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Experimental investigation of the applicability of a thermoelectric generator to recover waste heat from a combustion chamber

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HIGHLIGHTS

- Applicability of turning waste heat into electricity by thermoelectricity.
- The thermoelectric prototype produces 21.56 W of net energy covering 0.25 m^2.
- Study of different variables under real conditions.
- Heat pipes outperform the conventional finned dissipators by 43% increase in power.
- Study on heat losses along the chimney obtains a 2.2% thermoelectric efficiency.

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ABSTRACT

A thermoelectric generator prototype has been built; it produces 21.56 W of net power, the produced thermoelectric power minus the consumption of the auxiliary equipment, using an area of 0.25 m^2 (approximately 100 W/m^2). The prototype is located at the exhaust of a combustion chamber and it is provided with 48 thermoelectric modules and two different kinds of heat exchangers, finned heat sinks and heat pipes. Globally, the 40% of the primary energy used is thrown to the ambient as waste heat; one of the many different applications in which thermoelectricity can be applied is to harvest waste heat to produce electrical power.

Besides, the influence on the thermoelectric and on the net power generation of key parameters such as the temperature and mass flow of the exhaust gases, the heat dissipation systems in charge of dispatching the heat into the ambient and the consumption of the auxiliary equipment has been studied. In terms of heat dissipation, the heat pipes outperform the finned dissipators, a 43% more net power is obtained.

1. Introduction

The development of the modern civilizations is characterized by a sharp rise in the energy consumption. This fact has resulted into an untenable energetic system with significant environmental impacts. One of the essential challenges of today's societies is energetic sustainability aiming to stimulate energetic models with low carbon consumption and less energetic consumption. Two are the cornerstones to achieve the energetic challenge: the development of renewable energies and the improvement of the energetic efficiency. In the past decade, the development of the renewable energies has been very noticeable; in 2012 the 21.7% of the worldwide electric energy consumed was produced by green means [1]. Nevertheless, the 80% of the energy that is consumed by the human beings comes from the use of fossil fuels [2]. This fact outlines the efficiency importance of the combustion processes, still nowadays the majority, as well as the impact of a better recovery of the heat generated at the combustion processes, reducing to the minimum the unused waste heat. The 40% of the primary energy used is being thrown to the ambient as waste heat [3].

Thermoelectric generation (TEG) has attracted the attention of many researchers due to its capacity to produce electric energy from waste heat originated at very different applications, from industrial processes to domestic boilers. The main element of a TEG is the thermoelectric module (TEM) which is in charge of turning heat into electricity. A TEM is a thermal machine where the electrons are the working fluid, eliminating the moving parts and thus providing to the TEGs with their inherent advantages, such

