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Active and passive cooling technologies for thermal management of avionics in helicopters: Loop heat pipes and mini-Vapor Cycle System

Claudio Zilio[a,*], Giulia Righetti[a], Simone Mancin[a], Romain Hodot[b], Claude Sarno[b], Vincent Pomme[c], Bertrand Truffart[c]

[a] *University of Padova, Department of Management and Engineering, Vicenza, Italy*
[b] *Thales Avionics, Navigation Packaging, Valence Cedex, France*
[c] *Airbus Helicopter, ECS & Thermal Departments, Marignane, France*

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ABSTRACT

This paper presents the development of a new electronic cooling concept especially conceived for helicopter avionics thermal management in the framework of 7 th FP EU project TOICA (Thermal Overall Integrated Conception of Aircraft, www.toica-fp7.eu). A prototype was developed and tested. It consists of a hybrid active-passive cooling system that combines a compact loop heat pipe (LHP) specifically designed for the hot spot treatment at blade level and an air cooled mini-Vapor Cycle System (mini-VCS), which is devoted to the overall heat rejection. This paper presents in details the design and the experimental assessment of each of the main components of the innovative cooling system at different operating test conditions. The tests explore the behavior of the LHP and of the integrated system at different hot spot heat loads, from 10 W to 50 W and heat sink temperatures. The results allow full exploitation of the potential of the proposed technology in a typical airborne scenario.

1. Introduction

As the number of electrical and electronics systems increases, their physical sizes decrease, and the spacing between electrical components decreases, both the total amount of heat generated (hence to be dissipated) and the power density (the heat generated per unit volume) increase significantly. There is a general agreement in the scientific community that current air-cooling technologies are asymptotically approaching their limits imposed by available cooling area, available air flow rate, fan power, and noise [1–3].

This scenario is even more critical in the new full fly-by-wire generation of more electric aircrafts and helicopters, where the heat dissipation loads are constantly increasing, pushing the air cooling scheme towards its intrinsic limitations [4–7]. However, air forced convection still represents the standard heat transfer mechanism used in the aeronautical industry for electronic devices cooling because it is considered by the aircraft manufacturers the most robust and reliable by virtue of its long history. In these systems, in order to maintain the equipment below the maximum temperature requested by manufacturer's specifications, air flow is supplied by fans to actively remove the heat from the electronics [8].

In any case, the thermal management architecture of aeronautical electronic packaging needs to be significantly stretched to meet these challenges [9,10]. Furthermore, when considering the aeronautical applications, the reliability, compactness, and lightness of the cooling systems represent essential and mandatory characteristics. With the continuous miniaturization of the components, passive and active two-phase cooling devices can now be considered as interesting options to be integrated in electronics systems while maintaining the fundamental compactness and lightness of the whole system.

Many types of passive devices, e.g. heat pipes, loop heat pipes, thermosyphons have been proposed as cooling systems for different civil and industrial applications [11–16]. 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 characteristic than active systems. They present several benefits: zero energy consumption, no moving parts, heat transfer for relatively long distances with low temperature difference, high layout flexibility and low maintenance requirements. On the other hand, the involved two-phase heat transfer phenomena (i.e. boiling, condensation, and two-phase flow) need to be carefully handled in order to design reliable heat pipe, vapor chambers or loop heat pipe devices.

Recently, Reyes et al. [17] proposed an experimental and

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[*] Corresponding author at: Dept. Of Management and Engineering, University of Padova, Str.lla S. Nicola 3, 36100 Vicenza, Italy.
E-mail address: claudio.zilio@unipd.it (C. Zilio).

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Nomenclature

IMA	Integrated Modular Avionics
LHP	loop heat pipe
LRU	line replacement unit
OAT	Outside Air Temperature (°C)
R	thermal resistance (°C/W)
RH	relative humidity (%)
T	temperature (°C)
VCS	Vapor Cycle System

Subscript

Heart	heart
Int	interface
LHP	loop heat pipe
Tot	total
w,i	Water inlet

theoretical/numerical study of a vapor chamber-based heat spreader intended for avionics applications. The tests were run in a mock-up of avionics box using air as cooling medium. The authors found that, from the thermal dissipation standpoint, the heat spreader was more efficient as compared to equivalent metallic fin plates, which, on the other hand, were lighter.

Sarno et al. [4] designed and experimentally characterized a passive cooling system based on heat pipe and loop thermosyphon to manage the thermal load generated by the in-flight entertainment system. The developed cooling apparatus used the seat as cold heat sink to transfer the heat coming from the electronic device.

