International Journal of Heat and Mass Transfer 101 (2016) 60–68

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer enhancement of ammonia spray cooling by surface modification

H. Wang [a,b,*], J.J. Wu [b], Qiang Yang [b], X. Zhu [a,b], Q. Liao [a,b]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems (Chongqing University), Ministry of Education, Chongqing 400030, China
[b] Institute of Engineering Thermophysics, Chongqing University, Chongqing 400030, China

ARTICLE INFO

Article history:
Received 29 February 2016
Accepted 12 May 2016

Keywords:
Ammonia
Spray cooling
Surface modification
Boiling site

ABSTRACT

This study presented a scenario for spray cooling in cryogenic applications. Liquid ammonia was employed for spray cooling through a two nozzle array. Three groups of modified surfaces were experimentally tested. The first group of surfaces included three surfaces treated by electrochemistry at different levels. The second group comprised of two surfaces coated by micro copper particles in different sizes. The final group composed two hybrid surfaces combining microporous coating with macro channels. A heat flux of about 350 $W{\cdot}cm^{-2}$ was obtained in this work and discrepancies in spray cooling performance for these surfaces were reported. It was found that the hybrid surface possessed the best heat removal capacity. During spray cooling, it showed a small temperature rise of 2.3 °C when heat flux increased from 100 $W{\cdot}cm^{-2}$ to 300 $W{\cdot}cm^{-2}$. Comparatively, the reference surface presented a temperature rise of 25.3 °C in the same condition. The results indicated that surface modification enhanced the spray cooling performance by virtue of (i) larger specific surface area and (ii) higher boiling sites density. The present study paves the way to further cryogenic applications and provides an insight for the surface modification targeting heat transfer enhancement.

1. Introduction

Spray cooling is one of the advanced cooling technologies for high-heat-flux dissipation [1,2]. It employs nozzle or orifice to produce small droplets, which are afterwards directed to the hot surface, and then removes the heat from surface through single phase convection, evaporation or boiling [3]. Enhancing the spray cooling performance by active approaches (for example, pulse spray [4] or synthetic jetting [5]) increases system complexities as well as energy input, thus potentially resulting in inconvenience and diseconomy for practical applications. As a result, finding a solution to effective heat removal through viable passive enhancement has become the major concern at present [6].

Previous efforts [6,7] reported that the spray cooling possesses excellent heat removal capacity ranging from 100 W/cm^2 for fluorinerts [8] to more than 1000 W/cm^2 for water [9]. The spray cooling performance is dominated by spray characteristics, liquid properties and surface morphologies [10]. The early works concluded that the spray cooling performance was strongly dependent on the spray parameters such as nozzle diameter [11], spray velocity [12], spray angle [13–15], etc. Equally important, the liquid properties play an important role in spray cooling. The liquids for spray cooling have been well summarized by Kandlikar and Bapat [7] and Ebadian and Lin [3]. The water-based spray cooling provides order-of-magnitude greater heat transfer coefficient in comparison with fluorinert-based spray cooling [16]. In terms of surface morphologies, the past decades witnessed the flourish of this prospective passive heat transfer enhancement technology i.e. surface modification. A vast number of research works have been devoted to elaborate the modified surface for better heat removal. Surfaces with different roughness [9,17–20], porous coatings [21–23], and special structures [6,24–31] have been widely studied for spray cooling. The above-mentioned results indicate that modified surface can significantly improve the heat transfer performance of the spray cooling. Besides, the nano-texted surfaces have also been extensively studied [32–36]. It is reported that a heat flux of 200–600 W/cm^2 could be achieved with these surfaces. As a result, numerous researchers have been motivated to advance the surface modification for more efficient heat removal.

Concurrently, the miniaturization and integration of electronic devices in modern society promote an ever-increasing need for heat dissipation. Deficient heat dissipation will lead to excessively large temperature rise which degrades the device performance [37–39]. Moreover, the electronic devices have to reach the consumers worldwide, thus inevitably confronting various environmental

---

* Corresponding author at: Institute of Engineering Thermophysics, Chongqing University, Chongqing 400030, China.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.052

conditions. For electronics operating at room temperature, the heat dissipation governed by the hierarchy of conduction and convection can be well addressed through material innovations. For electronics operating at cryogenic temperature, on the other hand, the management of the liquid and vapor phases could serve as alternative solution for high-heat-flux removal [40]. In this coincidence, spray cooling has received widespread attention in response to high-flux-heat removal. The spray cooling in cryogenic applications is primarily determined by selecting an appropriate coolant of considerable importance.

The literature survey shows that the frequently-used coolants can be roughly classified into two categories: (i) fluorides [18,19,30,41,42] and (ii) water [14,20,31,42–45]. The former can operate at cryogenic temperature but have limited latent heat at ambient pressure. While the latter has a large latent heat but is restricted at low-temperature running. This distinct gap between fluorides coolant and water coolant can be well bridged by the utilization of alternative coolant-ammonia.

