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Experimental study on the characteristics of a closed loop R134-a spray cooling

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ABSTRACT

Experimental investigation on the R134-a spray cooling characteristics is presented in a closed loop system. A full-cone nozzle was applied to spray onto a heated circular copper plate. The characteristics of the R134-a spray cooling under a series of different volumetric flow rate were obtained. The results shown that volumetric flow rate improves the critical heat flux (CHF). And larger volumetric flow rate prevent the dry-out phenomenon under high heat flux. However, volumetric flow rate bring the adverse condition that reduces the system efficiency. The maximum CHF of 117.2 W cm^{-2} was achieved with 319 K target surface temperature at 0.356 L min^{-1}. The results indicate that R134-a owns a great cooling characteristics in spray cooling system.

1. Introduction

With the development of the high compact electronic devices and the high power density equipment, the cooling methods which are able to remove huge heat flux at a relatively low cooling surface temperature are needed urgently. As an efficient heat flux removal technique, spray cooling technology has many advantages such as high heat transfer coefficient, little liquid inventory and outstanding thermal uniformity. Therefore, spray cooling owns a prosperous application foreground in high power thermal management compared with other cooling methods [1–3].

The spray cooling mechanism combines several heat exchange methods; for instance, convection and evaporation of thin liquid film on the cooling surface; nucleate boiling on the cooling surface; secondary nucleation between spray droplets and liquid film. Due to the diversity of the spray characteristic and the physical characteristics difference of spray liquid, such as spray density, Sauter Mean Diameter (SMD), droplets velocity and film thickness, the mechanism of spray cooling heat transfer appears very complex [4]. Because of the existence of these influencing parameters, various working fluids bring a noticeable difference in atomization performance (based on different physical properties and atomization characteristics) that affects the spray cooling characteristic. As one of the common investigated fluid, water spray cooling has a really good performance which has been validated by published research works. Zhang et al. [5], Anna et al. [6] and Wang et al. [7] studied the performance of water spray cooling in different experimental conditions. And results indicated that water could achieve superior heat flux because of the large latent heat. Nonetheless, the high boiling point of water leads to the high temperature of cooling surface. The same problem appeared in some Fluorinerts such as FC-72 [4]. Ammonia was investigated at different experimental conditions by Yang et al. [8] and Bostanci et al. [9]. It could obtain high CHF and low surface temperature in difference experiments conditions. The critical heat flux of ammonia spray cooling could reach 1100 W cm^{-2}. However, ammonia is a toxic, flammable and explosive substance that restricts its application in spray cooling region.

Recently, experiments on HCFCs and HFCs spray were carried out, such as the experimental studies on R600-a [10] and R22 [11]. The critical heat fluxes of R600-a and R22 were 50 W cm^{-2} and 276.1 W cm^{-2}, respectively. Moreover, its cooling target surface temperatures were below 303 K. Because of low boiling point and large latent heat, R134-a has superior performance in spray cooling. However, it lacked a comprehensive study. Hsieh et al. [12] compared spray cooling characteristics between R134-a and water. Tan et al. [13] explored cooling performance of R134-a in a multi-nozzle spray cooling system. The heat transfer coefficient reached 39 KW m^{-2} K^{-1} and the critical heat flux arrived to 145 W cm^{-2}. Meanwhile, the target surface temperature was 321 K. Souza and Barbosa [14,15] investigated the influences of enhanced surfaces on small flow rate spray cooling characteristics. The CHF reached 30 W cm^{-2} with 3.0 kg h^{-1} mass flow rate.

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Nomenclature

A	target surface area, m^2
c_p	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
CHF	critical heat flux, $W\,m^{-2}$
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_{fg}	enthalpy of vaporization, $J\,kg^{-1}$
$\dot{m}$	mass flow rate, $kg\,h^{-1}$
q	heat flux, $W\,m^{-2}$
T_1	temperature of the first thermocouple, K
T_{sat}	saturation temperature, K
T_{sub}	subcooling degree, K
T_w	cooling surface temperature, K

Greek symbols

ΔT	temperature difference between two thermocouples, K
ΔT_{sat}	Superheat degree, K
Δx	Distance between two thermocouples, m
Δx_{w-1}	distance between cooled surface and the first thermocouple, m
λ	copper thermal conductivity, $W\,m^{-1}\,K^{-1}$
η	spray efficiency

Martínez-Galván [16] studied the R134-a spray cooling performance with different roughness of cooling surface. And the experiment concentrated on the influence of film thickness at different nozzles and flow rates. They found that the Nusselt number is related to the total average film thickness.

