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Research Paper

Experimental investigation of aircraft spray cooling system with different heating surfaces and different additives

Yu Wang, Nianyong Zhou, Zhang Yang, Yanlong Jiang *

Institute of Air Conditioning and Refrigeration, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing 210016, PR China

HIGHLIGHTS

- An open loop spray cooling experimental setup with large heating surface and high heating capacity is established.
- Four different surfaces are applied in one experiment, considering the influence of both surface area and surface roughness.
- Two different solutions with different mass fraction are applied in one experiment.
- Suggestions on surface structure and additives are provided for aircraft spray cooling system.

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ABSTRACT

As an efficient cooling method for high heat flux, spray cooling has a great application potential on aircraft directed energy weapon cooling. Based on the analysis of previous research results, an experimental system of open loop spray cooling was established. Four different surfaces and two additives were applied and spray cooling performance including surface heat flux, surface temperature and heat transfer coefficient was experimentally investigated with water as the cooling medium. The experimental results indicate that among the four surfaces, drilling surface has the highest heat transfer coefficient and combined surface has the highest cooling efficiency. Meanwhile heat transfer can be enhanced by adding potassium chloride to a certain concentration and then deteriorated with higher concentration; heat transfer is deteriorated with the increase of ethylene glycol concentration. Therefore for aircraft spray cooling system combined surface should be applied for its advantages of low surface temperature and high cooling efficiency while ethylene glycol is preferred to improve the application range of the system in consideration of the corrosion of salt solution.

1. Introduction

Directed energy weapon as standard weapon for fighters of next generation has attracted more and more attention. Power in the magnitude of megawatt can be produced within several seconds after the launch of the directed energy weapon, which leads to high heat load and high heat flux of several hundreds and thousands of watts per square centimeter on weapon surface. When the weapon operates, large amount of exhaust heat will impair the output power and increase weapon heating capacity, increasing the risk of system damage. Therefore heating dissipation problem becomes a hidden trouble for the application of directed energy weapon. How to solve the problem of heat dissipation with high efficiency is of great importance.

In the spray cooling process cooling medium is atomized into countless droplets and then be sprayed to the heating surface to remove the exhaust heat. It has the advantages of small temperature difference, no boiling hysteresis, good heat transfer performance, uniform surface temperature and low requirements for cooling medium [1–3]. It has been widely utilized in many fields such as electronic equipment cooling, medical treatment, nuclear industry and steeling [4–8]. Therefore spray cooling owns an application potential in the field of aircraft directed energy weapon cooling.

Unlike other application fields, stealth performance and system adaptability under severe flight conditions should be considered in the application field of aircraft weapon cooling. To reduce the infrared radiation, heating surface temperature should be controlled as low as possible. Changing heating surface structure is an economical way to reduce surface temperature. The adaptability of the system is also of great importance. In standby condition

* Corresponding author.
E-mail address: jiang-yanlong@nuaa.edu.cn (Y. Jiang).

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Nomenclature

A	surface area (cm^2)
c	specific heat (J/(kg K))
D	equivalent diameter (cm)
G	volume flow rate (m^3/s)
H	fin height (m)
h	heat transfer coefficient (W/(cm^2 K))
P	inlet pressure (MPa)
Q	heating capacity (W)
q	heat flux (W/cm^2)
T	temperature (K)
u	velocity (m/s)
y	distance between thermocouples (mm)
Greek symbols	
η	heat transfer efficiency
θ	angle between nozzle and edge of heating surface (°)
λ	heat conductivity coefficient (W/(cm K))
μ	dynamic viscosity coefficient (mPa S)
ξ	heat transfer enhancement factor
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	time (s)
Subscripts	
0	cross section
b	fin base
c	rib end
e	the circumferential side
f	fin
p	pressure
w	heating surface
in	inlet
sat	saturation

in winter or severe flight condition, system may not operate normally using water as cooling medium when the cabin temperature is below 0 °C. The use of auxiliary heating system will consume extra energy and take a long time to warm up the system, which makes the spray cooling system not performable in an emergency situation. In contrast, adding different types of additives can reduce system freezing point in order to expand the system application range and improve the system reliability.

