EFFECT OF FILLING MODES ON BOILING HEAT TRANSFER MECHANISMS IN LIQUID NITROGEN COOLING SYSTEM

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Abstract

Liquid nitrogen (LN_2) cooling is widely utilized in the cooling systems of superconducting devices and scientific instruments. During the cooling process, the boiling heat transfer mechanism plays a decisive role. When the solid surface temperature significantly exceeds the saturation temperature of the liquid nitrogen, the Leidenfrost effect occurs, forming a vapor film at the solid-liquid interface that drastically reduces heat transfer efficiency. Previous research has primarily focused on altering the boiling curve and enhancing the Critical Heat Flux (CHF) through surface roughness, micro-nano structures, or various material properties. Few studies have explored the impact of filling modes within the cooling system on disrupting the vapor film and improving boiling heat transfer. This study utilizes a self-developed liquid nitrogen cooling experimental platform to investigate four distinct filling and cooling modes designed for an Oxygen-Free High Conductivity (OFHC) copper test block. By examining the boiling curves under various filling modes, this thesis analyzes the underlying mechanisms influencing the wall superheat at the Leidenfrost point (ΔT_{LP}) and the Critical Heat Flux (ΔT_{CHF}). The results indicate that the bottom-filling method, characterized by impingement kinetic energy, effectively increases fluid disturbance and disrupts the vapor film encapsulation. This significantly reduces the duration of the Leidenfrost effect and facilitates an earlier transition into the high-efficiency nucleate boiling stage.

INTRODUCTION

Cryogenic cooling technologies are increasingly utilized in modern industry and advanced scientific research. However, when cryogenic liquids contact solid surfaces at room temperature, the extreme temperature gradient typically triggers vigorous boiling. In the initial cooling stage, the system inevitably enters the film boiling regime. During this phase, due to the Leidenfrost effect, the solid surface becomes entirely encapsulated by a continuous vapor film. The vapor layer, characterized by extremely low thermal conductivity, acts as a thermal insulator, leading to a significant reduction in the heat transfer coefficient and overall cooling efficiency. To enhance the efficiency and safety of cooling systems, effectively shortening the duration of film boiling and elevating both the Leidenfrost Point (LP) and Critical Heat Flux (CHF) have become primary challenges in the field of cryogenic heat transfer. The boiling curve is standardly used to characterize the relationship between surface heat flux (q) and wall superheat ($\Delta T = T_{wall} - T_{sat}$). This curve encompasses four primary regimes: single-phase natural convection, nucleate boiling, transition boiling, and film boiling. When liquid nitrogen contacts a high-temperature surface, it immediately enters the film boiling regime. As the surface temperature decreases to the Leidenfrost Point temperature (T_{LP}), the vapor film becomes unstable and collapses, allowing intermittent contact between the liquid and the solid surface; at this point, the system enters the transition boiling regime. Subsequently, as the temperature further drops to the Critical Heat Flux point (T_{CHF}), the system enters the nucleate boiling regime. In this stage, heat transfer efficiency peaks as bubbles rapidly form and detach from the surface, removing a substantial amount of thermal energy. In practical cooling applications, the system must successfully transition from film boiling to nucleate boiling to achieve stable and efficient thermal management. Figure 1 presents the typical boiling heat transfer curve.

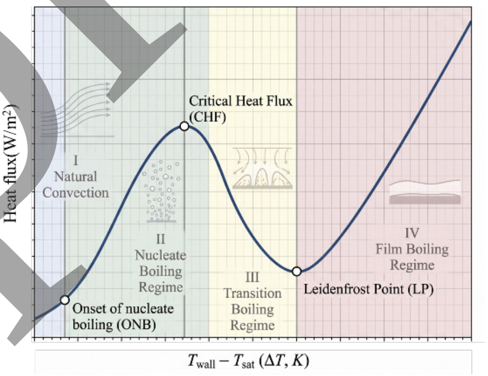

Figure 1: Typical boiling heat transfer curve.

Extensive prior research has focused on enhancing boiling heat transfer performance by modifying the physical or chemical properties of solid surfaces. Increasing surface roughness provides more micro-cavities to serve as bubble nucleation sites, thereby significantly improving the heat transfer coefficient during the nucleate boiling stage [1]. Nano-porous structures, fabricated via techniques such as Micro-arc Oxidation or femtosecond laser processing, can substantially increase surface capillary forces and hydrophilicity. Such superhydrophilic surfaces facilitate liquid penetration through the vapor film to contact the wall, leading to extraordinary shifts in the Leidenfrost temperature—in some cases exceeding 175°C [2]. In liquid nitrogen pool boiling experiments, CHF performance varies across materials such as copper, aluminum, and stainless steel, with copper surfaces typically exhibiting the highest CHF [3]. While surface treatments and roughening effectively improve boiling heat transfer, large-scale implementation is

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often constrained by high costs and durability concerns. Consequently, this study approaches the problem from a system design perspective. By altering the liquid nitrogen filling modes, we investigate the influence of fluid dynamics and injection methods on boiling heat transfer mechanisms, Leidenfrost Point superheat (ΔT_{LP}), and Critical Heat Flux superheat (ΔT_{CHF}).

