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Thermal management & advanced cooling technologies of power electronics converters for hybrid aircraft applications

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Abstract

Nowadays, aircraft constructors are working on innovative solutions to minimize fuel consumption. In this context, power electronics components, supplying eMotors, should be cooled as efficiently as possible. A study of high efficiency cooling systems is proposed in this work. The purpose is to find the most performing and efficient cooling solution to allow power electronic converters to operate with the highest performances possible for a hybrid propulsion aircraft. After a study focused on the most suitable solutions, this work aims to compare and highlight limits and potentialities of different cooling systems adapted for this particular application field. A focus is made on a specific passive capillary pumped system because of its performances and energetic efficiency: the Capillary Pumped Loop for Integrated Power (CPLIP). Previous numerical and experimental results show the performances of this loop, able to ensure the temperature requirements for power modules: the temperature map of power converter modules meets the specifications. Other than the capability to ensure the temperature controllability, it will be shown how this loop is able to go beyond the required power-to-mass ratio to allow these systems to fly.

Introduction

The subject of the present research is part of the European project Cleansky2. It is managed by HASTECS consortium (Hybrid Aircraft Academic reSearch on Thermal and Electrical Components and Systems). The most part of aircraft constructors are working to find innovative solutions to minimize fuel consumption. In this context, power electronics and power electronics cooling design have to be considered for optimizing highly integrated power electronics and their associated high-efficiency cooling system to be used for the hybrid propulsion aircraft of 2035. The increasing power and the miniaturization of electronic components make the classical cooling solutions inadequate to evacuate the thermal load generated by chips: different technologies have been continuously compared and studied to find the most performing ones, as reported by Agostini *et al.* [1]. Since this review, many developments have been carried out on different kinds of cooling approaches, and this paper briefly summarizes the main ones that should be considered in such context.

Specifications for cooling systems in avionics environment

Power electronics converter losses have a great impact on cooling system design and the transient capacity influences converter-sizing point. It is so necessary to maintain them as low as possible. In addition to internal architectural improvements to these components, the nowadays most performing cooling technologies have to be found to ensure the adequate cooling with high heat transfer coefficients. In the context of this study, a heat power up to around 20 kW has to be evacuated with the lowest encumber possible.

As for classical power electronics, the cooling system has to be able to limit the temperature of electronic components and to ensure a constant operating temperature during the entire mission of the aircraft. However, the thermal management of these components requires the specificities of their aeronautic use, and must take these aspects into account in its choice and sizing:

- One of the main objectives is to design and optimize power electronics and associated cooling system with the purpose to obtain the lowest overall specific power density possible (overall electric + thermal powers-to-mass ratio): they must be as light as possible. A target of 25 kW·kg⁻¹ has to be reached for horizon 2035.
- The electronic losses depend on the airplane mission profile as function of time (Fig. 1). Each stage of the profile is related to a different amount of thermal energy to be evacuated: taxi out (I), take-off and climb (II), cruise (III), descent and landing (IV), taxi in (V). During stage I, IV and V, the quantity of thermal energy is lower than during the take-off or cruise stages (II and III respectively). The design point choice is so impacted by these two flight phases.
- Due to the difference of altitudes, ground and flight altitude temperature conditions are much different. A temperature difference of more than 40 K exists between these two conditions, and will have consequences on the temperature stability of the power electronics chips.

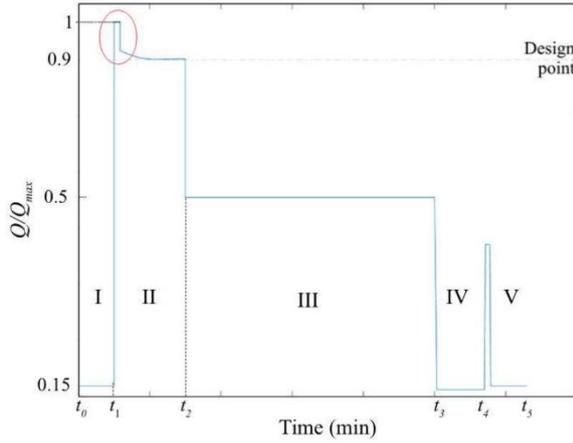


Fig. 1: Example of power electronic converter total thermal losses as function of time during a flight mission profile [2]

Overview of existing cooling solutions

Due to high complexity of cooling systems, the number and typology of components and the physics phenomena at the base of their working principle, it does not exist a universal way to classify them. Fig. 2 presents an overview of existing cooling solutions, first from closed or open loop configuration point of view: it is obvious that the performances obtained with air direct cooling no longer respond to the severe cooling constraints of this type of component. Thus, only closed loop circuit will be considered in the following.