In this paper, a closed loop spray cooling system was setup based on the previous experience [11]. The cooling characteristic of spray fluid R134-a was investigate. A circular copper plate with the upward surface which could be heated by an embedded and adjustable heating bar was configured as the cooling target. The experiments focused on the influence of volumetric flow rate on spray cooling characteristics. The boiling curves and heat transfer coefficient were discussed with different flow rate. The relationship between heat transfer coefficient and surface cooling temperature was observed and discussed. Moreover, the influence of flowrate on system efficiency was compared and analyzed.

2. Experimental study

2.1. Test rig

Fig. 1 shows the apparatus of spray cooling system. It includes of the R134-a refrigerant loop, the sub-cooling cycle and the data acquisition system.

The R134-a refrigerant loop consists of a compressor (KB134VFNC rotary compressor by Mitsubishi Electric Compressor CO., LTD), a reservoir, a water condenser I, a water evaporator and the spray chamber. In the test, the R134-a vapor is pressurized by the compressor firstly (11-1). Then it is condensed into liquid by cooling water in Condenser I (1-2). The second stream through the bypass (3-8-9) is used to change the system flow rate. The inlet temperature (point 6) of the first liquid R134-a stream is controlled to be a certain value by the sub-cooling system and an adjustable electric heater (3-4-5). After the volumetric flow meter (5-6), the refrigerant sprays onto the target surface. Then the two R134-a streams are vaporized as much as possible in the evaporator (9-10). The reservoir after the spray chamber is used to increase the system flow rate area. The wounded tube on the top of the compressor can superheat the R134-a vapor before it enters into the compressor. The sub-cooling system is a typical refrigeration cycle in which the waste heat can be removed by Condenser II.

The spray chamber is shown in Fig. 3. The spray chamber was used to observe the cooling performance with R22 in previous literature [11]. The detailed structure of the spray chamber could be found in article [11]. One improvement in R134-a spray cooling system was that the condition of spray could be photographed by a high speed camera system (seen from Fig. 2). In this experiment, the distance between nozzle and target surface was 13 mm. The target surface could be totally covered by the spray flied (the optimum distance is a necessary requirement for spray cooling to obtain ideal cooling performance [17]). A commercial full cone nozzle B1/4TT + TG-0.4 with the nozzle orifice diameter of 0.46 mm from Spraying Systems Co. was applied.

Fig. 4 shows the structure of the heating assembly. It included six cylindrical electric heaters, a copper thermal medium and the insulating layer. The height of the cooper cylinder and the top temperature measurement part were 98 mm and 28 mm, respectively. The diameter of the target surface was 16 mm. The Bakelite cover plate was fitted onto the copper heater target. To avoid the subsidence of the target surface caused by heat expansion and cold contraction, the target surface was designed to be 2 mm higher than the Bakelite cover. Meanwhile, silicone glue was used as sealing medium between the upper part of the copper cylinder and the Bakelite. The bottom part of the copper cylinder was supported by a Teflon block. The heating assembly was enclosed in rock wool (thermal conductivity is about 0.04 $W\,m^{-1}\,k^{-1}$) for thermal insulation. Six cartridge electric heaters (10 mm diameter) were imbedded in the bottom of the copper cylinder. Their heating conditions were adjusted by a DC voltage regulator ranges from 0 W to 900 W.

Six T-type thermocouples were embedded in the upper section of the copper cylinder to measure the temperatures. Thermocouple 1, 2 and 3 were positioned vertically in the center of the axial layer with a distance of 7 mm below the target surface (seen from Fig. 5). Thermocouples 4, 5 and 6 which were used to determine the thermal inhomogeneity were placed with an angle of 120 degree at the same axial layer corresponding to thermocouples 1, 2 and 3. Data acquisition system in the R134-a spray cooling system has been used in the previous R22 experiment which has a good performance. And the components of data acquisition could be found in previous publication [11].

The steps are described as below:

1) Clean the target surface and set the distance between nozzle and the target surface (13 mm). Start the data acquisition system and the electric heater (10 V DC).
2) Turn on the compressor when the target surface temperature reaches to the set point (293 K).
3) Make a required flow rate by Valve I and keep the pressure of spray chamber at 0.3 MPa by Valve II. Maintain inlet temperature through the sub-cooling system and the electric heater.
4) Continue to increase the heating power by 10 V (5 V when close to the CHF point) after a 30 min stable state of the target surface until reach to the CHF point.
5) Turn off the electric heater.
6) Turn off and recover the system for next experiment.