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An experimental comparison of heat transfer characteristic between R134-a and R22 in spray cooling

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ABSTRACT

Spray cooling is one of the promising technologies in heat removing for high power density equipment, especially for the equipment with high heat flux surface. R134-a is one of the most prospective alternative refrigerants of R22 due to the zero ODP, low GWP, non-toxicity and non-inflammability, it is necessary to do comparative study on the heat transfer characteristics of R22 and R134-a in spray cooling. In this article, two closed loop spray cooling test rigs with the same spray nozzle are established to investigate the thermal performance of R22 spray cooling and R134-a spray cooling. The main parameters such as critical heat flux (CHF), heat transfer coefficient and target surface temperature are compared in the same thermal condition. The CHF of R134-a spray is lower due to the lower latent heat. The heat transfer coefficient of R22 spray is higher than that of R134-a spray with the same spray chamber pressure. However, R134-a spray cooling could replace R22 spray cooling in the phase change heat transfer region when the heat flux is less than 80 W cm^{-2}.

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1. Introduction

As a high effective cooling technology, spray cooling has a promising application potential in thermal management in laser equipment, electric vehicles and advanced military avionics. Being combined with convection heat transfer, evaporation and other high efficiency heat exchange methods, such as nucleate boiling and second nucleate boiling, spray cooling can obtain high heat flux in a small surface [1,2]. Oliphant et al. studied the difference between jet cooling and spray cooling. They found that the spray cooling could achieve the same heat transfer coefficient with the lower heat flux in non-boiling regime [3].

Spray cooling performance could be influenced by some factors, such as the Sauter mean diameter (SMD), droplet velocity and flow rate. Estes et al. [4] investigated the impact of SMD and flow rate on spray cooling performance. The SMD highly depended on CHF and the boiling curves were different under different volumetric flux. Cheng et al. [5] focused on the effects of surfactant on the heat transfer enhancement. Water was used as the spray fluid, and the dissolving salt additive and high-alcohol surfactant were tested in the experiments. The results showed that both additives could improve the heat transfer coefficient. Visaria et al. [6] used FC-77 as spray fluid and studied the subcooling effect on heat transfer characteristics. The results showed that the increase of subcooling effect delayed the occurrence of boiling. Meanwhile, the slope of the nucleate boiling region decreased in the spray boiling curve. The CHF value was raised by 100% with the increasing subcooling degree from 22 °C to 70 °C. Vorster et al. [7] investigated the water spray field development. They found that the primary bubble growth was inhibited by the intense-vertical fluid motion. Meanwhile, the primary bubble coalescence began from the inner regions of the wetted domain to the quench front.

Due to the effect of thermo-physical properties, such as latent heat and saturation temperature, various spray fluids were characterized by different cooling performance. Lin et al. [8] compared the heat transfer behaviors with different spray fluids. In the experiments, water, FC-72, FC-87 and methanol were applied to cool down an upward surface. The CHF of FC-87, methanol and water were 90 W cm^{-2}, 490 W cm^{-2} and 500 W cm^{-2}, respectively. However, the temperature of cooling surface were all above 80 °C due to their high saturation temperature. In order to achieve lower cooling surface temperature, other spray fluids were used in spray cooling. Ammonia was used in a closed loop spray cooling system by Bostanci [9] and Yang [10]. In their experiments, the CHF achieved by ammonia spray reached 1000 W cm^{-2} which was far higher than that of water spray. Meanwhile, the cooling surface temperature was lower than 0 °C when the CHF was 451 W cm^{-2}. However, as a toxic, flammable and explosive working medium, the application of ammonia was limited.

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Nomenclatures

CHF	critical heat flux, W m^{-2}	Q	refrigerating capacity, W
c_p	specific heat capacity, J kg^{-1} K^{-1}		
h	heat transfer coefficient, W m^{-2} K^{-1}	*Greek symbols*	
h_{fg}	latent heat, kJ kg^{-1}	ΔT	temperature difference between two thermocouples, °C
H	spray height, mm	ΔT_{sat}	Superheat temperature, °C ($\triangle T_{sat} = T_w - T_{sat}$)
$\dot{m}$	mass flow rate, kg s^{-1}	Δx	distance between two thermocouples, m
N	input power, W	ΔP	pressure difference between nozzle, MPa
q	heat flux, W m^{-2}	ε	COP
T_{in}	liquid inlet temperature, °C	δ	uncertainty
T_{sat}	saturation temperature, °C	ρ_f	density of fluid, kg m^{-3}
T_w	cooling surface temperature, °C	ρ_g	density of gas, kg m^{-3}
P_c	spray chamber pressure, MPa		
Pin	spray pressure, MPa		