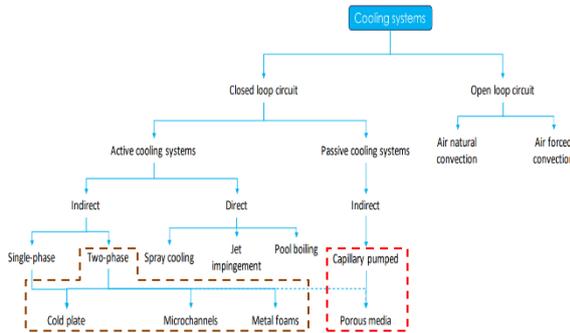


Fig. 2: Cooling systems classification [3]

The left main branch of Fig. 2 concerns the « *closed loop circuits* », which cool the device using an intermediate circuit. They can be divided in two categories : active and passive. Active cooling systems are characterized by the presence of a pump or a compressor, to move the fluid into the circuit; whereas passive cooling systems use gravity or capillary forces to make the fluid flow inside the loop. The difference, obviously, is in the amount of energy and in the level of mass flow rate required by the cooling system to operate. This can be illustrated by equation (1) below, giving the heat flux balance at the dissipative hot source heatsink:

$$\dot{Q} = \dot{m}[h_{lv}\Delta x_{i-o} + c_p\Delta T_{i-o}] \quad (1)$$

In Eq. (1), \dot{Q} represents the heat losses to be removed from the hot source; \dot{m} the fluid mass flow rate; h_{lv} and c_p are, respectively, the latent heat of vaporization (in J.kg^{-1}) and heat capacity of the fluid (in $\text{J.kg}^{-1}\text{K}^{-1}$); finally, Δx_{i-o} , and ΔT_{i-o} , are, respectively, the fluid vapor mass fraction, and temperature, differences between inlet and outlet of the heatsink. Thus, the first term between square brackets represents the latent heat of evaporation/condensation, whereas the second one the sensible heat.

If one considers single phase flow active cooling solution of Fig. 2, then, in the absence of evaporation, $\Delta x_{i-o} = 0$, and only sensible heat will be effective in the heatsink. Compared to two-phase active cooling systems, this requires considerable mass flow rates to evacuate a given heat power, because the temperature difference between inlet and outlet of the heatsink, ΔT_{i-o} , should be reasonable, below a few tens of K. Furthermore, as mentioned in the previous section, considering the fact that, according to mission profile, the cold source inlet temperature is not constant, but cyclically varies depending on altitude. Temperature differences up to about 80 K may occur and impact the hot source junction temperature, unless a regulating system is used on the primary or secondary side to control heatsink inlet condition. The higher the altitude and the lower the external air temperature, the lower the required mass flow rate. In this case a regulation valve, a three-way-valve or a variable-speed-pump should be considered, but seriously affecting the overall efficiency of the cooling system and increasing the overall system mass.

In Fig. 2, direct cooling systems, characterized by a direct contact between the fluid and electronic components, require dielectric fluids, and, due to the high heat flux to be removed, very high local heat transfer coefficients. This can be achieved through performant solutions such as spray cooling and jet impingement, but at the cost of complexity and great sensitivity to fouling. Nevertheless, direct cooling should be considered when the cooling of critical components is considered together with electronic and mechanical internal design. These solutions should be retained in the future.

In general, two-phase (liquid/vapour) pumped cooling systems are among the most effective way to evacuate the thermal load from dissipative components into distant heat sinks [4]. If now one considers indirect two-phase pumped cooling systems, in this case the coolant is confined in a case in close contact with the power electronics baseplate. Different architectures can be used, like those surrounded by the dashed brown frame of Fig. 2. Some of them are already widely used, even with single phase cooling of power electronics, like cold plates [1]. Microchannels or metal foams generally give better heat transfer

performances, but at the price of high pressure losses which lead to an oversizing of the pump. The rest of the cooling circuit is made up of the liquid and liquid/vapor lines, the heat exchanger used to evacuate the thermal load from the coolant (condensing part) to the external air, and an expansion tank designed to compensate the liquid volume variation in the loop during operation due to the appearance of vapor (from evaporator to condenser). The overall design of the loop is a compromise illustrated by Eq. (1): a low value of vapor mass fraction, Δx_{i-o} , will result in a higher mass flow rate and a lower expansion tank size. On the contrary, a higher vapor mass fraction will reduce the mass flow rate (and the power of the pump), but increase the size of the tank.

