Applied Thermal Engineering 104 (2016) 603–615

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Investigation on weight consideration of liquid coolant system for power electronics converter in future aircraft

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ARTICLE INFO

Article history:
Received 7 January 2016
Revised 28 April 2016
Accepted 16 May 2016
Available online 20 May 2016

Keywords:
Cold plate
CFD
Thermal performance
Power electronic cooling

ABSTRACT

Cooling systems significantly contribute to the total mass and volume of power electronic systems. In the case of aerospace application, it will directly increase the operating cost of the aircraft. This paper experimentally and numerically investigates the weight contribution of the liquid cooling system for power electronics converter in future aircraft. In order to investigate, a cooling system of 2 and 6 pass cold plates is designed and its cooling performance is analyzed. The weight and size contribution is discussed based on available coolants in the aircraft, flow rate ranges from 2 to 8 LPM and 1% to 3% power loss dissipation. Water is added and examined for completeness of the studies. This paper concludes that oil is inappropriate coolant for this particular case. The optimum parameters (Q = 8 LPM with 9.5 kg pump weight) for most promising coolant (fuel) that give high extraction rate with low weight contribution for the highest density cooling system are indicated.

1. Introduction

More electric engine (MEE) technology can improve the fuel efficiency, reliability and reduce cost in operation of aircraft as this technology has already been proven in automotive sector. In aerospace sector, the MEE technology is implemented by replacing the mechanically driven engine accessories, oil pump, fuel pumps, hydraulic pump, etc. with electrically driven versions in aircraft. This replacement results in increase of electric loads compared to traditional aircraft system. For high efficiency system these electric loads is supplied from power buses by using power converter as an interface. The weight of power converter has to be considered because it will influence the consumed fuel in aircraft.

Therefore, a high power density converter is required. The power density reflected to volume and weight of power converter. The demand for cooling power converters in aerospace factor is progressively increasing [1]. Size and weight are the main challenges in aeronautical industry [2]. Power dissipation density shows tendency to enhance therefore it results in more heat needs to be dissipated. Hence thermal management should not be neglected. The cooling system must able to cope with the increased thermal loads of the upgraded systems without adding too much burden to the weight and size. Natural and forced air cooled heat sink approach is the most widely used cooling system due to simplicity and most primitive form. However, the stringent requirements of aircrafts make air cooling unsuitable for high power electronic devices. Liquid cooling is an attractive solution for the thermal management of power electronic components. Engine oil and fuel are readily available on-boards coolants. Water is another type of coolant with the relatively good thermos-physical properties. However its application will results in extra pump weight and size penalty as well as system complexity due to non-availability on the aircraft. However there are no studies in available literature regarding usage of oil and fuel in avionics. Although both the coolant is available coolants found in automotive sector. Oil and fuel are used where water is unsuitable. Oil has higher boiling point than water, it can be raised above 100 °C without introducing higher pressures within the system.

The most widely used and promising liquid cooling methods are mini/microchannel heat sink (MCHS), cold plate heat sink, jet impingement, pin fin heat sink, porous medium, liquid metal cooling and thermoelectric cooling. However some of them have cooling limitations which make them inappropriate for aircraft applications. Jet impingement has not received as much attention as compared with MCHS, due to its design difficulty [3]. Reliable analytical or numerical models for pin–fin heat sinks have not been developed yet due to the complex nature of fluid flow and heat transfer in its pin–fin arrays [4]. Porous medium requires high pump power and bulky packages [5]. Metal cooling (coolant)

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http://dx.doi.org/10.1016/j.applthermaleng.2016.05.097
1359-4311/

Nomenclature

c_p	specific heat (J/kg K)
h	heat transfer coefficient (W/m^2 K)
H	pump head diameter (cm)
k	thermal conductivity (W/km)
Nu	Nusselt number
Δp	pressure drop (Pa)
P_{pump}	pumping power (W)
q	heat flux (W/cm^2)
Re	Reynolds number
T	temperature (K)
U	velocity vector (m/s)
u, v, w	flow velocity (m/s)
x, y, z	Cartesian coordinates

Greek symbols

μ	viscosity (N s/m^2)
ρ	density (kg/m^3)

Subscripts

f	fluid
i	inlet
o	outlet
s	solid

demands 7 times more pump power than water and leads to severe corrosion. Thermoelectric cooling is not efficient for high heat flux [6]. Due to ease of fabrication and being relatively cost-effective the cold plate heat sink is concluded as an attractive cooling technique for aircraft application.

