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A study of intermittent liquid nitrogen sprays

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HIGHLIGHTS

- Use of intermittent liquid nitrogen sprays for a wide range of operating temperature.
- Nozzle height is critical beyond nucleate boiling regime.
- Below −160 °C, higher heat flux and lower surface temperature lead to lower fluctuations.
- The transient heat transfer coefficients during spray-on and spray-off periods were found.

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ABSTRACT

Cryogenic spray cooling using liquid nitrogen as coolant is an attractive option for open loop cooling applications involving sub-zero temperatures. But for applications which require higher operating temperature (−180 to 20 °C) an intermittent spray is required, where the spray is pulsed at a certain frequency and with a certain open period. This versatile spray process can be adjusted using the mass flow rate, frequency and duty cycle (percentage of open time in one cycle) to match the required cooling rate on the target. Liquid nitrogen sprays were studied by conducting steady state experiments and intermittent spray cooling for various temperature ranges covering all regimes. The intermittent spray experiments were conducted for various ranges of surface temperatures (−180 °C–20 °C), and the r6ange of heat flux removable at each of the regimes was identified along with quantification of surface temperature amplitude, duty cycle and frequency.

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1. Introduction

Liquid nitrogen sprays have diverse applications like in food preservation, transportation and storage, cryosurgery, cryo electronics etc. There have been advances in material science (in 1990's) to operate superconducting circuits even at liquid nitrogen temperature ranges of 77–100 K. This led some researchers in the past to study liquid nitrogen sprays on simulated chips to estimate the operating temperature and flux levels before the critical heat flux (CHF) is reached.

On the other hand for some applications it may not be required to cool down up to 77 K, but the operating range might be for example between −30 °C and 10 °C. Although water has the highest latent heat and specific heat capacity, and also easily available, it cannot be used for sub-zero temperatures due to its freezing point (unless it is mixed with glycol, which would make it an expensive coolant). There are other refrigerants that can be used for such applications but the drawback is that the system has to be a closed loop system, where the spent vapor and liquid has to be condensed/cooled back for subsequent use due to high cost of refrigerant.

Liquid nitrogen is an alternative, as it is easily available, cheap and can be used in open loop applications. The objective was to explore the heat removal capacity of typical liquid nitrogen sprays at various regimes of boiling. Intermittent spray experiments were conducted for a range for temperatures spanning across different regimes: 20, 10, 0, −10, −20, −50, −100, −125, −150, −160, −172, −180 and −185 °C. This would enable us to understand the maximum heat flux that can be removed at various surface temperatures.

In an intermittent spray the spray is periodically injected for a certain period of time at a certain frequency of intervals. The injection time is proportional to the amount of coolant injected per cycle and frequency of injection is proportional to the time allowed for each set of droplets to undergo phase change. To achieve this, the amount of coolant sprayed, injection time, frequency of injection should be precisely controlled to match the rate of evaporation

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and boiling of the coolant at a specified heat flux. Intermittent spray cooling promotes phase change and utilizes the coolant efficiently and helps in maintaining a variable range of surface temperatures using the same coolant. However there is a penalty of having some temperature fluctuations. The methodology of closed loop feedback, intermittent spray cooing is explained in detail in previous work [1,2]. The aim of this work is to understand the relationship between various parameters of an intermittent spray cooling process (for a liquid nitrogen spray) – like frequency of injection, duty cycle of injection, and the spray pressure on the heat transfer performance measured by quantifying the temperature fluctuations at various surface temperatures or wall superheat, ΔT (difference in temperature between wall and saturated liquid).

There has been very limited study of use of purely saturated liquid nitrogen sprays. These are discussed below first. Later some reports of heat transfer performance of liquid nitrogen droplets/sprays (in application to cryogenic food freezing) in the film boiling regime are summarized.

Thermal management aspect of superconducting circuits at liquid nitrogen temperature led a group of researchers [3] to study the spray cooling of power electronics at cryogenic temperatures. In these set of experiments, a 1 cm^2 copper surface served as a simulated electronic chip, as the copper block was powered by cartridge heaters. Four full cone spray nozzles of orifice diameters of 0.51, 0.61, 0.76 and 0.38 mm were used. The experiments were conducted in the range of 2–8 bar pressure where the flow rates ranged between 6.1×10^4 kg h^{-1} m^{-2} to 3.2×10^5 kg h^{-1} m^{-2}. The inlet liquid to the nozzle was maintained at about 78 K by cooling the high pressure, high temperature liquid nitrogen from the high pressure Dewar, in a heat exchanger. Heat fluxes of up to 165 W cm^{-2} were removed at wall superheat temperatures of about 16–18 K. It was observed that critical heat flux (CHF) increased with mass flow rate but the effect was more prominent at low flow rates. However they also observed that smaller nozzles with lower flow rates had a very similar range of CHF compared with larger nozzles having higher flow rate and they proposed that a thinner liquid film at low flow rate, increased velocity of droplets from a smaller orifice and increased number of droplets per unit area, could be some possible reasons why smaller nozzles displayed a better heat transfer performance.

