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Modification and enhancement of cryogenic quenching heat transfer by a nanoporous surface

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ABSTRACT

Since the average chilldown efficiency for cryogenic systems is only about 8%, significant improvements to heat transfer are needed for many applications. An experiment was performed to evaluate the modification and enhancement on the quenching heat transfer by a nanoporous heat transfer surface in this study. For comparison purposes, two sample surfaces were used. One is the mechanically polished conventional normal aluminum surface serving as the base case and the other is an aluminum surface with the anodized aluminum oxide (AAO) nanoporous finish. In this work, the effect of the nanoporous surface on the heat transfer during chilldown in a liquid nitrogen pool is investigated. The results indicated that the nanoporous surface completely modified and enhanced the phase-change heat transfer in all three quenching regimes. Comparing to the conventional surface case, the Leidenfrost temperature was increased by 32 K and the critical heat flux (CHF) was raised by 160% due to the nanoporous surface. However, the most significant modification on the boiling mechanisms by the nanoporous surface was found in the transition regime that is composed of transitional film and transitional nucleate sub-regimes with quite different quenching curve slopes. For cryogenic quenching applications, it is estimated that the nanoporous surface could save 20% in the amount of cryogen consumption by shortening the chilldown time. The modification and enhancement are mainly attributed to the superhydrophilic property and nanoscale nucleation sites offered by the nanoporous surface.

1. Introduction

Cryogenic fluids are widely used in industrial applications, space exploration, and cryosurgery systems. Specifically, in space exploration, cryogenic fluids are used in power and propulsion, thermal management, and life-support systems of a spacecraft during space missions that involves transport, handling, and storage of these fluids under both terrestrial and microgravity conditions. For example, cryogens are usually used as liquid fuels, such as liquid hydrogen and oxygen, that are burned in liquid-fueled rocket engines.

When a cryogenic fluid transport system is first started up, its walls and hardware must go through a transient chilldown period prior to reaching steady-state operation. Therefore, chilldown is the process of adjusting the system to the low temperature regime, which is usually several hundred degrees below room temperature. The chilldown or quenching process is a complicated phase-change phenomenon involving unsteady two-phase flows as well as heat and mass transfer; its characteristics have not been fully understood, resulting in very low chilldown efficiencies.

Fig. 1 is a typical boiling curve where the heater surface heat flux, q'', is plotted against the heater surface degree of superheating, $T_W - T_{sat}$, where T_W is the surface temperature and T_{sat} is the saturation temperature corresponding to the system pressure. Boiling is characterized by the surface temperature and heat flux on the wall according to the boiling curve. Since the wall temperature is strictly determined by an energy balance of the wall, the heat fluxes in and out of the tube wall are important parameters. In boiling, the heat source is externally supplied and, thus, can be controlled independently, such as the constant wall heat flux condition. In this case, boiling is a heat flux (independent variable) controlled process. For the heat flux controlled condition, boiling follows the route of A → B → D. In order to avoid a huge temperature jump, boiling usually runs safely below B in the nucleate boiling regime.

In contrast, the wall does not have an external source of heat (except a small amount of residual heating) during chilldown; therefore, heat coming out of the wall can only be supplied internally from the thermal capacity (stored energy) of the wall. The only way to get heat to be removed from the system is by lowering the inner wall surface temperature by cooling from the cryogenic flow. Accordingly, the wall inner surface temperature is the independent variable and the control parameter. In summary, quenching

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is a conjugate process involving both heat transfer and wall–fluid interaction. The quantity of heat (heat flux) that is released to the fluid can only be associated with the temperature change of the wall inner surface. As a result, the wall surface temperature is the controlling parameter that forces the quenching process to follow the route D → C → B → A.

In boiling applications, such as those in the cooling of a nuclear reactor, a super high flux of heat transfer in the nucleate boiling regime is standard practice. The only precaution is not to exceed the critical heat flux (CHF) and enter the film boiling regime. However, film boiling is the first mode of boiling encountered in chilldown and it cannot be avoided. Due to its low heat fluxes at high wall temperatures, the chilldown efficiency in general is extremely low. According to Shaeffer et al. [1], the average chilldown efficiency that is defined as the ratio of the amount of thermal energy removed from the wall versus the maximum cooling capability of the cryogen spent in a phase change process is about 8%, highlighting the tremendous need to improve the quenching efficiency for many applications that require a cryogen as the working fluid. Advances in nanotechnology enable modification and enhancement of heat transfer based on the phase change from liquid to vapor. This paper reports significant modification and enhancement to heat transfer throughout the entire boiling regime with the purpose of substantially improving the quenching thermal efficiency.

