Energy 112 (2016) 1–7

Contents lists available at ScienceDirect

Energy

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

Thermoelectric self-cooling for power electronics: Increasing the cooling power

Alvaro Martinez [a, b, *], David Astrain [a, b], Patricia Aranguren [a, b]

[a] Mechanical, Energy and Materials Engineering Department, Public University of Navarre, 31006 Pamplona, Spain
[b] Smart Cities Institute, 31006 Pamplona, Spain

ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form
31 May 2016
Accepted 2 June 2016

Keywords:
Thermoelectric self-cooling
Power electronics
Seebeck effect
Heat pipe exchanger

ABSTRACT

Thermoelectric self-cooling was firstly conceived to increase, without electricity consumption, the cooling power of passive cooling systems. This paper studies the combination of heat pipe exchangers and thermoelectric self-cooling, and demonstrates its applicability to the cooling of power electronics.

Experimental tests indicate that source-to-ambient thermal resistance reduces by around 30% when thermoelectric self-cooling system is installed, compared to that of the heat pipe exchanger under natural convection. Neither additional electric power nor cooling fluids are required. This thermal resistance reaches 0.346 K/W for a heat flux of 24.1 kW/m^2, being one order of magnitude lower than that obtained in previous designs. In addition, the system adapts to the cooling demand, reducing this thermal resistance for increasing heat.

Simulation tests have indicated that simple system modifications allow relevant improvements in the cooling power. Replacement of a thermoelectric module with a thermal bridge leads to 33.54 kW/m^2 of top cooling power. Likewise, thermoelectric modules with shorter legs and higher number of pairs lead to a top cooling power of 44.17 kW/m^2. These results demonstrate the applicability of thermoelectric self-cooling to power electronics.

1. Introduction

Cooling and thermal management of electronic devices is a growing challenge in the field of power electronics, from small microprocessors to large electric power converters. It is a fact, that recent developments always involve higher electric power and smaller size, which inevitably leads to higher cooling demands.

Anandan [1] categorized thermal management systems into active and passive, those in the former being able to provide higher cooling power than those in the latter, but also requiring electric power for operation. Forced air/liquid convection, air/liquid jet impingement and refrigeration systems belong to this group.

However, as this author underlines, when electric power consumption and/or space limitation are key issues, passive techniques are more practical. Effective heat spreaders attached to finned heat sinks are the most used passive cooling techniques. Nowadays, heat pipe exchangers are under deep investigation. As indicated by Jouhara [2] and Chernysheva [3], a heat pipe exchanger presents continuous vaporization and condensation of an enclosed fluid, which leads to extremely high heat transfer coefficients. Furthermore, no electric power is needed to pump the fluid. On the other hand, working as a passive cooling system (i.e. under natural convection) a heat pipe exchanger presents limited cooling power.

In this regard, thermoelectric self-cooling (TSC) sets out to increase the cooling power of passive cooling systems. Contrary to other techniques, this technology increases the cooling power without additional electric power consumption. As Martinez indicates [4], this technology transforms a passive cooling system into an active cooling system, but requires no electric power to perform this process. The basic layout of a TSC includes several thermoelectric modules installed between a heat source and a passive cooling system. By Seebeck effect, the modules transform part of the heat emitted by the source into electricity, which is directly used to operate a fan installed over the passive system. As a consequence, the cooling power increases without electric power consumption.

This concept was firstly proposed by Yazawa [5], who applied it to the cooling of a 11.6 × 11.6 mm^2 microprocessor. Yazawa's

* Corresponding author. Mechanical, Energy and Materials Engineering Department, Public University of Navarre, 31006 Pamplona, Spain.
E-mail address: alvaro.martinez@unavarra.es (A. Martinez).

http://dx.doi.org/10.1016/j.energy.2016.06.007
0360-5442/

Nomenclature

b	Systematic standard uncertainty
I	Electric current A
k	Thermal conductivity of the thermal bridge W/m °C
L	Leg length mm
N	Number of thermoelectric pairs in a thermoelectric module
P	Electric power supplied by the modules to the fan W
$\dot{Q}$	Heat flux generated by the heat source W
R	Thermal resistance °C/W
T	Temperature °C
V	Electric voltage V
ΔT	Source-to-ambient temperature difference °C

Subscripts

amb	Ambient
c	Convective heat transfer
eq	Equivalent of thermoelectric modules and thermal bridge
hp	Heat pipe exchanger
mod	Thermoelectric module
source	Heat source

prototype included one "off-the-shelf" thermoelectric module operating a fan installed over a finned heat sink. This author reported source-to-ambient (or global) thermal resistances of around 4 K/W, which despite far from being acceptable for microprocessor cooling, resulted 40% lower than the thermal resistance provided by an optimized passive cooling system under similar working conditions. Note that the comparison was valid, since none of the systems consumed electric power. Yazawa's work showed the potential of TSC and established lines for improvement, which involved the reduction of the high thermal resistance of the heat sink.

