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Spray cooling with ammonium hydroxide

Huseyin Bostanci *, Bin He, Louis C. Chow

Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL 32816, United States

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ABSTRACT

An experimental study was conducted to investigate the performance characteristics of spray cooling with ammonium hydroxide (NH_4OH) binary mixture for high heat flux removal. Two mixtures, having ammonia mass fractions of 0.3 and 0.5, were selected to represent practical operation conditions near atmospheric pressure and room temperature. Experimental setup involved a closed loop system with a vapor atomized spray nozzle and a 1-cm^2 heater sample that simulated a high heat flux source. Tests were performed with gradually increasing heat fluxes of up to 800 W/cm^2 and maintaining surface temperatures below ~75 °C at varying liquid and vapor flow rates. Results indicated that the heat transfer coefficient (HTC) values from NH_4OH mixtures can be lower than those from pure water and pure ammonia. The data suggested that boiling depression, due to mass diffusion resistance at liquid vapor interface, could greatly affect the overall spray cooling performance, especially when the binary mixtures comprise components with widely different boiling points. The study therefore provides performance characteristics, as well as some fundamental insights, for a potential spray cooling scheme suitable for low temperature, low pressure operations in various applications including thermal management of aerospace electronics and electro-optics.

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1. Introduction

Two-phase spray cooling has been an emerging thermal management technique characterized by its major capabilities of high heat transfer rate, near-uniform surface temperature, and efficient coolant usage that leads to compact and lightweight systems. Due to these capabilities, spray cooling is a promising approach for high heat flux applications in computing, power electronics, and electro-optics.

Selection of working fluid is very important as it directly affects both performance characteristics and operation conditions of a cooling system. The working fluid should have a high latent heat of vaporization to remove high heat flux levels, a boiling point close to the desired operating temperature of the target device being cooled, and a freezing point low enough to provide protection against system freeze-up at anticipated cold ambient. A proper temperature-pressure relationship is also critical to avoid excessively low pressure (high vacuum) or excessively high pressure in the system. Moreover, the working fluid should be chemically stable, noncorrosive, and safe.

Certain applications, such as thermal management of high-power diode-pumped solid-state lasers for aerospace systems, poses multiple challenges and necessitates careful consideration to determine a proper working fluid. The laser diode arrays generate high heat fluxes at substrate-level (>600 W/cm^2), they mandate operation at low temperatures (<25 °C) to attain high electrical-to-optical energy conversion efficiency, and the emitters (and surface temperature of diode arrays) also require nearly-uniform temperature distributions, within a few °C, to achieve high quality optical beam. Due to the ambient conditions for aerospace applications, the cooling system should be able to operate at very low temperatures (−70 °C) without freezing issues. Additionally, the system pressure should ideally be close to atmospheric pressure levels during operation.

Based on all these challenging conditions, two-phase spray cooling seems to be the appropriate thermal management scheme. Considering thermophysical properties, particularly high latent heat of vaporization, water and ammonia are the two best heat transfer fluids. However, each fluid has undesirable saturation temperature-pressure characteristics for diode laser cooling. In order to use water for low temperature cooling, its boiling point should be reduced significantly from 100 °C at 1 bar to 20 °C at 0.02 bar by maintaining the system under high vacuum. This would then complicate the system design, and cause potential leak issues. Water also has a very high freezing point for aerospace con-

* Corresponding author at: University of North Texas, Department of Engineering Technology, UNT Discovery Park, 3940 North Elm St. F115, Denton, TX 76207, United States.

E-mail address: huseyin.bostanci@unt.edu (H. Bostanci).

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Nomenclature

A	area, cm^2	q''	heat flux, W/cm^2
CHF	critical heat flux, W/cm^2	T_{surf}	surface temperature, °C
h	heat transfer coefficient, kW/m^2 °C	TC_{avg}	average thermocouple reading, °C
h_{fg}	latent heat of vaporization, kJ/kg	V	voltage, V
HTC	heat transfer coefficient, kW/m^2 °C	$\dot{V}$	supplied liquid flow rate ($ml/cm^2.s$)
I	current, A	$\dot{V}_{req}$	required liquid flow rate ($ml/cm^2.s$)
k	heater wall thermal conductivity, W/m °C	x_1	liquid mass fraction of more volatile (NH_3) component
l	TC to spray surface distance in heater wall, m	ρ	liquid density (kg/m^3)

ditions. Ammonia appears to be an ideal working fluid for spray cooling of diode laser arrays due to its high latent heat, low boiling point and low freezing point at the normal pressure. However, ammonia has a very strong temperature-pressure dependency. The ammonia pressure can easily exceed 10 bar at room temperature. High saturation pressure (4–10 bars) would deform the heat source structure (i.e., diode bar package) and may lead to failure. This is especially true when the substrate accommodating the heat source is made very thin in order to minimize the internal thermal resistance. Therefore, for room temperature spray cooling applications, water dictates very low system pressure leading to serious fluid sealing problems, while ammonia dictates very high system pressure leading to serious structural problems.

