the impact of the nanoparticles on cooling rates. The effect of the initial temperature of the coolant will also be measured.

The data acquisition system (DAQ) is used to record quantitative measurements throughout the quenching process. At a sampling rate of 40 Hz, the thermocouples' temperature–time history is captured. For all studies, the water level in the pool is measured and kept constant. Four consecutive experiments are run for each sample. To investigate the heat transfer properties of the different nanofluids, it is used as a coolant and compared with distilled water as the reference case. Finally, the rod's temperature drop is measured and plotted graphically with respect to time. These graphs will be shown to compare T_{min} for all cases.

3. Results and Discussion

Figure 2 illustrates the temperature decay profiles during the quenching of FeCrAl rods in both distilled water and Gum Arabic (GA)-water solutions at varying subcooling temperatures (80, 85, 90, and 98°C). The cooling process in both fluids is monitored over time, with the x-axis representing time and the y-axis representing temperature. In Figure 2a, which shows quenching in distilled water, the temperature decay is consistent with the typical behavior observed in quenching processes. As expected, the temperature of the FeCrAl rod drops rapidly at the beginning of the quenching process, especially at lower subcooling temperatures (80°C and 85°C), which shows the most significant temperature change during the initial few seconds. However, as the quenching continues, the cooling rate slows, especially after the liquid reaches boiling. The curve flattens at higher times, with the cooling rate decreasing significantly when the temperature approaches the ambient fluid temperature.

In contrast, Figure 2b, which shows quenching in GA-water solutions, presents a more efficient cooling profile. The temperature of the FeCrAl rod drops more rapidly compared to the distilled water, particularly at the initial stages of quenching. GA surfactant enhances the heat transfer process by reducing the surface tension of the water, forming smaller and more numerous bubbles that facilitate better heat dissipation [14]. This increased bubble dynamics in the GA solution leads to a more effective cooling rate, especially in the early stages of quenching, as shown by the steeper slopes in the cooling curves for all subcooling temperatures. Quenching efficiency is noticeably improved with the GA solution compared to water, particularly at higher subcooling temperatures (90°C and 98°C).



(a) (b)

Fig. 2: Temperature-time history for rods quenched in: (a) water and (b) GA-water.

To summarize the findings, Figure 3 illustrates the relationship between subcooling temperature and T_{min} for both coolants: distilled water and GA-water solutions. The x-axis represents the subcooling temperature, while the y-axis shows each condition's corresponding T_{min} values (in °C). It is evident that as the subcooling temperature increases, T_{min} also increases for both fluids. However, the GA-water solution consistently results in higher T_{min} values than pure water, indicating that the surfactant significantly enhances the cooling process.

This behavior highlights the potential of surfactant solutions, like GA-water, in enhancing the cooling efficiency during quenching, offering better control over thermal management and safety in high-temperature systems such as nuclear reactors and other industrial applications. The results provide valuable insight into optimizing cooling systems and improving heat dissipation performance in scenarios requiring rapid temperature changes.

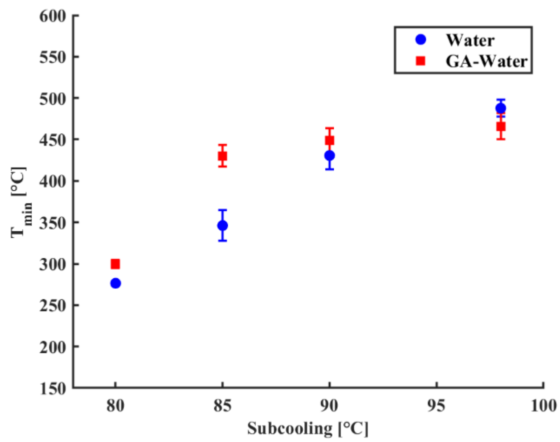
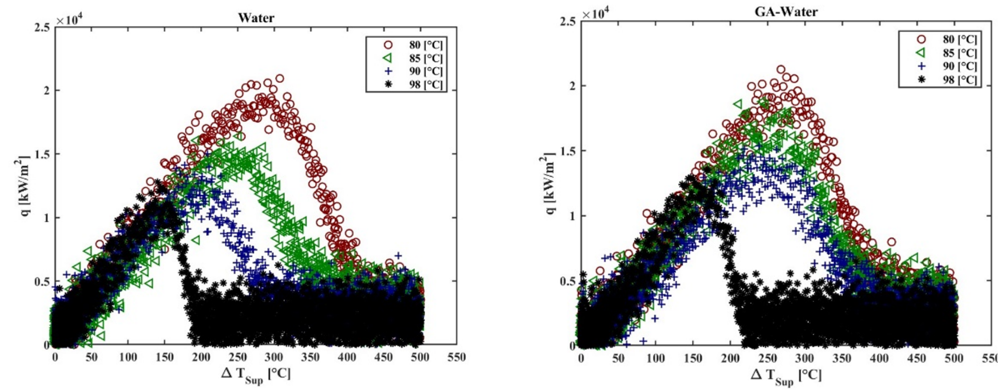


Fig. 3: Minimum film boiling temperature (T_{min}) for various subcoolings for rods quenched in water and GA-water.