MATERIALS AND SETUP

Materials

The experimental apparatus employed in this study primarily consists of a 40 L pressurized cryogenic liquid nitrogen (LN_2) Dewar and a 5 liters LN_2 tank. The LN_2 tank was constructed by welding a cylindrical oxygen-free high conductivity (OFHC) copper base (RRR=50, dimensions: 116mm outer diameter, 20 mm height) to a stainless steel tube (430 mm length, 3 mm wall thickness, 110 mm inner diameter). The stainless steel exterior was encased in low-thermal-conductivity insulation cotton to minimize parasitic heat leakage. Under these conditions, heat transfer is assumed to occur predominantly in the axial direction, while lateral heat transfer is considered negligible [4]. A T-type thermocouple (temperature sensor) was installed at the center of the bottom surface of the OFHC copper block. These sensors were interfaced with a data acquisition (DAQ) system to record temperature variations throughout the cooling process. Liquid nitrogen was supplied from the Dewar to the LN_2 tank via a 1-meter-long stainless steel flexible hose (1/2" inner diameter) at a supply pressure of 0.4 bar (gauge), while the vaporized gaseous nitrogen (GN_2) was vented to the atmosphere through an exhaust port at the top. Figure 2 presents the different filling modes.

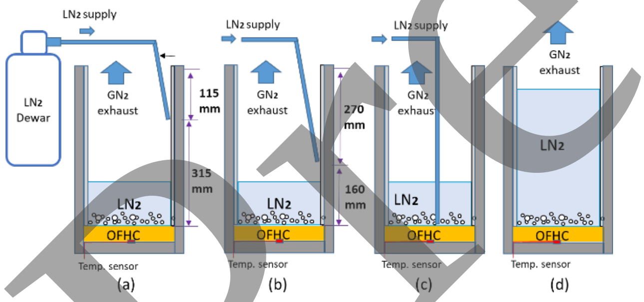

Figure 2: Filling modes (a) Top filling (b) Middle filling (c) Bottom filling (c) Pure liquid nitrogen cooling.

Calculation Methodology

The cooling curves, which represent the T_{bottom} temperature-time data, were obtained through experimental trials (as illustrated in Fig. 3). Since cooling curves do not directly reflect surface heat flux, the Lumped Capacitance Method (LCM) [5, 6] was employed to derive the boiling curves (q vs ΔT), as shown in Equation (1). In Equation (1), q, Q, A, c_p, m, T, and t represent the heat flux, heat, OFHC copper contact area, specific heat capacity (temperature-dependent), mass, T_{bottom} temperature, and time, respectively.By applying Fourier's Law of Heat Conduction, as shown in Equation (2), where k is the temperature-dependent thermal conductivity of the OFHC copper, the approximate inner bottom wall temperature was calculated as shown in Equation (3). Although this method provides an approximation, it offers practical utility for rapid estimation using a single-point temperature measurement (T_{bottom}), under the assumptions of zero heat leakage and strictly axial heat flow.

$$q = \frac{Q}{A} = \frac{c_p(T)\cdot m}{A}\frac{dT}{dt} \tag{1}$$

$$q = k(T)\cdot\frac{dT}{dx} \tag{2}$$

$$T_{wall} = T_{bottom} - \left(\frac{c_p(T)\cdot m\cdot L}{A\cdot k(T)}\right)\frac{dT_{bottom}}{dt} \tag{3}$$

RESULTS AND DISCUSSION

Figure 3 presents the cooling curves for the OFHC copper under different filling conditions. The temperature of the copper base was recorded starting from a room temperature of approximately 290 K. A characteristic rapid temperature drop is observed near 100 K before the system converges toward the liquid nitrogen saturation temperature (77 K). The initial stage of the curve exhibits a relatively gentle slope, attributed to the encapsulation of the surface by a vapor film. As the wall temperature drops below the Leidenfrost Point (ΔT_{LP}), the vapor film collapses, allowing direct liquid-solid contact and causing a sharp increase in the cooling rate (as indicated by the blue line at approximately 7.6 min and the red line at approximately 13.5 min). Thermal equilibrium with the liquid nitrogen is reached as the curves plateau at approximately 77 K. Among all test groups, Bottom Filling (blue line) exhibited the highest cooling rate, completing the cool down from 290 K to near 77 K in 7.6 minutes. In contrast, the Pure Liquid Nitrogen (green line) control group required approximately 12.5 minutes, while Top Filling (black) and Middle Filling (red) were the slowest, exceeding 13 minutes and 13.5 minutes, respectively.