The first improvement for microprocessor cooling was provided by Solbrekken [6], who introduced a secondary path for the heat flux. Thus, only a part of the heat crossed the module and the finned heat sink, whereas the rest went through another finned heat sink. As a result, Solbrekken was able to halve the global thermal resistance to 2 K/W. Furthermore, he stated that a thermal resistance of around 1 K/W for 50 °C of source-to-ambient temperature difference would be required for reliable microprocessor cooling.

One step further, Kiflemariam confirmed that the thermal resistance of the heat sink acts as bottleneck [7], so he replaced it with a complete microfluidic dissipation system, composed of a microchannel heat sink, fluid conduits, a secondary heat sink and a pump [8]. For a 15 × 15 mm^2 heat source, this author reported global thermal resistance of around 1.3 K/W, almost independent of source-to-ambient temperature difference. The idea of introducing fluidic heat sinks is correct in terms of heat transfer, since higher convection coefficients are achievable, as this author indicates. However, loss of compactness is obvious, compared to previous designs, thus limiting its applicability. Furthermore, the electric power consumption increases, since the modules not only must provide force convection to the secondary heat sink but also operate the driving pump.

Martinez applied Yazawas's TSC to power electronics [4], where the number of potential applications seems enormous. Electric power converters, transformers, control systems, etc. present cooling demands of at least 25 kW/m^2 but low working temperatures, so that source-to-ambient temperature difference is usually limited to 80 °C, as stated by Buttay [9] and Anandan [1]. Martinez developed a prototype for a 220 × 160 mm^2 heat source, which included 4 thermoelectric modules that operated a fan installed over a finned heat sink. For the cited source-to-ambient temperature difference, 140 W of dissipated heat was obtained, leading to 0.57 K/W of global thermal resistance, 30% lower than that provided by the finned heat sink working under natural convection. The cooling power reached 4 kW/m^2, far from 25 kW/m^2 required by low-power electronic devices. Again, the thermal resistance of the heat sink was too high, accounting for around 40% of the global thermal resistance. This author also developed a computational model for TSC applications [10], and demonstrated that this first design could be directly applied to prevent overheating in solar collectors, obtaining a low-power-consumption [11] or even zero-power-consumption [12] thermal management system.

The present paper goes one step further, aiming to increase the cooling power of TSC to surpass 25 kW/m^2, so that these systems could be used in the cooling of power electronics. To do so, the combination of heat pipe exchangers and TSC is evaluated.

The paper presents two primary objectives: The first one is to compare the heat removed from a hot spot by a heat pipe exchanger under natural convection, and that removed by a TSC that uses a similar heat pipe. The objective is to show the potential of TSC and prove that the cooling power of a heat pipe could be increased without electric power consumption. To this end, Section 2 describes the TSC test bench, presenting the arrangement of the heat source, the heat pipe exchanger and the thermoelectric modules; Section 3 describes the methodology used in this experimental study; and, finally, Section 4.1 presents the results.

The second objective is to increase the cooling power of the TSC used in the previous experimental study. Two approaches are proposed, and the performance is assessed by a simulation process that involves the use of a computational model developed specifically for TSC applications [10]. Results are presented in Section 4.2. Finally, Section 5 provides the main conclusions of the paper.

2. Test bench description

2.1. Heat source

As can be seen in Figs. 1 and 2, the heat source consists of a 120 × 80 × 10 mm^3 aluminium block containing five cartridge heaters, connected electrically in parallel to an adjustable Grelco GVD electric power supply [13]. It has been considered that 100% of the electric power produced by this Grelco GVD is transformed into heat power. Furthermore, this power supply presents 4 Ω of internal electric resistance −that is, voltage is always four times higher than electric current.

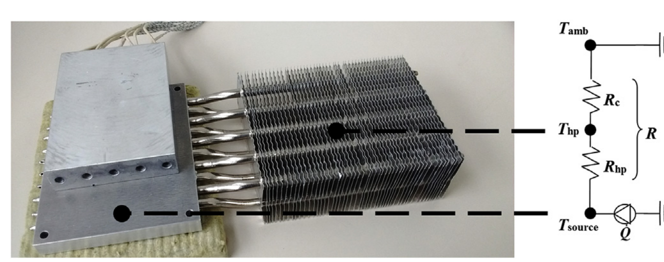

Fig. 1. Heat pipe exchanger and heat source. Electrical analogy of configuration 1.