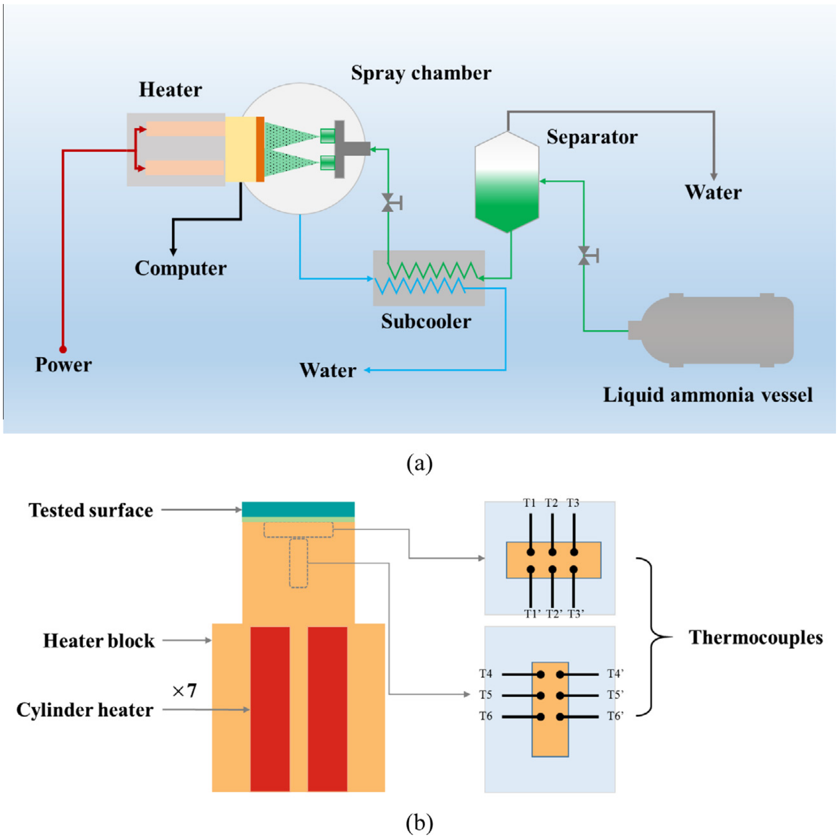
The ammonia is historically known for its low boiling temperature down to $-33.3\,^{\circ}\mathrm{C}$ and high latent heat of $\sim$1200 kJ/kg only inferior to water at atmospheric pressure [46]. It requires stringent standard for anticorrosion and sealability due to its corrosivity and flammability [47]. However, with the rapid development in materials, the hazardousness of ammonia can be well confined and managed. Therefore, ammonia spray cooling can be broadened into low-temperature operations. Several studies focusing on ammonia spray cooling were mainly conducted by Bostanci et al. [48–54]. In their works, various surfaces with micro-scale indentations and protrusions [48,49,53], as well as hybrid structured surface [52,54] were systematically tested for heat transfer enhancement. The ammonia spray cooling combined with enhanced surface can improve the critical heat flux significantly up to 910 W/cm^2 [52], showing excellent heat removal capacity. Besides the extremely low temperature (or hash environment defined by Ohadi and Qi [55]), the surface for heat transfer will potentially face with corrosion, thus requiring corrosion-resistance treatment [56]. To date, the effect of surface corrosion on heat removal has rarely been reported.

To tackle the challenging issues for spray cooling in harsh environment i.e. cryogenic operation and surface corrosion, ammonia was employed as the coolant to implement spray cooling in this study. Meanwhile, corrosive surfaces with different microstructures were fabricated by means of electrochemical etching and the corresponding spray cooling performance was investigated. Porous surfaces were also tested. The results of this work can advance current understanding of ammonia spray cooling and also provides alternative surface design to enhance heat dissipation.

2. Experimental setup and procedure

2.1. Spray cooling system

An open loop spray cooling system was designed and built for the experiments. As illustrated in Fig. 1a, this system mainly consisted of three components, including the coolant supply and disposal unit, the spray cooling unit, and the data acquisition unit. In detail, the coolant supply and disposal unit included a liquid ammonia vessel, a liquid–gas separator and a subcooler. The liquid ammonia was supplied from the liquid ammonia vessel and the exhausted liquid and vapor ammonia was collected by means of water absorption. The spray cooling unit comprised a stainless-steel chamber, two pressure nozzles (Spray System Co. Shanghai) and the heater. The nozzles forming a spray array was mounted in the center of the chamber. The nozzle-to-surface distance was set at 10 mm to ensure the entire hot surface covered by the spray



(a)

(b)

Fig. 1. Schematic diagram of experiment setup: (a) spray cooling system; (b) heater part.