Experimental Thermal and Fluid Science 82 (2017) 402–413

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Passive cooling concept for onboard heat sources in aircrafts

C. Tecchio [a], K.V. Paiva [a], J.L.G. Oliveira [a,*], M.B.H. Mantelli [a], R. Gandolfi [b], L.G.S. Ribeiro [b]

[a] Mechanical Engineering Department, Lepten/Labtucal, Federal University of Santa Catarina, Florianópolis, SC 88040-900, Brazil
[b] Embraer S.A., São José dos Campos, SP 12227-901, Brazil

ARTICLE INFO

Article history:
Received 7 June 2016
Received in revised form 28 November 2016
Accepted 29 November 2016
Available online 30 November 2016

Keywords:
Aircraft
Cooling system
Heat exchanger system
Heat pipe
Thermosyphons
Couplings

ABSTRACT

A passive cooling system based on heat pipe technology was tested in-flight in an Embraer test aircraft. Avionics thermal behavior was simulated by employing electrical resistances with input power ranging from 40 to 850 W. Heat is transported from the resistances to the evaporator of a recently patented heat exchanger system (HES) by intermediary heat transfer elements (IHTEs), consisting of one heat pipe and four thermosyphons. The HES consists of loop-thermosyphons with a shared evaporator connected to two parallel condensers, one at the fuselage and another within the air-conditioning system. The couplings between HES evaporator and IHTE condensers were designed to assure practical fitting and low contact resistance. Experiments were conducted with Mach numbers of 0.55 up to 0.78 at altitudes of 4.5, 9.1 and 10.6 km, corresponding to air static temperatures of 0, −30 and −43 °C, respectively. IHTEs and HES behaviors were also investigated during roller coaster and G-load turn maneuvers. Heat sink changes surrounding the HES condensers owing to different altitudes hardly affect IHTEs. Heat pipe and thermosyphons with 0.7 m length can dissipate 120 W and 500 W, respectively. Convection can be an alternative where heat conduction between avionics and IHTE evaporators is not possible. Two thermosyphons with evaporator fins dissipated 586 W with the air temperature within the convective system of about 80 °C. Aircraft maneuvers do not affect the thermal behavior of heat pipe technologies. Efficient thermal control of avionics is at hand.

1. Introduction

Heat pipes and thermosyphons are high efficient heat transfer passive devices used in a wide range of engineering applications such as heat exchangers, cooling of electronics components and solar energy systems. In aeronautics, the demand for effective cooling systems has been triggered by the advances in electro-electronics systems [1–6]. This scenario is more evident in recent full fly-by-wire aircrafts, where the heat dissipation requirement has increased considerably [7–9].

Forced convection is the heat transfer mechanism largely used in the aeronautical industry for electronic devices cooling. Commonly, in order to maintain the equipment inside tolerable temperatures as specified from its manufacturer, air flow is provided by fans to remove heat from the electronics. This approach is energetically inefficient since energy is required to assist electrically the fans and some drawbacks are present, such as acoustic noise generation and periodical maintenance requirement [10,11].

Passive cooling systems based on heat pipe technology can otherwise be applied for aeronautical and aerospace purposes. These systems use a phase change heat transfer mechanism which allows passive heat transfer from a heat source to a heat sink with low overall thermal resistance, providing better thermal characteristics than active and semi-active systems [12]. They offer several benefits as cooling systems such as: zero electric power consumption, heat transfer for relatively long distances with low temperature differences, low noise generation, no moving parts, high layout flexibility and low maintenance requirements. On the other hand, the physical phenomena related to evaporation, condensation and two-phase flow that occur within these devices impose several restrictions to their correct operation. In order to ensure that the heat transfer requisites will be fulfilled and typical operating limits such as dry-out, flooding and boiling will be prevented the heat pipe design usually requires experimental, analytical or numerical investigations.

Several types of heat pipes and thermosyphons (wickless gravity-assisted heat pipes) have been proposed as cooling systems. Some important advances to electronic cooling by using heat pipe technology are summarized as follows. Sarno et al. [5] devel-

* Corresponding author.
E-mail addresses: cassianotecchio1005@gmail.com (C. Tecchio), kleber.paiva@ufsc.br (K.V. Paiva), jorge.goes@ufsc.br (J.L.G. Oliveira), marcia.mantelli@ufsc.br (M.B.H. Mantelli), ricardo.gandolfi@embraer.com.br (R. Gandolfi), lribeiro@embraer.com.br (L.G.S. Ribeiro).