Liquid cooling system is composed of a chiller, a pump, connection tubes and the cold plate. The cold plate contacts with the heat generation device for to remove the heat from the hot spot [7]. A broad review of the cooling technologies in the component level as well as in the cabinet level is summarized by Chu et al. [8].

Mu et al. [9] numerically investigated a water-cooled minichannel heat sink with different flow field configurations under high heat flux. They concluded that heat sink with circular turning configurations performs the best and could be adopted for high-heat flux cases. Xia et al. [10] experimentally and numerically investigated the cooling performance of MCHS with complex structure. At the end, they came to the point that MCHS with complex structure is more economical for chip cooling system. Gong et al. [11] numerically studied 4 types of MCHS (traditional MCHS, pin–fin MCHS, single-hole jet cooling and double-layer MCHS) with layout consideration. They claimed that jetting cooling heat sink possesses the best chip cooling followed by double-layer MCHS while traditional MCHS has a substantial development potential. Leng et al. [12] presented a multi-objective optimization method for double-layer MCHS. Wang et al. [13] introduced MCHS with micro-scale ribs and grooves for chip cooling. They indicated that cooling effectiveness of rib-grooved MCHS is up to 1.55 times higher than the smooth one but leads to the high pressure drop at the same time.

Besides the cooling structure, the author would also like to acknowledge one method to improve the heat transfer which is done by to applying nanofluids [14]. An optimal geometric structure for MCHS using nanofluids under different constraint conditions, and the impact of pumping power, volumetric flow rate and pressure drop were obtained by [15]. Passive technique to enhance the cooling performance is studied by [16]. The usage of nanofluids in aircraft application is not investigated in this work.

Many works studied the heat sink optimization and performance improvement with the target to achieve low thermal resistance. However key parameters in aircraft applications such as weight and size of the cooling system have been neglected. Moreover besides widely-used coolants such as water and air, the usage of the already existing fluids in aircraft haven't found due attention yet.

This paper experimentally and numerically investigates the weight contribution to the cooling system for a case study of 50 kW power converter in aerospace sector which has not been reported earlier. 2 and 6 pass cold plates are designed and cooling performance is then analyzed by applying the fuel, oil and water as the coolants. The cooling performance of these coolants are evaluated by the value of thermal resistance, pressure drop and pump power as well as the contribution to the weight and size of the cooling system. The research is done at the flow rate ranges between 2–8 LPM and 1–3% power loss dissipation of 50 kW maximum converter power.

2. Numerical method

The 50 kW power converter, structure of power module and schematic diagram of a 6 pass and 2 pass cold plates are shown in Fig. 1. The detailed parameters of the module are listed in Table 1. The cold plate coolant system is designed for three phase two level power converter. The dimensions of cold plates are presented in Table 2. The $L \times w$ size of cold plates fits three CAS100H12AM1 1.2 kV, 100 A silicon carbide half-bridge power modules (5 cm $\times$ 8.8 cm) [17]. The gap between power modules is 2 mm. The inlet coolant is defined with a uniform temperature of 70 °C. The outlet pressure is adopted with atmosphere pressure. 6 pass cold plate is designed in such a way that its copper pipe runs underneath the position of MOSFETs die inside the module to enhance heat extraction. The effective copper pipe length inside the cold plate is $6 \times w$ and $2 \times L$ for the 6 and 2 pass cold plates accordingly.

To investigate the impact of flow rate and types of coolant under 1–3% power loss of 50 kW power converter, flow rate ranging from 2 LPM to 8 LPM, and water, oil and fuel as the coolants are considered.

The boundary conditions are listed as below:

Channel inlet:

$$u = u_{in}, \quad v = 0, \quad w = 0, \quad T = T_{in} \tag{1}$$

Channel outlet:

$$p = p_{out} \tag{2}$$

Coolant–solid interface:

$$u = v = \omega = 0, \quad T_f = T_s, \quad -k_f \frac{\partial T_f}{\partial n} = -k_s \frac{\partial T_s}{\partial n} \tag{3}$$

Bottom wall of the heat sink:

$$q_w = -k_s \frac{\partial T_s}{\partial n} \tag{4}$$

Other solid walls and symmetric boundaries:

$$-k_s \frac{\partial T_s}{\partial n} = 0 \tag{5}$$