The main advantage of two-phase pumped cooling systems, in addition to their high efficiency, lies in that the reservoir, being two-phase, can be thermally controlled at a given saturated temperature: this temperature, fixed during operation, will impose the evaporation temperature on the hot source, which will also remain stable and constant, having considerable consequences on the lifespan of the electronics components.

Finally, the last branch of Fig. 2 (red dashed frame) concerns the indirect cooling by two-phase passive systems: in contrast with active cooling systems, they do not require an external source of energy to move the fluid, thanks to gravity forces (thermosyphons) or capillary forces at the liquid/vapor interfaces in the porous wicks (heat pipes, capillary pumped loops (CPL), loop heat pipes (LHP), and so on). In such systems, complete evaporation and condensation processes lead to a maximum value of vapor mass fraction difference ($\Delta x_{i-o} = 1$) and minimum temperature difference (ΔT_{i-o}) in Eq. (1), and so a minimum mass flow rate directly caused by evaporation. This results in pressure losses low enough to be compensated only by gravity and/or capillary forces. These systems have shown high cooling capacities for space [5] and terrestrial applications, such as railway [6] and, more recently, aeronautics applications [2,3]. The main advantages are their simplicity, adaptability and efficiency. However, if classical capillary heat pipes or thermosyphons have limited transport distances, capillary loops with porous wick appear as very promising technologies for this type of application: some devices were able to evacuate heat powers from 2 kW over 30 m [7] to more than 20 kW over 5 m [3,6].

Fig. 3 gives an overview from the literature of cooling capabilities of two-phase passive technologies such as loop heat pipes (LHP), heat pipes (HP) and thermosyphons, compared to high performing active single or two-phase ones in terms of heat transfer coefficient (HTC) versus evacuated heat power (Q). If

the performances of passive technologies seem to compete with other active ones, one in particular presents thermal performances beyond the others: the capillary pumped loop for integrated power (CPLIP, red dashed frame).

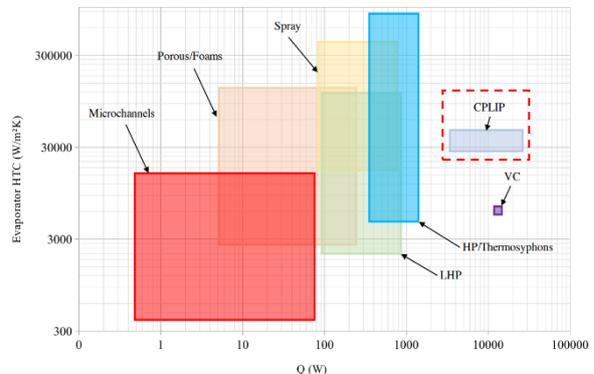


Fig. 3: Technology comparison [3]

Capillary pumped loop for integrated power (CPLIP)

This new type of loop typology has been developed in the last years by the Belgium Company Euro Heat Pipe to solve the problems of high dissipative power electronics cooling under gravity and acceleration environment. High simplicity, stability and reliability characterize the CPLIP: the primary circuit is composed by one or several parallel evaporators (in which the capillary porous wicks are confined), liquid and vapour lines, the condenser connected with the ultimate cold source, and the reservoir or expansion tank, situated above the evaporator (see Fig. 4). This specific configuration allows high reliability and absence of dry-out crisis particularly during start-up phases.