http://dx.doi.org/10.1016/j.expthermflusci.2016.11.038
0894-1777/

Nomenclature

A	area (m^2)
AC	air conditioning system
Bi	Biot number
c_p	specific heat at constant pressure (J/(kg K))
d	diameter (m)
d_w	wire diameter (m)
d_{evap}	evaporator inner diameter (m)
CTS	conical thermosyphon
FR	filling ratio (%)
FTI	flight test instrumentation
FTS	finned thermosyphon
FUS	fuselage
h	convective heat transfer coefficient (W/(m^2 K))
HES	heat exchanger system
HP	heat pipe
H_{sl}	altitude above sea level
IHTE	intermediary heat transfer elements
k_s	solid thermal conductivity (W/(m K))
l	characteristic length (m)
l_{evap}	evaporator length (m)
L	lift (N)
LP	loop thermosyphon
m	mass (kg)
M_∞	Mach number
N_z	vertical load factor
N	Mesh number ($in.^{-1}$)
Q	energy (J)
q	input power (W)
R_h	convective thermal resistance (°C/W)
R_{HP}	heat pipe thermal resistance (°C/W)
R_k	conductive thermal resistance (°C/W)
RTD	Resistance Temperature Detector
S	crimping factor
t	time (s)
T	temperature (°C)
T_∞	air static external temperature (°C)
T_{air}	convective system air temperature (°C)
T_{alum}	aluminum blocks temperature (°C)
T_{AC1}	air conditioning inlet temperature (°C)
T_{AC2}	air conditioning outlet temperature (°C)
TS	thermosyphon
v	velocity (m/s)
V	volume (m^3)
V_{evap}	evaporator volume (m^3)
V^*_{evap}	effective evaporator volume (m^3)
V_w	working fluid volume (m^3)
V_{ws}	wick structure volume (m^3)
V_t	wick structure volume as a continuum medium (m^3)
W	weight (N)
ε	porosity (%)

oped an alternative passive cooling system based on heat pipes and loop thermosyphons adequately integrated inside the structure of aircraft passenger seats. They used the seat frame as a heat sink. This arrangement allowed heat transfer rates of 10–100 W from in-flight entertainment systems to the heat sink. Lu and Wei [13] investigated the conditions for proper start-up of a novel loop heat pipe with a flat rectangular evaporator. The cooling device showed overall thermal resistances lower than those typically observed in conventional loop heat pipes. Mitomi and Nagano [14] developed loop heat pipes with the aim of transporting heat at long distances. Heat loads up to 160 W were transferred for distances of about 10 m. Nishikawara and Nagano [15] investigated the effects of working fluid properties on the performance of a miniature loop heat pipe with polytetrafluoroethylene as wick structure. Wang [16] researched heat pipes for cooling electronic systems. The thermal performance of a heat exchange system consisting of six L-type heat pipes was evaluated. Heat transfer rate of about 160 W was dissipated with an overall thermal resistance of 0.22 °C/W. More recently, numerical and experimental tests were investigated by Dang et al. [17] in order to evaluate the thermal performance of a modified rack for cooling CPUs with a plate pulsating heat pipe.

Chang et al. [18] evaluated the influence of the evaporation and condensation resistances in a water filled thermosyphon for the cooling of electronic equipment. The investigations were carried out with different evaporation surfaces, amount of working fluid in the evaporator casing and input power. They reported the occurrence of flooding with low filling ratios and high input power. Agostini et al. [19] evaluated the thermal performance of a setup consisting of two loop thermosyphons connected in series for the cooling of electric components. A mechanical fitting assured heat transfer from the condenser of the first loop to the evaporator of the second loop. The prototype removed about 1 kW with a mean operation temperature of 110 °C. An analytical model of a loop thermosyphon for cooling air inside a telecommunication cabinet was proposed by Chehade et al. [12]. Thermal and hydraulic characteristics of two-phase flows were taken into account in the mathematical model. Zuo and Gunnerson [20] studied the performance of a closed thermosyphon and compared their numerical results with experimental data. The study was carried out in a wide range of working fluid inventory and by varying the condenser thermal capacity. Jiang et al. [21] and Shabgard et al. [22] developed numerical models to simulate the operation of closed-thermosyphons with various filling ratios. In order to prevent the breakdown of the condensate film, the latter stated that the working fluid should occupy over 10% of the evaporator volume to assure stable steady-state operation.

In this paper, prototypes of a passive cooling system concept to manage heat sources have been tested in an aircraft. The setup consists of a heat exchanger system (HES) dissipating heat from mimicked avionics via intermediate heat transfer elements (IHTEs). Heat sources allow power dissipation ranging from 40 to 850 W. A heat pipe (HP) and four thermosyphons work as IHTEs. Two parallel condensers and a shared evaporator compose the HES system; see Fig. 1. One HES condenser was installed at the airplane fuselage, FUS, and another, in an air conditioning system duct, AC.

Water is applied as the working fluid in both HES and IHTEs, owing to its high figure of merit and compatibility with copper [23,24]. Besides, water is non-toxic and non-flammable, which are essential refrigerant properties for aerospace applications.

This work aims at:

- Verifying the thermal performance of the present passive cooling concept (HES and IHTEs) during a flight test in cruise conditions. Heat transfer from the heat sources to the evaporator of the IHTEs is tested by heat conduction and by forced convection. Although heat transfer by conduction is preferably because heat leakage is easily avoided and contact thermal resistance can be lowered, heat transfer via forced convection is also tested.