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Research paper

Passive aircraft cooling systems for variable thermal conditions

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HIGHLIGHTS

- The novel cooling system can handle a variety of thermal conditions as presented by aircraft operations.
- Refrigeration by the fuselage can reduce the air conditioning requirements.
- Cooling system malfunction is not observed when water inside the fuselage condenser is frozen.
- The evaporator temperatures can be as low as 41 °C for 1 kW of input power during flight.
- On ground the air conditioning condenser external area should be optimized with fins.

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ABSTRACT

A novel design for a heat exchanger system [1], for which a patent application has been filed, was experimentally evaluated in the laboratory under variable thermal conditions characteristic of an aircraft in operation. The passive heat exchanger prototype consists of a loop-thermosyphon with two condensers and a common evaporator. Water was applied as the working fluid. Natural convection, forced convection and a combination of forced and natural convection at each condenser were replicated. The fuselage condenser performance was tested at temperatures ranging from −30 to 50 °C with heat transfer coefficients ranging from natural convection to values of around 200 W/(m^2 K). Air supply to the air conditioning condenser was kept at 20 °C with coefficients ranging from natural convection to around 50 W/(m^2 K). Input power up to 900 W was provided to the evaporator section by an embedded electrical resistance. Cooling system malfunction is not observed when the water within the fuselage heat sink is frozen, for input power below 300 W. Under cruise flight conditions, the cooling system is able to dissipate 900 W maintaining vapor temperatures at around 41 °C. The evaporator temperature increases by approximately 0.014 °C/W when start-up occurs. Refrigeration on the ground requires air duct speeds of around 6.1 m/s to keep the vapor temperatures below 100 °C for an input power of ca. 1 kW. When forced convection acts in both condensers, the heat removal capacity of the fuselage heat sink is dominant (around 90%).

1. Introduction

The demand for cooling power in the aeronautical industry has gradually increased due to advances in the use of on-board electro-electronic equipment. This demand is evident in the case of aircraft which are dependent on electrically powered on-board systems, implemented to replace conventional pneumatic and/or hydraulic powered systems; e.g. electric flight control actuators, cabin compressors for environmental control systems and electric heaters to deal with the formation of ice [2–4]. Consequently, the electrical power needed to assist electrically powered systems and electronics (motor controllers, power converters etc.) has risen considerably thereby requiring the dissipation of more heat. Size and weight are significant penalties for aircraft components and, as they increase, the power dissipation density also tends to increase [5–7]. Therefore, in order to install on-board electronics with high heat dissipation, it is necessary to implement more efficient techniques to remove heat from such devices [8–11].

Aircraft cooling systems traditionally use air for heat dissipation. In natural convection there is inherently high thermal resistance

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between heat sources and sinks. Forced convection in air by fans reduces the inefficiency of air cooling systems, increasing the heat transfer coefficients. However, this approach has some drawbacks such as acoustic noise generation, electrical power consumption, weight addition and periodic maintenance requirements. Passive thermosyphons and heat pipes are technologies considered for heat dissipation in aircraft applications, as they are classified as heat superconductor devices. With design constraints, these devices present low thermal resistance and no acoustic noise generation. In addition, electric power consumption is not required as they operate through a two-phase flow mechanism and maintenance is expected to be considerably lower compared to cooling systems based on forced convection in air.

In this paper, a loop thermosyphon with one heat source and two heat sinks for aircraft applications has been tested. The working principle of the two-phase heat exchanger is as follows. The loop thermosyphon is positioned between one heat source (represented by an electrical resistance) and two heat sinks, namely aircraft cabin-external air and aircraft cabin-internal air (e.g., the air inside a pressurized environment such as the internal cabin air, cockpit air, air directed to exhaust valves, fresh air from the environmental control system etc.). In the setup described herein, the internal air environment is represented by the air flux inside the air conditioning ducts. The cooling system receives heat from a heat source (electrical resistance; representing a refrigeration system evaporator, for instance) while heat is transferred to the heat sinks by two condensers. Although other arrangements are possible [1], the evaporator is linked to each condenser by two parallel loop-thermosyphon arrangements. Water was used as the working fluid since other fluid refrigerants would represent a hazard, in case of leakage. A crucial point in this research was to evaluate the behavior of water as a working fluid exposed to subzero temperatures. The cooling system must handle the characteristic diversity of thermal conditions presented by aircraft operations.

