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Thermoelectric generators for waste heat harvesting: A computational and experimental approach

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Waste heat generation has a widespread presence into daily applications, however, due to the low-temperature grade which presents, its exploitation with the most common technologies is complicated.

Thermoelectricity presents the possibility of harvesting any temperature grade heat; besides it also includes many other advantages which make thermoelectric generators perfect for generating electric power from waste heat. A prototype divided into two levels along the chimney which uses the waste heat of a combustion has been built. The experimentation has been used to determine the parameters that influence the generation and to validate a generic computational model able to predict the thermoelectric generation of any application, but specially applications where waste heat is harvested.

The temperature and mass flow of the flue gases and the load resistance determine the generation, and consequently, these parameters have been included into the model, among many others. This computational model incorporates all the elements included into the generators (heat exchangers, ceramics, unions) and all the thermoelectric phenomena and moreover, it takes into account the temperature loss of the flue gases while circulating along the thermoelectric generator. The built prototype presents a 65% reduction in the generation of the two levels of the thermoelectric generator due to the temperature loss of the flue gases. The general computational model predicts the thermoelectric generation with an accuracy of the ±12%.

1. Introduction

Severe environmental issues, such as global warming, greenhouse gases emissions, climate change, acid rain and ozone depletion, have arisen due to the excessive use of fossil resources. Hence one of the most prominent issues to face in the 21st century is to satisfy the energetic demand in an environmentally friendly manner.

Thermoelectric generation is emerging as a potential technology to help meet the goal of producing clean electric energy, due to its capacity to generate electricity from any temperature level heat. The harvesting of waste heat, a by-product heat of a process, is very convenient due to its gratuity and its widespread presence, the 40% of the primary energy utilized in industrialized countries is emitted to the ambient as waste heat [1]. Nevertheless, most is low-temperature grade heat, explaining why its most common use is warming of fluids for heating or other purposes [2–4]. Thermoelectric generation is a promising technology for recovering low-temperature grade heat [5,6], it presents attractive characteristics such as no moving parts, modularity, reliability, robustness and maintenance free [7]. Moreover, its production of electricity is environmentally friendly [8].

The harvesting of waste heat by thermoelectric generators (TEGs) improves the efficiency of the applications and contributes to reducing fuel consumption [6]. Waste heat recovery can be widely produced: in industrial plants, power plants, waste incineration plants, vehicles, aircraft, helicopters, marine vessels and so on [9,10]. Below are presented some key findings for different types of waste heat recovery applications. A TEG comprised of four thermoelectric modules (TEMs) was built for a pellet boiler obtaining a maximum power output of 8.5 W at a temperature difference of 112.8 °C and achieving self-sufficient operation of the combustion and heating system [11]. The waste heat harvesting of a diesel engine by a TEG formed by 40 TEMs produced a maximum power output of 119 W, with a maximum energy conversion efficiency of 2.8% [12]. A 1 kW TEG using the 95 °C spring water of Tohoku district obtained a total energy generation of 1927 kWh [13]. A 10 kW class grid connected TEG system for JFE's continuous casting line was implemented with a total of 896 TEMs, which generated power using radiant heat [14]. A thermoelectric power density of

