Chinese Journal of Aeronautics, (2016), **29**(3): 630–638

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Ground experimental investigations into an ejected spray cooling system for space closed-loop application

Zhang Hongsheng [a], **Li Yunze** [a,*], **Wang Shengnan** [b], **Liu Yang** [a], **Zhong Mingliang** [a]

[a] *School of Aeronautic Science and Engineering, Beihang University, Beijing 100083, China*
[b] *School of Automation Science and Electrical Engineering, Beihang University, Beijing 100083, China*

Received 24 June 2015; revised 8 October 2015; accepted 22 March 2016
Available online 9 May 2016

KEYWORDS

Ejected spray cooling system;
Evaluation models;
Ground experiment;
Heat transfer performance;
High heat flux;
Space closed-loop

Abstract Spray cooling has proved its superior heat transfer performance in removing high heat flux for ground applications. However, the dissipation of vapor–liquid mixture from the heat surface and the closed-loop circulation of the coolant are two challenges in reduced or zero gravity space environments. In this paper, an ejected spray cooling system for space closed-loop application was proposed and the negative pressure in the ejected condenser chamber was applied to sucking the two-phase mixture from the spray chamber. Its ground experimental setup was built and experimental investigations on the smooth circle heat surface with a diameter of 5 mm were conducted with distilled water as the coolant spraying from a nozzle of 0.51 mm orifice diameter at the inlet temperatures of 69.2 °C and 78.2 °C under the conditions of heat flux ranging from 69.76 W/cm^2 to 311.45 W/cm^2, volume flow through the spray nozzle varying from 11.22 L/h to 15.76 L/h. Work performance of the spray nozzle and heat transfer performance of the spray cooling system were analyzed; results show that this ejected spray cooling system has a good heat transfer performance and provides valid foundation for space closed-loop application in the near future.

1. Introduction

High heat flux density electronics are widely used in modern industry, and their cooling technologies are most important for sustaining their working temperature in a certain range and lengthening their lifetime.[1] However, conventional cooling approaches (like air-cooling solutions and single-phase fluid loop[2]) could not meet the ever-increasing need in high heat power dissipations, which may exceeds 250 W/cm^2.[3] Spray cooling technology has proved its cooling ability for the ground applications,[4–8] such as electronic card cooling,[4]

* Corresponding author. Tel.: +86 10 82338778.
E-mail addresses: Hongsheng.Zhang@buaa.edu.cn (H. Zhang), buaalyz@163.com (Y. Li), qfwangshengnan@126.com (S. Wang).
Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

http://dx.doi.org/10.1016/j.cja.2016.04.005

in-wheel motor cooling,[5] hot strip mill cooling[7] and on-chip cooling.[8] An open water spray cooling system was applied to a lateral diffused metal oxide semiconductor field effect transistor (LD-MOSFET) with a heat flux of 162 W/cm^2 in a 500 MHz radio frequency power amplifier[9] and an air–water spray cooling system was used to cool high-speed switching insulated gate bipolar transistors (IGBTs) with a heat flux of 825 W/cm^2.[10] Furthermore, a high flux up to 1200 W/cm^2 was removed from rough heat surface through the spray cooling technique using water as working fluid[11]. Due to its superior performance with only small liquid mass flow and other merits like temperature uniform distribution, small surface superheat and strong control ability,[12,13] the spray cooling technology may become one of the most promising cooling techniques for high flux density devices.

For the space application of spray cooling system, several problems need to be well addressed. Firstly, the future spray cooling system loaded on spacecraft will run in a microgravity or zero gravity space environment; therefore, how to dissipate the vapor–liquid mixture from the heat surface in time and ensure no coolant hydrops on the heat surface are very important for the heat transfer performance. What's more, how to design a closed-loop system to realize the coolant circulation is critical for the heat being effectively transmitted by the spray coolant and then being exhausted to the outer space environment.