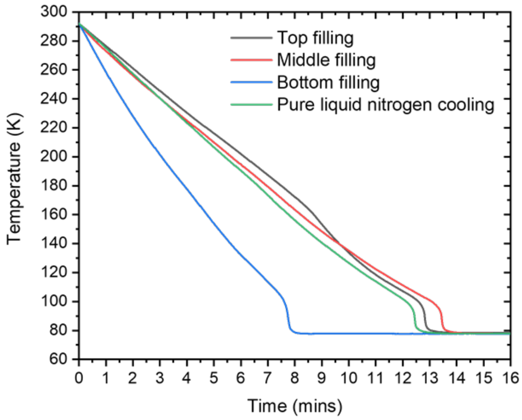

Figure 3: Experimental cooling curves.

Boiling curves were derived using the methodology described in previous section, as shown in Fig. 4. During the initial stage of cooling, the extreme temperature gradient triggers the immediate formation of a continuous vapor film, entering the film boiling regime. This vapor layer insulates the solid surface, resulting in a relatively low and stable heat flux (approximately 20 kW/m^2). The heat flux for the Bottom Filling mode (blue line) was significantly higher than other groups during this stage, indicating a superior cooling rate at high superheat. As the superheat (ΔT) decreases, the vapor film becomes unstable. The Leidenfrost Point (ΔT_{LP}) identified in the figure represents the minimum heat flux point, marking the onset of vapor film collapse. In the bottom filling configuration, the ΔT_{LP} occurs at a higher temperature compared to other modes, facilitating an earlier transition into the high-efficiency cooling regime. During the Transition Boiling Region (10 K < ΔT < 35 K), the rapid collapse of the vapor film allows frequent and large-scale liquid-solid contact, leading to a precipitous increase in heat flux. The cooling efficiency peaks at a superheat of approximately 10 K, defining the CHF point. Interestingly, while the bottom filling mode performs better in the early stages, the Pure Liquid Nitrogen mode (green line) exhibits the highest peak CHF (~ 175 kW/m^2). The peak CHF for bottom filling was notably lower than other modes. Following the CHF, the system enters the nucleate boiling regime, where heat exchange is driven by small bubble formation and detachment, eventually transitioning to single-phase natural convection as the temperature approaches 77 K.

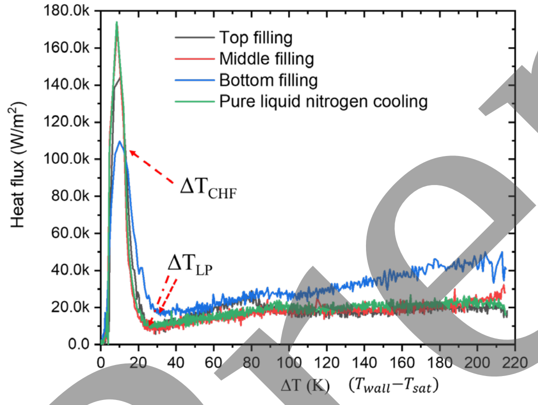

Figure 4: Boiling curves.

Synthesizing the observed phenomena, Bottom Filling demonstrates the most effective overall cooling rate. This is attributed to the direct injection of liquid nitrogen onto the heated wall, which mimics the mechanism of impingement cooling. The kinetic energy and forced convection associated with the fluid flow provide mechanical disturbances that destabilize the vapor film adhering to the OFHC surface. This promotes intermittent liquid-solid contact and significantly reduces the duration of the film boiling phase. In the Middle and Top Filling modes, the liquid nitrogen is discharged from a higher elevation. Although the descent through the chamber generates some splashing and turbulence, the kinetic energy is largely dissipated before the fluid reaches the bottom heating surface, resulting in cooling performance that is inferior to both bottom filling and pure immersion cooling. The boiling curves further indicate that the filling mode significantly influences the position of ΔT_{LP} and the magnitude of the CHF. Under bottom filling conditions, a significant shift of ΔT_{LP} toward higher superheat was observed. However, the lower CHF observed in this mode compared to other configurations suggests a complex interaction between fluid dynamics and bubble departure mechanisms, which warrants further investigation.

CONCLUSION

In this study, an experimental platform for liquid nitrogen boiling heat transfer was successfully established. The influence of fluid dynamics on the boiling mechanisms of OFHC copper surfaces was analyzed across four distinct filling modes: top filling, middle filling, bottom filling, and pure immersion. Based on the experimental results and theoretical discussions, the following conclusions are drawn: The bottom filling mode exhibited the highest cooling efficiency. By directly injecting liquid nitrogen onto the bottom wall, the resulting forced convection and impingement effects effectively disrupted the vapor film. This led to a significant shift of the Leidenfrost Point superheat (ΔT_{LP}) toward higher temperatures, allowing the system to transition into the high-efficiency nucleate boiling regime earlier and substantially reducing the overall cool down time. While the superheat at the Critical Heat Flux (ΔT_{CHF}) showed no significant variation among the different modes, the magnitude of the CHF in the bottom filling mode was notably lower than that of the other configurations. This research demonstrates that optimizing the filling configuration (position and flow path) within a cooling system serves as a viable and effective strategy for overcoming the Leidenfrost bottleneck in cryogenic applications.

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