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Nomenclature

Symbol	Definition
A	area (m^2)
$b_{\dot{W}_{TEM}}$	systematic standard uncertainty of the thermoelectric generation
c_p	specific heat at constant pressure (J/kg K)
D_H	Hydraulic diameter (m)
E_t	electromotive force (V)
$h_{H,he}$	heat transfer coefficient of the interior of the chimney (W/m^2 K)
I	current (A)
I^i_{TEM}	current generated by the TEMs of block “i” (A)
k	thermal conductivity (W/mK)
M_{sample}	number of samples for each configuration
$\dot{m}_{gas}$	mass flow of the flue gases (kg/s)
n_{blo}	number of blocks
$Nu_{H,he}$	Nusselt number of the hot side heat exchanger
$\dot{Q}^{TEM}_C$	heat power to dissipate by a TEM (W)
$\dot{Q}_{Peltier}$	Peltier heat flux (W)
$\dot{Q}_{Thomson}$	Thomson heat flux (W)
$\dot{Q}_{Joule}$	Joule heat flux (W)
$\dot{Q}_{TEM}$	heat power that flows along the TEMs
$\dot{Q}^i$	heat power extracted from the flue gases in block “i” (W)
$\bar{q}$	volumetric heat generation (W/m$^{3)}$
R_L	load resistance (Ω)
R_0	electrical resistance of the material (Ω)
R^i_{CD}	thermal resistance of the cold side heat dissipator of block “i” (K/W)
R^i_{cont}	contact thermal resistance of block “i” (K/W)
R^i_{HD}	thermal resistance of the hot side heat dissipator of block “i” (K/W)
R^{TEM}_{CD}	thermal resistance of the cold dissipator per TEM (K/W)
R^{TEM}_{HD}	thermal resistance of the hot dissipator per TEM (K/W)
R^i_{loss}	thermal resistance of the heat losses through the free surface of block “i” (K/W)
R^i_{scr}	thermal resistance of the heat losses through the bolts of block “i” (K/W)
$s_{\overline{\dot{W}_{TEM}}}$	random standard uncertainty of the mean thermoelectric generation
t	time (s)
T_{amb}	ambient temperature (K)
T^i_C	temperature of the heat sink in block “i” (K)
T^{TEMi}_C	temperature of cold side of the TEMs in block “i” (K)
T_{en}	entry temperature of the flue gases (K)
T^i_{en}	entry temperature of block “i” (K)
T^i_{ex}	exit temperature of block “i” (K)
T^i_H	temperature of the heat source in block “i” (K)
T^{TEMi}_H	temperature of hot side of the TEMs in block “i” (K)
T^i_m	mean temperature of block “i” (K)
T^{TEM}_m	mean temperature of the TEMs (K)
$U_{\dot{W}_{TEM}}$	expanded uncertainty of the thermoelectric generation
v_{gas}	velocity of the flue gases (m/s)
V^i_{TEM}	voltage generated by the TEMs of block “i” (V)
$\dot{W}_{aux}$	auxiliary consumption (W)
$\dot{W}_{net}$	net generation (W)
$\dot{W}_{TEM}$	total thermoelectric generation (W)
$\dot{W}^i_{TEM}$	thermoelectric generation of block “i” (W)

Greek symbols

ρ	density (kg/m$^{3)}$
α	seebeck coefficient (V/K)
π	Peltier coefficient (V)
σ	Thomson coefficient (V/K)
η_{TEM}	efficiency of the TEMs
ΔT_{smoke}	temperature difference in the flue gases (K)
ΔT_{TEM}	temperature difference between the sides of the TEMs

Abbreviations

TEG	thermoelectric generator
TEM	thermoelectric module
TEU	thermoelectric unit
CFD	computational fluid dynamics

259 W/m^2 was obtained recovering waste heat from a paper mill’s combustion boiler using TEGs provided with thermosyphons [15]. The objective of improving a 5% the fuel economy of light-duty and/or personal automobiles by the use of TEG is nowadays is widely studied [16,17]. Some are the approaches: researching on the non-uniformity of the temperature difference across thermoelectric units along the streamwise direction [18], evaluating the weight penalty incurred when a TEG is located at the vehicle [19] and studying interior inserts to enhance thermal transfer but not negatively influence the back pressure [20] among others.

The experimental setups are not very common in the literature, most of the studies are referred to mathematical models able to simulate the behavior of the TEGs. Nevertheless, the computational models need to bear in mind all the thermoelectric effects, the dependence of the temperature on the properties and effects, and each of the element present in the system (including the heat exchangers, the contacts, the ceramics of the TEMs ...) [21–23]. Moreover, for those cases where the waste heat is scavenged, the temperature decrease of the flue gases must be taken into account to obtain accurate results, due to the big difference between the entry and exit temperatures that they experiment while flowing through the TEG [24]. Due to the low efficiency that the TEGs present [25,26], great amounts of energy are needed in these applications, resulting in a big temperature decrease that needs to be accounted for.

This study presents a novel computational model that accurately simulates the behavior of TEGs which harvest waste heat. It includes the temperature drop of the flue gases while they flow across the TEG, a very important variable to consider taking into account that the temperature difference between the entry and exit can be very considerable. Besides, this research includes a TEG that has been designed, built and experimentally tested to be located at the exhaust of a combustion chamber. The experimentation includes different parameters which influence the generation, such as the temperature and mass flow of the flue gases and the load resistances, parameters that have been included in the computational simulation.

2. Methodology and computational model

The computational model includes each of the thermoelectric phenomena (the Peltier, Seebeck, Thomson and Joule effects), it incorporates the totality of the elements included into the TEG (heat exchangers, ceramic plates, unions, screws, thermoelectric material...) and the properties of the materials are a function of the temperature. Moreover, it solves the transient state, and it