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Nomenclature

ε_a	absolute error
ε_r	relative error
$\in$	emissivity
ε_{net}	net efficiency
ε_{TEM}	efficiency of the thermoelectric generator
ε_{global}	global efficiency
σ	Stefan–Boltzmann coefficient (W/m^2 K^4)
A_e	external area (m^2)
A_{rad}	radiation area (m^2)
C_p	specific heat (J/kg K)
e	thickness (m)
h_e	exterior convection coefficient
h_{rad}	radiation coefficient (W/m^2 K)
I_{aux}	intensity consumed by the auxiliary equipment (A)
I_{TEM}	intensity produced by the TEMs (A)
k	thermal conductivity (W/m K)
$\dot{m}_{gas}$	mass flow of the exhaust gases (kg/s)
$\dot{Q}_C$	heat emitted to the ambient by the TEG (W)
$\dot{Q}_H$	heat absorber by the TEG (W)
R_{cond}	conduction thermal resistance (K/W)
R_{cont}	contact thermal resistance (K/W)
R_{conv}	convection thermal resistance (K/W)
R_{iso}	thermal resistance of the isolation (K/W)
R_L	load resistance (Ω)
R_{rad}	radiation thermal resistance (K/W)
R_{TEM}	interior resistance of the TEM (K/W)
T_{CLLFD}	temperature of the cold side of the lower levels finned dissipators (°C)
T_{CLLHP}	temperature of the cold side of the lower levels heat pipes (°C)
T_{CULFD}	temperature of the cold side of the upper levels finned dissipators (°C)
T_{HLLFD}	temperature of the hot side of the lower levels finned dissipators (°C)
T_{HLLHP}	temperature of the hot side of the lower levels heat pipes (°C)
T_{HULFD}	temperature of the hot side of the upper levels finned dissipators (°C)
T_{iel}	temperature of the exhaust gas at the inlet of the elbow (°C)
T_{iLL}	temperature of the exhaust gas at the inlet of the lower levels of the TEG (°C)
T_{in}	temperature at the beginning of the exhaust channel (°C)
T_{ino}	temperature of the exhaust gas at the inlet of the nozzle (°C)
T_{iUL}	temperature of the exhaust gas at the inlet of the upper levels of the TEG (°C)
T_{mel}	mean temperature of the exhaust gas at the elbow (°C)
T_{mLL}	mean temperature of the exhaust gas at the lower levels of the TEG (°C)
T_{mno}	mean temperature of the exhaust gas at the nozzle (°C)
T_{mUL}	mean temperature of the exhaust gas at the upper levels of the TEG (°C)
T_{oel}	temperature of the exhaust gas at the outlet of the elbow (°C)
T_{oLL}	temperature of the exhaust gas at the outlet of the lower levels of the TEG (°C)
T_{ono}	temperature of the exhaust gas at the outlet of the nozzle (°C)
T_{oUL}	temperature of the exhaust gas at the outlet of the upper levels of the TEG (°C)
T_{out}	temperature at the end of the chimney (°C)
V_{aux}	voltage consumed by the auxiliary equipment (V)
V_{TEM}	voltage produced by the TEMs V)
$\dot{W}_{aux}$	power consumption of the auxiliary equipment (W)
$\dot{W}_{net}$	net generated power (W)
$\dot{W}_{TEM}$	TEG power production (W)

as lack of maintenance, easiness of control, reliability and robustness [4].

Large amounts of heat are emitted by the industry with too low temperatures (<200 °C) to be used by conventional energy conversion systems. This unused energy is wasted into the ambient. A theoretical study on the collocation of TEGs at 27,000 industrial firms of Thailand provided with diesel cycles and turbines was conducted obtaining 100 MW of power generation [5]. Alike, the 40% of the fuel energy is thrown to the ambient by the tailpipe of the vehicles [6]. Studies obtain fuel reductions of the 8–12.5% by thermoelectric means [7].

To address the thermoelectric phenomena two approaches are used by the researchers, computational simulation and experimental prototypes. The computational simulators solve the thermal and electrical dynamics of thermoelectricity (TE). Different computational software is used such as Matlab and Simulink via the resolution of blocks that represent the whole system [8], Mathcad using dimensional analysis [9], TRNSYS via a novel TEG model incorporated to the TRNSYS standard library [10] or Matlab via finite differences [11]. The computational models simulate the thermoelectric behavior; e.g. a theoretical study concluded that a TEG located on the tailpipe of an average car could meet the electrical needs of that vehicle [12].

The prototypes or test benches obtain experimental results. Most of the times the experimental data is used to validate a computational model, so that the conditions simulated are quite idealized, a chimney modelled with a blower and a boiler to simulate the flue gas from a boiler or a stove [13] or a prototype installed at a car tested at constant vehicle speed and constant engine rotation [14] when it is known that driving conditions set the waste heat ejected by vehicles with temperatures ranging from 100 to 800 °C. The consumption of the auxiliary equipment is not normally taken into account, [15] presents a study on the potential of recovering low-temperature waste heat by thermoelectrics in which the power of the fan used to cool down the device is not present in the results. This paper presents a prototype built at the exhaust of a combustion chamber working under real conditions.

TEGs installed at big scale applications have the potential to generate electric energy recovering waste heat, improving the overall efficiencies of energy conversion systems, reducing the emissions of CO_2, and hence helping to reduce the global warming. In this paper a prototype shows the possibilities that thermoelectric generation has if applied to recover waste heat from exhaust steams at industry applications. A TEG composed by 48 TEM located at the exhaust of a combustion chamber has been built to that purpose. A study on the influence of key variables of the waste heat, temperature and mass flow has been developed. Previous scientific researchers present different ways of optimizing the thermoelectric generation. The optimization of the heat exchangers present at the TEG greatly influence the electrical power generation [16], the electrical current produced, therefore the influence of the load resistance, is also a key factor [17] as well as the occupancy rate of the thermoelectric generators [18] and the working conditions [19]. In this paper, to characterize the influence