More recently, Tecchio et al. [8] tested a passive cooling system based on heat pipe technology in in-flight conditions on an Embraer aircraft. The heat was removed by a heat pipe and 4 thermosiphons and then transferred to two parallel condensers, one at the fuselage and another within the air conditioning system. The authors found that the system was able to dissipate the rated input power and that the aircraft maneuvers did not affect the thermal behavior of developed cooling systems.

Active cooling systems implementing vapor refrigeration cycles have also attracted the attention of researchers and manufacturer because, as suggested by Phelan et al. [18] and by Barbosa et al. [19], they present many interesting potential advantages: ability to dissipate heat while maintaining a low junction temperature; increase in device speed thanks to the reduced operating temperature; increase in device reliability and lifetime because of the reduced operating temperature; increase in device reliability and lifetime as a benefit of the constant operating temperature.

On the other hand, the potential disadvantages of refrigeration cooling are considered the following: possible increase in complexity and cost; possible decrease in system reliability.

Phelan et al. [18] compared several active cooling technologies, among them: thermoelectric both single and multi-stage, vapor compression, Stirling, pulse tube, sorption and reverse Brayton. The authors [18] stated that the vapor compression system exhibits the highest value of cooling capacity and the achievable sizes of the system agrees with the volume constrains of electronics devices. They concluded that vapor compression system technology represents the most promising solution for electronics thermal management.

Regarding the application of active refrigeration system to aeronautical applications, Godecker et al. [20] described a thermal control system for navigation and targeting pods that utilized a R114 vapor compression system to provide the needed cooling. The system was designed to dissipate 2.6 kW of heat during flight and 2.0 kW while on the ground.

Another application of a Vapor Cycle System to avionic electronics thermal management has been suggested by Scaringe [21], who proposed a compact thermal control system for aircraft avionics POD cooling. Scaringe [21] proposed an optimised configuration of a heat pump which cooled several different components. As highlighted by the author, certain electronics must be cooled to maintain an operating temperature near the ambient whereas other components such as antenna that needs to be cooled yet they can operate at much higher temperatures. Accordingly, the system proposed by Scaringe [21] provided cooling below the heat rejection temperature for temperature sensitive components and cooling above the heat rejection temperature for the remaining components that tolerate a much higher temperature.

More recently, Mancin et al. [22] presented an experimental analysis of the performance of a small-scale refrigeration system with the aim of investigating the suitability of miniature refrigeration systems for electronic thermal management of aeronautical packaging. Particular attention was devoted to the cold plate design, which had to comply with aeronautical volume constraints. The mini-Vapor Cycle System implemented a new concept oil-free linear DC compressor prototype with variable piston stroke. The application of this system to aeronautical packaging was then evaluated within the EU funded research project PRIMAE [10].

From this brief overview, it clearly appears that both active and passive two-phase cooling schemes are worth of interest in aeronautical applications because they present many potential capabilities to cope with the challenging heat transfer requirements of the new avionics electronics components.

Both active and passive two-phase cooling systems require a heat sink to reject the heat load extracted from the hot spots; unfortunately, this is not always easily reachable or in some cases even present. This implies that a local hot spot treatment by means of a passive system may require the use of intrinsically complex architectures; for instance, this is the case of uncontrolled avionics bays where the many racks are piled and where both temperature and pressure are not controlled.

This paper aims at demonstrating that, by means of a proper combination of passive and active cooling techniques, it is possible to overcome the issues related to the particular layout onboard of helicopters and aircrafts. This paper presents the development and experimental assessment of an innovative cooling system based on passive and active two-phase technologies: a loop heat pipe is used to cool down a hot spot on an Integrated Modular Avionics (IMA), and then the heat is rejected to the cold heat sink through a mini VCS. This solution has the intrinsic advantage to disconnect the heat load and the available heat sink, which can be physically located in a different aircraft partition.

In Section 2 the major features of the integrated mini-loop heat pipe/miniature Vapor Cycle System are reported together with Integrated Modular Avionics characteristics and relevant thermal constraints.

In Section 3 the experimental tests carried out on the loop heat pipe alone, then on the Vapor Cycle System alone and finally on the integrated hybrid system are reported and analyzed with reference to the main affecting parameters in order to exploit the viability of the proposed architecture in aeronautical applications.

2. Modular avionics cooling demonstrator

2.1. Integrated Modular Avionics (IMA) system

Integrated Modular Avionics (IMA) represents a real-time airborne computer network system. This network consists of a number of computing modules capable of supporting numerous applications of different criticality levels.