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Experimental study on the thermal performance of loop heat pipe for the aircraft anti-icing system

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ABSTRACT

The objective of this research is to experimentally investigate the start-up and operating characteristics of the Double Compensation Chamber Loop Heat Pipe (DCCLHP) anti-icing system. The loop was made of stainless steel with nickel wick, and the working fluid was ethanol. Experiments were carried out with the heat loads from 10 W to 180 W. The angle of attack (AOA) is from −10° to 5°. It was found that: (1) in order to obtain a good anti-icing result, the DCCLHP anti-icing system should be turned on approximately ten minutes before the aircraft encountered cloud with super-cooled droplets; (2) temperature oscillations happened in the start-up process when the AOA is not 0°; (3) the positive AOA can increase the surface temperature, as a result of which the anti-icing effect could also be enhanced.

1. Introduction

The flight safety of aircraft can be seriously threatened if icing occurs at the leading edge of the wing or the engine lip when the aircraft encounters clouds containing super-cooled droplets. Therefore, an anti-icing/de-icing system is required to ensure the flight security. Currently, we primarily use engine bleed air [1–3] or place electro-thermal pads [4–6] in the aircraft skin. Both of the two methods need plenty of onboard energy. However, for some Unmanned Aerial Vehicles (UAVs), the size and weight of the vehicles are reduced due to the utilization requirements, which results in the deficiency of the onboard heat and electricity. Fortunately, there are several other systems, such as the airborne electronic equipment or the lubrication oil with high temperature, generating much heat and requiring cooling to maintain a proper working temperature. Based on the above facts, it is very urgent to look for a new method to use these heat for anti-icing/de-icing.

As the passive closed two-phase heat transfer devices, Loop Heat Pipes (LHPs) [7] utilize the vapor-liquid phase change of working fluid to transfer heat and the capillary force of fine-pored porous wick to circulate the working fluid with no extra power. Because of their characteristics, such as high heat transfer capability, long transfer distance, small temperature difference and flexibility in design and installation, they are now widely used in the thermal control applications of aircraft [8] and space [9,10]. Different from the ground environment [11,12], the adaptation of LHP into the UAVs' anti-icing system has some difficult design and operation problems to overcome: (1) During the flight, there are high vibration and acceleration in the UAVs, which makes it quite difficult for the LHP system to start working or maintain a stable operation; (2) The flight attitude of the UAVs are variable such as pitching and rolling, which will change the relative orientations between each component of the LHP system. Based on some researches [13–15], these changes may have different effects on the start-up situation and the operation characteristics of the LHP, which puts forward higher requirements to the reliability and the operation stability of the LHP; (3) Flight safety is a crucial problem in the aircraft, so for the working fluid, there are several strict requirements, for instance, chemical stability, advantageous transport properties and excellent infiltration with the wick. Furthermore, excellent sealing performance is also expected.

For aircraft anti-icing/de-icing applications, some researches have been made to prevent ice formation in the engine inlet. In 1995, Anderson and Chow [16] proposed a conceptual design, using LHP to extract heat from the air-oil cooler for anti-icing. In the study of Phillips et al. [17,18], a passive anti-icing system was designed in the engine cowl of Global Hawk UAV, where five LHPs were utilized and removed 3.8 kW of the waste heat from the hydraulic system during the icing conditions. In 2007, Gregori et al. [19] introduced the design approach of the LHP anti-icing system in detail and investigated the performances of different kinds of working fluids. They recommended that water and alcohols were the best choice after a comprehensive survey.

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There are limited but still some investigations on the operating characteristics of the LHP under varying acceleration conditions. Ku et al. [20,21] experimentally studied effects of the acceleration on the startup and operating temperature of an aluminum-ammonia LHP. Their results presented that the steady-state acceleration forces significantly influenced the liquid vapor distributions in the LHP and temperature oscillation. Yerkes et al. [22] also focused on the acceleration's influence, where the experiment was conducted in a sine-waved acceleration field.

To ensure the sufficient supply of the working fluid from the CC to the wick in the evaporator under the variable flight attitude, the Dual Compensation Chamber Loop Heat Pipe (DCCLHP), which have two CCs on both ends of the evaporator, is manufactured and investigated. The work of Lin et al. [23,24] performed a fundamental study of the influence of the relative orientations on a DCCLHP through partial visualization of the flow phenomenon inside its CCs and the condenser. They found that the relative orientation affected initial vapor-liquid distribution inside the loop and subsequently the start-up performance of the DCCLHP. The experimental results can help solve the installation and the maintenance problems in the variable aeronautic environment. Furthermore, Xie et al. [25] focused on the effect of acceleration on the operating characteristics of a DCCLHP. Their results demonstrated that the acceleration force changed the vapor-liquid distribution and then resulted in some specific operating characteristics such as the sensitivity to the direction of the acceleration at small heat load and insensitivity at large heat load.

