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Computational and experimental study of a complete heat dissipation system using water as heat carrier placed on a thermoelectric generator

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The heat dissipation systems which have liquids as heat carriers outperform conventional dissipation systems at TEGs (thermoelectric generators). However, new elements need to be introduced such as pumps, secondary heat exchangers and piping.

A predictive computational model of a dissipation system involving refrigerant liquids has been implemented. The accuracy of the model is 93% for all its outputs: the total thermal resistance, the hydraulic losses and the auxiliary power consumption. The validation of the model has been done with a prototype mainly composed by a multi-channel heat exchanger, a fan-coil, a pump and several sensors: temperature, pressure and flow meters.

A study on the influence of the water and the air mass flow over the total thermal resistance has been conducted. The total resistance dependence on the air mass flow shows the importance of including the secondary heat exchanger into the thermal and hydraulic calculations. The smallest resistance does not always obtain the highest net power generation, the high demanding power of the auxiliary equipment needed to obtain this resistance influences negatively on the net power generation. Among the experimental points, the optimum scenario obtains a 40% additional power generation with respect to the smallest resistance point.

1. Introduction

Compactness, robustness, reliability and lack of moving parts are the main advantages of TEGs (thermoelectric generators) (TEGs). These features cause less maintenance and easiness of control, making TEGs a better solution than other energy conversion systems such as turbines or thermal engines. These benefits did not get unnoticed by the aerospace field; thermoelectricity has been present over 40 years at several spacecraft and satellites, with a special remark on Voyager probes capable of producing 150 W (~350 W/cm^2) with 7% efficiency [1]. The latest thermoelectric experience in the outer space is the vehicle space mission to Mars [2].

On the earth, several researches study the possible application of thermoelectricity in residual energy conversion. The origin of the waste energy can be very wide: vehicle exhaust gases, electricity generation or conventional industry chimneys. The 50% of the power consumption of automotive electronics can be generated recovering part of the waste energy being thrown to the atmosphere [3], a 10% fuel efficiency increase can be obtained locating TEGs on the exhaust tailpipe of vehicles [4].

Despite the costless nature of waste heat, the reduced efficiency that thermoelectricity presents is a decisive aspect over the applicability and profitability of big scale systems. Great efforts are being made to improve the overall efficiency of TEGs. Two are the main objectives: the optimization of materials, in order to improve the figure of merit, and the study of new heat exchangers towards the reduction of the thermal resistances on both sides of the TEMs (thermoelectric modules). The importance of reducing the thermal resistance between the heat source and the hot side of the TEM and its analogous in between the cold side and the ambient was demonstrated by Astrain et al. [5].

A high heat flux per area is what makes thermoelectricity special in terms of refrigeration. This issue occurs in other applications such as: electronics, laser diodes or microchemical reactors. One of the solutions focuses on heat exchangers provided with fluids as heat carriers (involving one or two phases). The dissipator can be composed by small channels or porous media [6]. For example, a

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Nomenclature

A	area m^2
C_p	specific heat J/kgK
D	pipe diameter m
f	friction losses coefficient
g	gravity m/s^2
$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu}$	grashof number
h	convective coefficient K/m^2W
k	thermal conductivity W/mK
k_{local}	local losses coefficient
L	pipe length m
$\dot{m}$	mass flow kg/s
N	number of fins
$Nu = \frac{hk}{D}$	nusselt number
$\mathrm{Pr} = \frac{C_p\mu}{k}$	prandtl number
$\dot{Q}$	heat power exchanged/transmitted W
R	thermal resistance K/W
$\mathrm{Re} = \frac{\rho v D}{\mu}$	reynolds number
$Ra = GrPr$	rayleigh number
T	temperature K
U	global heat transfer coefficient K/Wm^2
v	fluid velocity m/s
$\dot{W}$	generated/consumed electric power W

Greek symbols

ρ	fluid density kg/m^3
$\in$	material roughness m
η	efficiency
ΔP	hydraulic losses kPa
Δy	absolute measurement error
μ	fluid dynamic viscosity kg/ms
ν	fluid kinematic viscosity m^2/s

Subscripts

1	TEM-to-water heat exchanger entrance
2	TEM-to-water heat exchanger exit
3	water-to-ambient heat exchanger entrance
4	water-to-ambient heat exchanger exit
air	air
amb	ambient
C	thermoelectric module cold side
cond	conduction
cont	contact
conv	convection
CP	cold plate
e	exterior
exp	experimental
f	fan-coil
fin	fin
i	interior
net	net power generation
p	pump
sim	computationally simulated
sys	piping assembly
TEM	thermoelectric module
tot	total
water	water

thermosyphon loop cooling system obtains double refrigeration power than a traditional air convection system [7].

In terms of thermoelectricity, Zhou et al. [8] stated that liquid refrigerant heat exchangers generate higher net powers than conventional finned dissipators. Nevertheless, heat exchangers that include liquids need pumps to circulate the refrigerant. Each heat exchanger has a unique flow rate that obtains maximum net power generation [9]. At low mass flows, the pumping power can be negligible; however, the opposite occurs when the mass flow is considerable or the pressure drop is significant. Increasing 100 times the pressure drop (from 0.5 to 50 kPa) produces an increase of 3656 times of the pumping power in a specifically built heat dissipation system for a TEG [10].

The geometry optimization for the latter heat exchangers focuses on: number and geometry of the channels, flow distribution or the inclusion of inserts. The reduction of the diameter of the channels leads to heat transfer enhancement [11], parallel channels obtain higher net generation that serpentine ducts [12] and panel inserts can achieve a 50% net gain relative to the absence of inserts [13]. Latest researches present a 10% enhancement in power generation by introducing stirred flows into the heat exchangers [14]. They also propose the use of high thermal conductivity nanofluids as a feasible optimization field [11].

In the previous mentioned studies there is no treatment of the refrigerant; the costs of reusing the refrigerant are not included. Water can be used as refrigerant, but normally there are no big reservoirs near the generators where the water can be taken from.

In the present work each element involved in the refrigeration system has been taken into account. The dissipator located on the cold side, a secondary heat exchanger needed to reduce the temperature of the refrigerant, the pump and the piping itself. The computational model implemented in MATLAB computes the global thermal resistance, the hydraulic losses and the auxiliary equipment consumption. A specifically built prototype validates the model using 20 operating points that present different values of water and air mass flows. This global computational model is a powerful optimization tool for dissipation systems. Including its outputs in the TEG computational model presented in Ref. [5] the net generated power can be obtained.

The main objective of this study is to create and validate the tool which obtains the thermal resistance and the auxiliary power consumption. A study of the influence of water and air mass flows on the thermal resistances of the heat dissipation system has been included as well as a sample of the optimization potential that the methodology presented in this paper has.

2. Water-to-ambient heat dissipation system for a TEG system

A water-to-ambient heat dissipation system for a TEG dissipates the heat coming from the TEM to the heat sink. TEMs, due to the Seebeck effect, convert part of the heat received on their hot side into electric power. The rest of the heat is emitted through the cold side to the heat sink, normally the ambient.

In this work, the water is used as heat carrier due to its high convection coefficient. Nevertheless, the dissipation system which involves water is not as simple as in Fig. 1; the water needs additional devices such as pumps, pipes and additional heat exchangers. Fig. 2 shows every element of the dissipation system built.

Below the cold plate the TEMs are collocated. Their cold sides are in direct contact with the multi-channels heat exchanger, named cold plate. The cold plate of Fig. 2 dissipates heat form the cold side of the TEMs as the dissipator of Fig. 1 does. However, the