2. Cooling system requirements

In this study, the heat exchanger consisting of a loop thermosyphon with two condensers and a common evaporator is evaluated. The system was tested under different thermal conditions, which correspond to an aircraft in operation, including exposure to subzero temperatures.

The heat sinks are comprised of aircraft cabin-external air and aircraft cabin-internal air. Under cruise flight conditions the unpressurized external air can achieve temperatures of around −60 °C. Zhang et al. [12] reported external convective heat transfer coefficients of 332.47 W/(m^2 K) in flight. On the ground, however, natural convection takes place and temperatures vary according to the season and location. In this case, the heat transfer coefficients for natural convection are dependent on the inclination angle, surface dimensions, fluid, temperature and atmosphere pressure [13,14]. Typical values for air natural convection vary roughly from 1 to 5 W/(m^2 K).

The cabin-internal air is here represented by the air flux inside the air conditioning ducts. Temperatures around 20 °C are usual due to human comfort requirements. Air speeds can be as high as 20 m/s to satisfy internal cooling needs, and can be zero if the cabin refrigeration is switched off. In this case, natural convection will occur if a loop thermosyphon condenser is positioned inside the duct.

A multitude of thermal conditions can take place for a cooling system with condensers exposed to the aircraft cabin-external air and to the aircraft cabin-internal air. Therefore, natural convection, forced convection and a combination of forced and natural convection at each condenser may occur at different temperatures, and the proposed cooling system should be able to cope with these variations.

2.1. Working fluid properties

The heat transfer capacity of a thermosyphon is dependent on the working fluid applied. A measure of the influence of the working-fluid properties on the temperature drop for a given rate of heat transfer is provided by a figure of merit, ϕ, defined in Ref. [15] as:

$$\phi = \left(\frac{L\lambda_l^3\rho_l^2}{\mu_l}\right)^{1/4} \quad (1)$$

where L stands for the specific latent heat of vaporization, λ is the thermal conductivity, ρ the mass density and μ the dynamic viscosity. The subscript l denotes the value for the saturated liquid. Clearly, ϕ should be maximized to obtain the best performance. Values of ϕ for a series of fluid refrigerants commonly applied in loop thermosyphons are given in Fig. 1.

It should be noted that the wide temperature range covers all possible values for the air stream outside the aircraft in flight or on the ground. Temperatures as high as 300 °C are useful to simulate heat sources inside the aircraft which require cooling. It can be observed in Fig. 1 that water provided the highest mean ϕ value for temperatures above 0 °C, whereas ammonia gave the highest values for subzero temperatures.

While the ϕ value is a useful guide, it is not the only criterion for the selection of the working fluid. Other factors such as vapor pressure and the compatibility of materials (including fluid stability) are also important considerations [16,17].

Non-toxic and fireproof working fluids inside cooling systems are desirable for aircraft applications. The design of an evacuation system could be necessary depending on the aircraft certification requirements and the fluid used. Therefore, the use of fluids such as ammonia, methanol, acetone, ethanol, toluene, R134a and R22 are discouraged. Water offers the greatest potential for application as a fluid (highest figure of merit, non-toxic, fireproof and low cost). However, subzero temperatures can freeze the fluid within the closed thermosyphon. Nevertheless, despite the freezing issue, water was selected as the working fluid in this study.

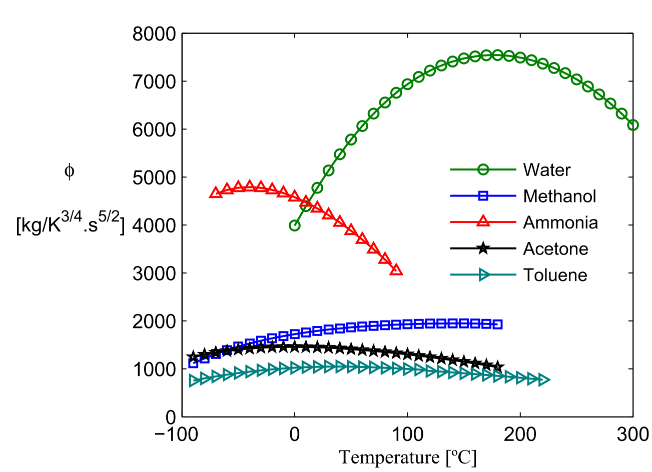

Fig. 1. Figure of merit for two-phase closed thermosyphons. Water, ammonia, methanol, acetone and toluene are evaluated from −100 to 300 °C.