Up to now, most of the experimental studies on the LHP anti-icing systems mainly focus on the engine inlet. Very few investigations about the wing's LHP anti-icing systems have been reported, due to which forms the main objective of the present research. Based on the planning arrangements, the whole investigation is separated into two parts: Part 1 mainly focuses on the start-up and the operating characteristics of the designed DCCLHP in the dry air environment; Part 2 focuses on the anti-icing effect of the DCCLHP system in the wet air and cold environment. There are flight conditions (flight velocity, AOA, flight altitude) and meteorological conditions (environment temperature, Liquid Water Content, droplet diameter) which could affect the anti-icing results. As a result, a wind tunnel was employed to simulate the flight and the meteorological conditions on the ground. This paper introduces the detailed experimental process and results in Part 1. Considering the characteristics of the aeronautic flight, double CCs are employed with part visualization to study the effects of the flight attitude on the operation performance of the DCCLHP and the anti-icing results. Steel-ethanol combination and the nickel wick are chosen for the present investigation.

2. Experimental model

An experimental prototype of the DCCLHP anti-icing system as shown in Fig. 1 was constructed to carry out the present investigation. For the vapor line, liquid line and the condenser tube, the color represents the temperature – red[1] is high and blue is low (similarly hereinafter). Fig. 2 shows the inner structure of the evaporator and the CCs. The evaporator, condenser and liquid/vapor line were made of steel and the wick was made of nickel. In order to be distinguished, the compensation chamber with the bayonet is called CC1 and the other one is called CC2. Table 1 presents the geometric parameters of the tested DCCLHP, where OD and ID represent the outer and inner diameters respectively. The airfoil is NACA 0012. The model blocking in the test section of the wind tunnel is taken as 15%, due to which the chord length of the wing is calculated to be 375 mm.

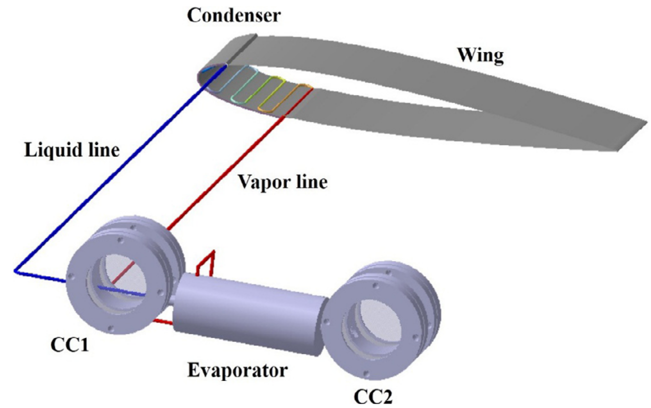

Fig. 1. Schematic of the DCCLHP anti-icing system.

3. Experimental set-up and experimental procedures

3.1. Experimental set-up

The schematic of the test system is shown in Fig. 3. The experimental apparatus includes heating system, wind tunnel, data acquisition system and the DCCLHP. In the heating system, the heat load is provided by a thin film heater, which is attached directly on the evaporator casing symmetrically, and adjusted by altering the AC power output voltage imposed on the heater. In the data acquisition system, the temperature of the wing surface is measured using T-type thermocouples. Agilent 34972A is utilized to monitor and record the temperature at a time interval of every 20 s.

The experiments are conducted in BH-505 wind tunnel, which can simulate the flight and meteorological conditions such as the ambient temperature and the air speed. The schematic view of the BH-505 wind tunnel is shown in Fig. 4. The test section is $0.5 \times 0.4 \times 0.3$ m.

In order to minimize the heat loses to the ambient, the adiabatic sponge and thermal insulation coating are used for the thermal insulation of the transport lines. The inner layer is thermal insulation nano coating, which is made from ceramic ball and the poly acrylic water-based chemical, with the thermal conductivity 0.0012 W/(m·K). The outer layer is the heat insulation ceramic fiber paper.

In order to raise the accuracy of the experiment, it is important to maintain the wind field stable around the wing. Due to the uneven flow field near the tunnel wall, only the middle part of the wing is utilized, where the condenser tubing of the LHP is located, as shown in Fig. 5. For the condenser, to make sure all the heat of the vapor working fluid can be transferred to the aircraft skin, the insulation of the tubing must be made to reduce the heat transfer between the vapor and the air inside the wing. Layer 1 is thermal insulation nano coating, which is made from ceramic ball and the poly acrylic water-based chemical, with the thermal conductivity 0.0012 W/(m·K). Layer 2 is rubber with the thickness of 3 mm. There is also thermal silica gel filled between the aircraft skin and Layer 2 in order to decrease the contact thermal resistance and increase the thermal conduction. In the middle of the aircraft skin, seven T-type thermocouples are set along the chord direction to record the surface temperature. Point 6 is the stagnation point. The distance between each thermocouple is 20 mm along the chord direction on the surface.

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.