Figure 4 presents the boiling curves obtained during the quenching of stainless steel rods in water at four different bulk temperatures: 80°C, 85°C, 90°C, and 98°C. The heat flux (q”) is plotted against the wall superheat (ΔT_{sup}), defined as the temperature difference between the rod surface and the saturation temperature of water. As observed in Figure 4a, all curves follow classical boiling behavior, beginning with film boiling, transitioning through transition boiling, and culminating in nucleate boiling, after which the cooling process enters the single-phase convection regime. At lower water temperatures, such as 80°C and 85°C, the maximum heat flux values are significantly higher, reaching 2.2×10^4 kW/m² and 1.85×10^4 kW/m², respectively. This enhancement is attributed to the greater subcooling at these conditions, intensifying bubble collapse and microlayer evaporation and promoting more effective surface rewetting.

As the water temperature increases to 90°C, the peak heat flux reduces to approximately 1.45×10^4 kW/m², and further drops to just below 1.0×10^4 kW/m² at 98°C, where the fluid is nearly saturated. This decrease is due to the weaker thermal driving force and lower subcooling, which limits heat removal during nucleate boiling. Furthermore, at higher coolant temperatures, the film boiling regime is extended, indicating that a stable vapor film persists for longer, delaying the transition to efficient boiling. This effect is especially visible at 98°C, where the rewetting of the surface is delayed and peak heat transfer performance is limited.

Figure 4b illustrates the boiling curves for a GA-water nanofluid during quenching at bulk fluid temperatures of 80°C, 85°C, 90°C, and 98°C. Compared Figure 4a, notable changes in boiling behavior are observed due to the presence of gum arabic in the fluid medium. At all coolant temperatures, the general trend of the boiling curve remains similar transitioning from film boiling to nucleate boiling and finally to single-phase convection.



(a) (b)

Fig. 4: Boiling curves for rods quenched in: (a) water and (b) GA-water.

To analyse the results in depth, the comparison of critical heat flux (CHF) values for water and GA-water mixtures at varying subcooling levels reveals distinct trends influenced by the fluid composition and thermal conditions, as shown in Figure 5. At 80°C, the GA-water mixture exhibits a slight CHF enhancement of approximately 4.6%, increasing from 1.94×10^4 kW/m² (water) to 2.03×10^4 kW/m². A more notable improvement occurs at 85°C, where the CHF rises by about 13.6% from 1.47×10^4 kW/m² to 1.67×10^4 kW/m², suggesting that moderate subcooling enhances the effect of GA on bubble dynamics and surface rewetting. However, at 90°C, the CHF values for both fluids converge to ~1.28×10^4 kW/m², indicating a negligible influence of GA under this condition. At near-saturation temperature, a minor CHF increase of ~4.3% is observed in the GA-water mixture, likely due to marginal improvements in wettability. Overall, the data suggest that adding GA improves CHF primarily at intermediate subcooling levels, while its effect diminishes as the system approaches saturation or low subcooling extremes. In conclusion, GA modifies boiling performance through wettability enhancement, viscosity-induced bubble dynamics, and potential surface film formation. The result is a peaked CHF improvement at moderate subcooling ~85 °C, followed by diminishing gains as temperatures approach saturation or when fouling effects become dominant [15-17].

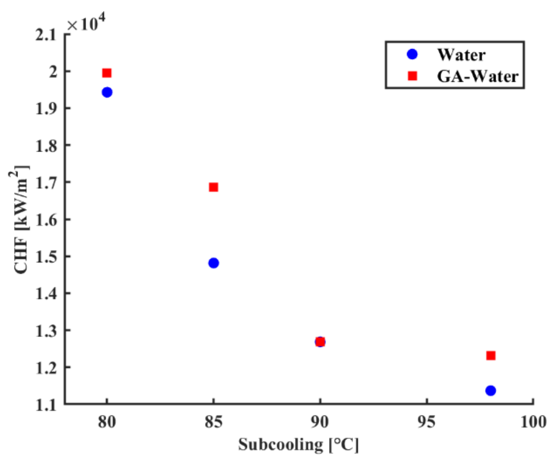


Figure 5: Critical heat flux for various subcoolings for rods quenched in water and GA-water.

4. Conclusions

This investigation demonstrates the significant impact of GA surfactant addition on the quenching behavior of FeCrAl rods across varying subcooling temperatures. Compared to distilled water, the GA-water solution exhibited a measurable enhancement in critical heat flux (up to 13.6%) and elevated T_{min} (up to 34.2%), indicating improved cooling efficiency and delayed rewetting. The surfactant's role in modifying surface tension and facilitating stable vapor film collapse contributed to these performance gains, particularly at moderate subcooling (85°C). However, its effect diminished near saturation due to reduced thermal driving forces. These findings underscore the promise of using bio-based surfactants such as GA to enhance the cooling performance in nuclear thermal hydraulics and industrial heat transfer processes. Future work should explore long-term stability, surface deposition effects, and the synergistic use of GA with nanoparticles for further performance optimization.

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