2. Literature review

2.1. Cryogenic chilldown experiments

Because of the difficulties associated with the design and measurements of cryogenic experiments, there is less chilldown data for cryogenic fluids compared to traditional fluids. Researchers began to investigate heat and mass transfer during cryogenic liquid transfer line chilldown because that this area is of extreme importance to spacecraft design. Chilldown of these transfer lines were first studied by Brennan et al. [2] under normal gravity conditions for liquid nitrogen (LN2) and liquid hydrogen (LH2). Antar and Collins found a unique flow pattern in microgravity conditions, which is known as the filament flow. Kawanami et al. [3] also observed a similar flow pattern in terrestrial conditions. They claimed that the gravity effects on heat transfer of forced convective boiling decreased with an increase in the mass velocity. Verthier et al. [4] have studied the effect of gravity during quenching using FC-72. LN2 was used as the working fluid [4] to investigate the heat transfer characteristics and flow pattern during the quenching of a vertical tube under both terrestrial and ten-second microgravity conditions. It is claimed that the heat transfer and quenching front velocity under microgravity conditions increased up to 20% compared to those in traditional gravity conditions.

2.2. Heat transfer enhancement by nanoscale surface structures

The majority, if not all, of the boiling heat transfer enhancement endeavors focused on the nucleate boiling regime and the CHF. There have been a number of experiments to measure the contact angle and wettability on the nanoporous surface. Luo's group [5–7] have introduced more detail discussion both theoretically and experimentally on the wettability on nano pillar surface and derived an angle criterion determining transition from Cassie-Baxter to Wenzel states. Singh et al. [8] investigated the wetting and evaporation of sessile droplets on nanoporous anodic aluminum oxide (AAO) substrates having different pore distribution (uniform, random and linearly arranged) morphologies and pore sizes (70–120 nm). They claimed that nano structured surface is an applicable tool to control wettability as well as the diffusive evaporation process. In addition, physical morphology and pore distribution affect wettability as well as evaporation rates. Tasaltin et al. [9]

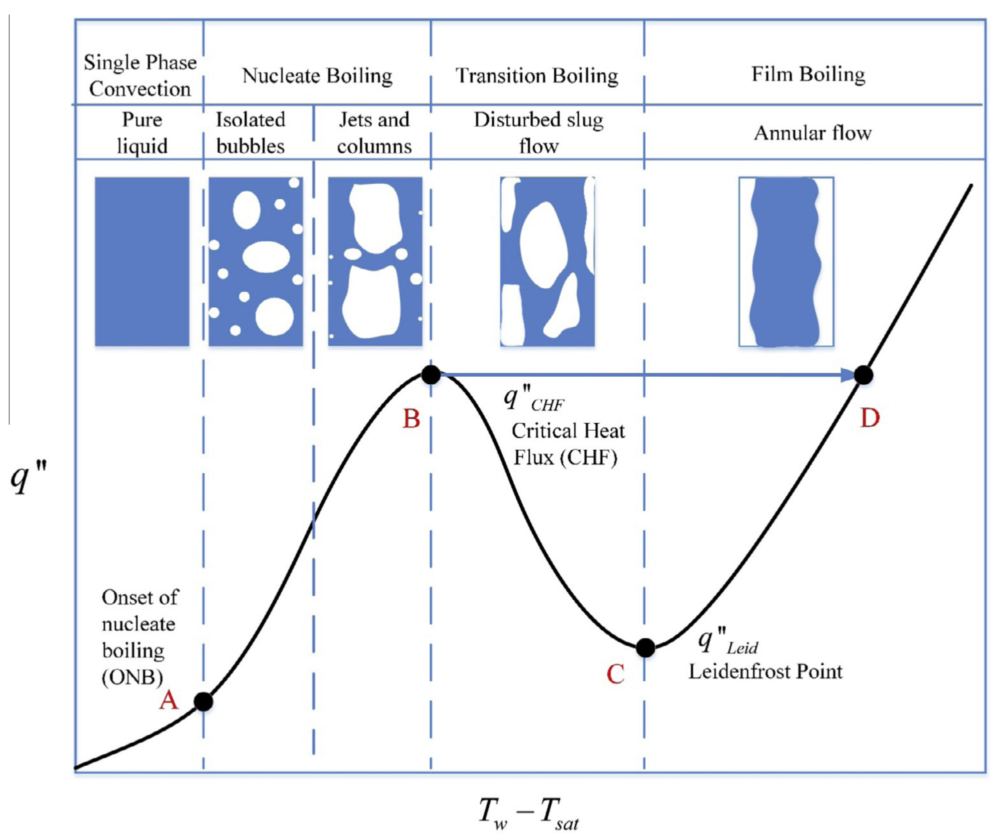

Fig. 1. A typical boiling curve including different boiling regimes and corresponding flow patterns.