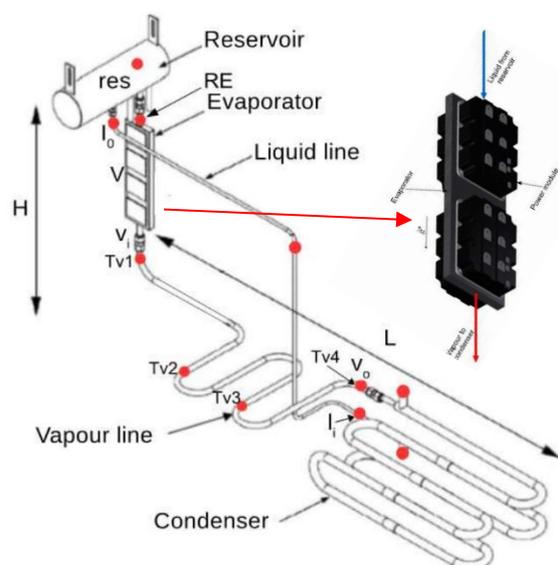


Fig. 4: Concept scheme of a CPLIP and power electronics module/evaporator assembly [2]

The only active control comes from maintaining the two-phase saturated temperature of the reservoir at a

constant level thanks to a heater. It represents only few tens of Watts compared to the few tens of kWatts managed by this loop. The controllability of the reservoir temperature makes possible the great stability of the loop especially during transient regimes. On Fig. 4, an example of power modules/evaporator assembly is shown. The evaporator dimensions are related to the power modules dimensions. Particular attention has to be paid on the condenser/cold source design: this is the heaviest component of the whole loop. For hybrid aircraft application, the condenser can be installed in the nacelle and cooled by a secondary external air flow, always available when power electronics operate.

Several experimental and numerical analyses have been performed on this specific type of capillary loop [2,3,6]. Numerical calculations of 3-D conduction simulations in specific power electronics modules cooled by this loop has been performed and showed maximum temperatures spots lower than 127°C for cases of diode losses of 155 W (corresponding to heat flux density of about 242 W.cm⁻²), which is lower than the maximum admissible junction temperature of 150°C [2].

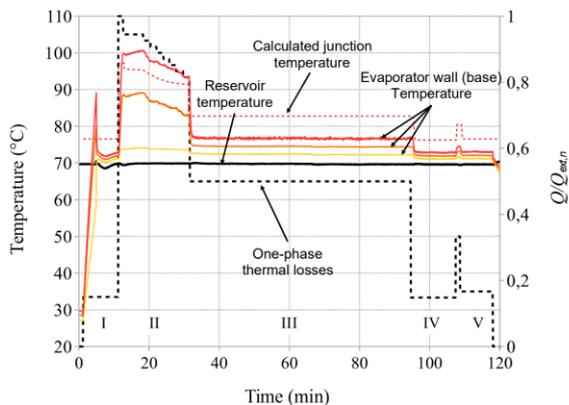


Fig. 5: Experimental response of a single-evaporator CPLIP to a one-phase thermal losses mission profile corresponding to Fig. 1 [2]

Lastly, an example of experimental test, performed on a single evaporator loop, and simulating the heat power mission profile (depicted in Fig. 1), is represented in Fig. 5 [2]. The maximum heat power capability for this loop was higher than 5 kW with only one evaporator. During transient stages, thermal inertia of the different components of the electronic-cooling assembly play also an important role on the dynamic thermal process. This graph highlights the very high efficiency and stability of the CPLIP for this type of mission: the resulting (calculated) electronics junction temperature remains here below 100°C even during the severe take-off stage II; and the overall temperature variations remain reasonable during all severe transient cycle. Pushing to its limit the optimization of both power electronics technology and

adjoined cooling solution leads to power coefficient value higher than the target of 2035, of 25 kW·kg⁻¹.

Conclusions

In this paper, a panel of solutions is presented for power electronics cooling in the context of hybrid aircraft application. Among the most efficient solutions adapted to aeronautical constraints, indirect cooling by two-phase loops are still the most adequate technologies. Special emphasis is made on the passive two-phase capillary pumped loop designed for integrated power cooling: the CPLIP. Many experimental tests and numerical modelling have demonstrated its ability to evacuate high levels of heat power over several meters between hot and cold sources. However, further development to these systems are still to be considered, and hybrid cooling loops, combining passive operation with other elements of improvement, are expected in the future. This is the case for the so-called « capillary jet loop », which combines the capillary evaporator to a two-phase cooling loop driven by vapor jets at the outlet of the evaporator(s); or with a capillary evaporator coupled with a two-phase thermosyphon loop. Hybrid technologies will likely be adapted solutions to high dissipative component cooling in severe environment.

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