The same group of researchers did a study [4] on effect of spray parameters by measuring the droplet size and velocity by a Phase Doppler Particle Analyzer at 1 cm below the nozzle exit, at different radial positions. The velocity was in the range of 14–30 m s^{-1}. The authors also studied the effect of surface roughness by testing three different surface roughness –Ra (arithmetic mean of absolute values of surface peaks and valleys) values of 0.05, 0.3, 0.6 μm. It was observed that the rougher surfaces showed a significant shift in slope and the temperature at which CHF is reached is much earlier, though the actual value of CHF did not vary much. They also suggested a correlation of heat flux as a function of droplet velocity, d_{32} (Sauter mean droplet diameter), wall superheat and volume flow rate.

Tilton et al. [5] investigated evaporative spray cooling with liquid nitrogen as a candidate method for thermal management of electronic assemblies utilizing High Temperature Super Conducting (HTSC) materials. A heated copper surface (15 mm square) was used to simulate an electronic chip. Three full cone nozzles (orifice diameters of 0.41, 0.46, 0.53 mm) were used to spray liquid nitrogen vertically upwards onto the heater surface. Heat transfer characteristics were studied for a range of inlet liquid temperature (77.4, 81 and 84 K) and inlet pressures (1.4, 2 and 2.8 bar) and nozzle heights (6, 13 and 19 mm). It was concluded that the heat transfer characteristics did not vary much within the tested range of operating conditions. Heat fluxes (q) of up to 75 W cm^{-2} was removed at a surface temperature of 83 K. Due to experimental limitations CHF was not reached in all cases. It was observed that below 20 W cm^{-2}, the heat transfer is dominated by forced convection and heat transfer coefficient (h) remained constant. As heat flux increased, the thin film evaporation increased and contributed to more efficient heat transfer mechanism and thus the surface temperatures remained between 81 and 82 K for heat fluxes in the range of 20–70 W cm^{-2}.

There has also been report of liquid nitrogen spray experiment in reference to cryosurgery. Fillipov [6] has reported use of nozzles (orifice diameter of 0.5–3 mm) to spray liquid nitrogen at 0.196 MPa onto a hemispherical copper surface having an inside radius of 3/6/7 mm. The nozzle height (H) was varied between 0.1 and 10 mm and the mass flow rates were between 0.4 and 1.65 g s^{-1}. It is reported that a 1 mm orifice nozzle at a height of 0.1 mm with flow rate of 2 ml s^{-1} can have a critical heat flux of 70 W cm^{-2} at a wall superheat of 29.5 K.

There has also been a study of liquid nitrogen sprays in the food industry as liquid nitrogen is used for cryogenic freezing of foods. The regime is mostly Leidenfrost owing to high wall superheat. In the work of Awonorin [7] liquid nitrogen from a pressurized Dewar was used at pressures of 2–6 bars. The spray nozzle had an orifice diameter of 1 mm and the spray target was a gelatin slab of 150 mm diameter. The spray nozzle height (H) was about 120 mm similar to the conditions in the cryogenic plant for food processing. They did observe that heat transfer coefficient (h) of a single droplet was inversely affected by the droplet size (d) and the wall superheat temperature (ΔT) as $h = f(d^{-1/4}, (\Delta T)^{-1/4})$. Higher pressure resulted in higher mass flow rates and smaller droplet sizes and therefore a higher heat transfer coefficient. They reported average h values of about 240 W m^{-2} K^{-1} at ΔT of 80 K and about 180 W m^{-2} K^{-1} at ΔT of 180 K.

The heat transfer performance of liquid nitrogen sprays in the stable film boiling regime (for wall superheat of 200–450 K) has been reported [8]. The target surface was an electrically heated platinum plate of size 120 × 100 × 0.3 mm. The nozzle had an orifice diameter of 1 mm and the liquid pressure at the nozzle inlet ranged from 2 to 12 bars. The Sauter mean diameter and velocity were estimated based on the work of Mugele [9]. The spray efficiency or thermal utilization ratio (which is the ratio of heat energy actually removed to the maximum possible energy removable) ranged from 0.74 to 0.89. It was observed that with increase in wall superheat the heat flux removed increased and heat transfer coefficient decreased. The heat transfer coefficient increased with the increase in mass flux and decrease in droplet size. Heat transfer coefficients (h) were about 160–170 W m^{-2} K^{-1} at wall superheat of 200 K and about 90–110 W m^{-2} K^{-1} at wall superheat of 450 K.

In summary, the three works [3–5] on liquid nitrogen spray cooling describe the spray cooling behavior before the CHF regime. The rest of the works describe the spray cooling behavior in the film boiling regime. Moreover the film boiling regime experiments used a two phase mixture of liquid and gaseous nitrogen and did not ensure that all the mass flux that was sprayed was fully in liquid state. The operating conditions like height of nozzle and target surface were larger.

It is important to know the heat removal limit at various regimes for a fully saturated liquid nitrogen spray. The present study explores the intermittent spray cooling using liquid nitrogen and the feasibility and limitations of maintaining a target surface at a given temperature (20 °C to −180 °C). It was chosen to explore and study closed loop feedback controlled intermittent spray. The present work involves study of a feedback based intermittent spray cooling and the inter-relationships between frequency and duty cycle of injection with heat flux and surface temperature. The study is done for a range of heat fluxes and set-point temperatures.

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