In this case, utilizing a mixture of compatible fluids is an attractive approach to obtain the desirable saturation temperature-pressure behavior needed for spray cooling of diode lasers. Ammonium hydroxide (NH_4OH) is made by dissolving ammonia into water. Varying the mass fraction of the solution can modify the saturation temperature-pressure relationship. For instance, NH_4OH with an ammonia mass fraction, x_1, of 0.45 provides 0 °C saturation temperature at approximately 1 bar pressure. Its latent heat of vaporization is still 5–10× higher than those of common refrigerants. The low freezing point (around −80 °C for x_1 >0.3) also prevents the plumbing from freezing when spray systems are used in aerospace vehicles. This binary fluid takes advantage of the high latent heat of vaporization associated with the parent fluids without the drawbacks of excessively low or high saturation pressures of water and ammonia, respectively. In addition, NH_4OH has a reasonably high thermal conductivity comparable to that of water. Both the parent fluids of NH_4OH have very favorable spray cooling heat transfer rates as reported in the earlier research [1–6]. If the binary mixture of NH_4OH can provide cooling characteristics somewhere between those of its parent fluids – water and ammonia, it would enable spray cooling technology for high heat flux cooling capability at room temperature operation. This would then allow effective cooling of the delicate electronics and optics devices, such as diode laser arrays, without the excessively high or low system pressure.

Binary mixtures have been studied extensively for boiling heat transfer due to their wide use in industrial applications, such as petro-chemical, refrigeration, and power generation. Carey [7] provided a comprehensive review on the pool boiling of binary mixtures addressing thermodynamics aspects and major heat transfer characteristics, specifically the effects of mass diffusion resistance on nucleate boiling, and surface tension gradients on CHF. Some of the exemplary efforts in this area focused on developing prediction methods, including Thome and Shakir [8], Fujita et al. [9], and Kandlikar [10] regarding HTC, and McGillis and Carey [11], Fujita and Bai [12], and Yagov [13] regarding critical heat flux (CHF) correlations. However, there are very limited spray cooling research focusing on binary mixtures, as previous efforts mainly considered single-component working fluids [1–6,14–17], and none of which, to the best of authors' knowledge, studied NH_4OH.

Lin et al. [18] investigated spray cooling with water/methanol mixtures at methanol concentrations of 0, 20, 50 and 100% by volume. Their experimental conditions involved various chamber pressures to maintain saturation temperatures of 45 and 65 °C, and relatively low heat fluxes in the range of 15–75 W/cm^2. The data showed that HTCs were highest for water, and lowest for methanol. The performance of water/methanol mixtures was found to be between those of pure water and methanol, although in some conditions, the mixture with 50% ethanol concentration offered comparable performance to that of pure water. The authors noted that the nucleate boiling is a major heat transfer mode in spray cooling, and flashing of the more volatile component at the nozzle exit helps with atomizing liquid droplets and enhance the heat transfer performance. Turek et al. [19] evaluated the capabilities of spray cooling for power inverter applications using water/propylene glycol (WPG) at a 50% concentration by volume. They replaced the single-phase liquid cooled base plate of a commercial power inverter module with a custom-made base plate of comparable size, and integrated a spray nozzle array. DBC board in the module was sprayed with pressure atomizer nozzles featuring 0.19 l/cm^2·min liquid flow rate and 275 kPa pressure drop. Using WPG at 100 °C, heat fluxes of up to 148 W/cm^2 were removed without exceeding Insulated Gate Bipolar Transistor (IGBT) junction temperature of 125 °C. Their spray cooling approach reduced the overall thermal resistance with the help of a very high HTC and achieved up to a 3.4× increase in inverter power level. Later, Turek et al. [20] conducted experiments with pure water at 95 °C using the same setup. IGBT junction temperatures for the water spray cooling was about 10 °C lower compared to WPG spray cooling, although the difference in the boiling points of two cases was 6 °C. Considering the similar subcooling levels, they concluded that the vapor generated by WPG boiling is nearly all water, leaving a higher concentration mixture at the spray surface with a higher boiling. This locally higher boiling point diminishes the boiling performance and leads to higher temperatures. Bostanci et al. [21] evaluated a two-phase spray cooling scheme for the thermal management of automotive power inverter modules using an anti-freeze coolant (water/alcohol mixture). The experimental setup included pressure atomized spray nozzles with 0.15 l/cm^2·min liquid flow rate and 145 kPa pressure drop, and featured two types of enhanced spray surface with microscale structures. The spray cooling tests with azeotropic mixture at 88 °C saturation temperature and atmospheric pressure, showed that up to 400 W/cm^2 heat fluxes can be reached with only 14 °C surface superheat, resulting in a HTC of 280,000 W/m^2 °C. Compared to single-phase convective cooling, this spray cooling system offered up to 5.5× potential increase in inverter power. Most recently, Karpov et al. [22] performed an experimental study with water/ethanol mixtures, at ethanol concentrations of 0–96% by mass, and used air atomized

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