Recently, refrigerants spray cooling has been investigated by many researchers due to their large latent heat and low saturation temperature, which could achieve impressive cooling performance and lower cooling surface temperature. Si et al. [11] studied the R600a spray. The heat transfer coefficient could reach 30 kW cm^{-2} K^{-1}, and the cooling surface temperature was below 30 °C with a 50 W cm^{-2} heat flux. Zhou et al. [12] studied R-404a spray cooling designed for laser surgery. The experiments were focused on the droplets velocity and droplets diameter. The more efficient surface cooling was achieved with the larger droplet size and the higher spray speed. The performance of R22 spray cooling was investigated by Hou et al. [13]. The CHF of R22 spray reached 276.1 W cm^{-2} while the cooling surface temperature was lower than 30 °C. A number of advantages were found in R22 spray cooling, which indicated that the characteristics of R22 spray can meet the requirements of most electronic devices. However, R22 has some disadvantages such as depletion of the ozone layer and the greenhouse effect. It will be gradually replaced in the near future. As one of the alternative refrigerants, R134-a spray cooling was also investigated by Hou et al. [14]. The maximum CHF of 117.2 W cm^{-2} was achieved with 46 °C target surface temperature. However, a comprehensive comparison about the performance between R22 spray cooling and R134-a spray cooling in the same condition is necessary for the further understanding.

In the present study, performances of R134-a spray cooling and R22 spray cooling are respectively investigated in two closed loop systems. The heat transfer characteristics are compared with the same spray nozzle under the similar spray pressure and test chamber pressure. And the impacts of flow rate on CHF are also investigated carefully. The possibility of the replacement of R22 with R134-a is discussed. Although the heat transfer coefficient of R134-a spray cooling is smaller than that of the R22 spray cooling, R134-a is still expected to replace R22 within a low heat flux range.

2. Test system

Schematic diagrams and photos of the R22 and R134-a closed loop spray cooling systems are showed in Figs. 1 and 2, respectively. The two test systems are designed separately to adapt the different working conditions. The mainly differences between the two test systems are as follows.

1. Since the saturation pressure of R22 is larger than that of the R134-a, the discharge pressure of R22 system is larger than that of the R134-a system. The compressor in the R134-a system is an R134-a rotary compressor from Mitsubishi Electric Compressor CO., LTD (KB134VFNC), and the compressor in the R22 system is a R22 rotary compressor from Qingan Refrigeration Equipment CO., Ltd. (YZWF-F307). The details of the two compressors are listed in Table 1.
2. With same spray condition, the cooling capacity of R134-a spray cooling is smaller than that of the R22 spray cooling, the water condenser in R22 spray system is larger than that the water condenser (water condenser I) in the R134-a system. Furthermore, the lubrication oil and the desiccant for the two system are different too.
3. In the R22 spray cooling system, the inlet temperature of spray fluid is controlled by a flow bypass assembled in the main system. In the R134-a system, an independent sub-cooling system with the same refrigerant is used to remove the waste heat from the main system. With the independent sub-cooling system, the inlet temperature of the spray fluid can be controlled within ±0.3 °C, and the flow rate of refrigerant loop can be adjusted precisely.
4. In the R22 system, the flow rate is calculated according to pressure difference between the nozzle inlet and spray chamber. And a volumetric flow-meter is employed in the R134-a spray cooling system to measure the volumetric flow rate. The R134-a and R22 spray cooling systems own the same data acquisition system.

Fig. 3 shows the schematic drawing of the test chamber. The view windows installed on both sides of the chamber are used to observe the spray condition. A commercial full cone nozzle (B1/4TT+TG-0.4, from Spraying Systems Co.) with 0.46 mm diameter is used in both the two test systems. In order to achieve the best spray cooling performance, the target surface is totally covered by the spray field in the two systems. So, the distances of nozzle to target surface are set as 13 mm for R134-a spray cooling and 22 mm for R22 spray cooling. The heating element is composed of a copper heating element, six heating bars and the support element. As shown in Fig. 4(a), the Bakelite housing is used to prevent the heat conduction along the radial direction at the top section of the cooper element. Rock wool serves as the thermal insulation material to minimize the radial heat loss from the main body of the copper element. And a piece of Teflon is used to prevent the heat loss from the bottom of the copper element. Take into account the actual structure, the heat loss of the heat element are simulated via FLUENT software. The result in Fig. 4(b) shows that the total heat loss from the radial direction and the bottom is below 5.8 %, which indicates that the thermal insulation can meet the requirement. Therefore, axial heat conduction becomes the main heat transfer mode. Thus, the one dimension Fourier law is used to calculate q, T_w and h in Eqs. (1)–(3).

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