Currently, some approaches for the space application of spray cooling systems were studied by researchers. Spray cooling characteristics under reduced and elevated gravity (10^{-2} g for 20 s and 1.5–2.0 g for 15–20 s) in space application were conducted with the aid of the parabolic flights of an aircraft. Liquid was sealed in a cylindrical pressure vessel under constant pressure by nitrogen gas, which was used to evacuate the pressure in the chamber. The spray coolant in the spray cooling system was drained out of the chamber with the aid of a small auxiliary pump and the coolant was not repeatedly used. During the experiments, the acceleration direction of the aircraft was perpendicular to the heater surface.[14] Spray cooling experiments under specific microgravity conditions have also been conducted with the aid of parabolic flights.[15] Pressurized gas bottles were used to drive the coolant spraying through the full-cone pressure swirl atomizer and the gas and liquid in the spray chamber were not circulated in cycle. However, the schematic of this spray cooling experiments was an open system, which is not suitable for space application.

A closed-loop spray cooling system with sintered porous copper wick was proposed for space application[16] and sintered porous copper wick was arranged on the heat surface to capture the spray liquid droplets. When the droplets impinged on the wick surface, some of them evaporated and the rests diffused into the sintered porous copper wick. The vapor flowed out of the chamber through the vapor pipe line. With the help of the capillarity suction, which was provided by the sintered porous copper wick arranged in both the liquid pipeline (that links the reservoir and the spray chamber) and the reservoir, the liquid coolant in the spray chamber flowed to the reservoir along the liquid pipeline. The heat absorbed by the vapor and the liquid was dissipated to the outer environment with the help of the heat sink. In this spray cooling system, the sintered porous copper wick on the heat surface realizes the vapor–liquid separation in the spray chamber. What's more, the sintered porous copper wick, arranged in the liquid pipeline and the reservoir, realizes the circulation of coolant in the loop.

Research of a closed-loop spray-cooling system with a liquid–liquid ejector has also been carried out.[17] In the closed-loop spray cooling system, a condenser was arranged between the ejector and spray chamber to cool the two-phase mixture from the outlet of the spray chamber. With the help of the ejector, the vapor–liquid coolant can be effectively sucked away from the heat surface, and the heat transfer performance of the spray cooling system was enhanced. Another experimental investigation of a large area multiple nozzle spray cooler with an imbedded suction system was conducted, the suction system made up of thin copper tubes was used to extract liquid from the heat surface, and the heat flux removal increased 30 W/cm^2 with the help of the suction system.[18]

In the present paper, the normal spraying method was utilized to obtain good heat transfer performance. Water (or distilled water) as coolant with full-cone spraying has been researched mostly because of its largest heat latent, and hollow-cone pressure spray nozzles and dissolve gas assisted atomizing nozzles were not recommended for spray cooling of electronics.[19] What's more, inclination angle of spray cooling impinging on the heat surface has a significant impact on the spray cooling performance. Spray cooling experiments with PF-5052 as working fluid at various inclination angles were conducted and results show that a maximum critical heat flux (CHF) was achieved with the spray impinging normal to the heat surface.[20] Spray cooling experiments were also carried out with spray angles of 0°, 30°, 45°, 90° and the maximum CHF was achieved when the inclination angle is 30°.[21] Li et al. found that inclination angle had little effect on the heat transfer performance unless inclination angle exceeded 40° at the orifice-to-surface distance of 1.4 cm.[22] Spray cooling experiments were conducted with distilled water as coolant using the semi-solid swirl nozzle at different inclination angles, and both of the heat transfer performance and cooling efficiencies were enhanced with the inclination angle increasing from 0° to 49°.[23]

In Section 2, the ejected spray cooling system was described and its ground experimental setup was also illustrated. This section also presents the experimental conditions along with the experimental procedure, the models of work performance parameters characterized the spray nozzle, like Sauter diameter and the droplets velocity, as well as the parameters that appraise the spray cooling performance, including heat transfer coefficient, heat surface temperature, vaporization ratio and spray cooling efficiency, followed by the measurement uncertainties of these parameters. Section 3 presents and discusses the experimental results and Section 4 draws the conclusions.

2. Ejected spray cooling system and its ground experimental setup

2.1. Ejected spray cooling system

Fig. 1 shows the scheme of the ejected spray cooling system for space closed-loop application, which consists of a spray chamber, an ejected condenser, a radiator, two valves, a pump and a heat exchanger along with the linking pipelines.

In the ejected spray cooling system, the coolant is driven by the pump, and the volume flows through the spray nozzle and