Spray cooling on different surface structures has been widely investigated with experimental methods [9–13]. Silk et al. [14] studied the effects of macro-structured surface to spray cooling performance applying PF-5060 as cooling medium, and discovered that straight fin surface has the best heat transfer performance, followed by the cubic pin fins and the pyramids. Xie et al. [15] investigated the influence of micro-, macro- and multiscale-structured surface to spray cooling performance, and indicated that the micro-structured flat surface had an heat transfer enhancement of 32%, which was 36% for the macro-structured surfaces, and 65% for multiscale-structured surfaces. Meanwhile, some efforts have been carried out to study the influence of surface roughness. Sehmbey et al. [16] found that the influence of roughness mainly depends on the thickness of liquid film. Heat flux of smooth surface is 40–50% higher than that of rough surface. Ortiz and Gonzalez [17,18] observed the opposite conclusion that under low flow rate CHF of rough surface is twice than that of smooth surface while under high flow rate the difference is small, but still the CHF of rough surface is higher.

Meanwhile the influence of additives to spray cooling performance has been studied by many scholars. Cui [19] investigated the influence of soluble salt and gas to spray cooling performance, and found that adding soluble salt (NaCl, Na_2SO_4, $MgSO_4$) to water would enhance the heat transfer performance of spray cooling in non-boiling condition and nucleate boiling condition. Kim [20] summarized the results of Cui [19] and considered that dissolved gases and solids could enhance the heat transfer performance of spray cooling system. When mass fraction is 1%, $NaHCO_3$ in cooling medium could be resolved to Na_2CO_3 and CO_2, which could promote the expansion and boiling of droplets. Lin and Ponapean [21] did a spray cooling experiment with water and methanol as the cooling medium, and found that the critical heat flux could reach 490–500 W/cm^2. Lin and Harris [22] combined different mass fraction of methyl alcohol with water to carry out an experiment and proposed that heat flux of mixed working medium was between the value of water and that of pure methyl alcohol. Cheng et al. [23] measured the surface tension of water adding 1-Octanol or 2-ethyl-hexanol with different concentrations, and the conclusion was that there was a heat transfer enhancement in spray cooling process due to Marangoni convection. Qiao and Chandra [24] used 100 ppm of sodium dodecyl sulfate solution as cooling medium and found that surface temperature can be reduced by using this additive. Jia and Qiu [25] carried out experiments on the same solution as Qiao and Chandra [24], and found that a lower superheat rate and a safety critical temperature could be achieved.

It can be concluded from above that changing heating surface structures and adding additives have direct influence on heat transfer performance of spray cooling. Although numerous research has been done on the influence of surface structures and additives to spray cooling, most of them were focusing on small heating surface and low heating capacity. Due to the complicated heat transfer mechanism, previous research results could not directly be expanded to spray cooling with large heating surface and high heating capacity.

In this paper an open-loop spray cooling system was established and water was selected as the cooling medium. The heat transfer characteristics of four typical surfaces and two typical additives were experimentally investigated.

2. Experiment

2.1. Experimental setup

Schematic diagram of the experimental system is shown in Fig. 1.

In the loop, water is pressurized by the nitrogen first. Then it flows to the outlet valve, which controls the close and open of the spray. After the outlet valve it flows into the flow control valve, the handbrake valve and the turbine flowmeter in sequence. The function of the turbine flowmeter is to obtain the mass flow rate. After the flowmeter water sprays onto the heating surface. A drain valve is set for eliminating the water from the spray chamber timely.

The structure of the spray chamber is shown in Fig. 2. It can be seen that the heating assembly consists of six cartridge heaters, a copper block and the insulating layer.

Physical map of the system is shown in Fig. 3.

The spray nozzle with the type name of 1/8GG-SS1 manufactured by SPRAY CO was selected. This type of nozzle is an atomization nozzle. Nozzle parameters are listed in Table 1.