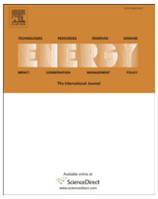
Energy 162 (2018) 715–727

Contents lists available at ScienceDirect

Energy

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



Effect of engine exhaust gas pulsations on the performance of a thermoelectric generator for wasted heat recovery: An experimental and analytical investigation

A. Nour Eddine [a, b, *], D. Chalet [b], X. Faure [a], L. Aixala [c], P. Chessé [b]

[a] French Alternative Energies and Atomic Energy Commission, District of Pays de la Loire, Bouguenais 44340, France
[b] Ecole Centrale de Nantes, LHEEA lab. (ECN/CNRS), Nantes, France
[c] French Alternative and Atomic Energy Commission, Thermoelectric Laboratory, Grenoble 38000, France

ARTICLE INFO

Article history:
Received 24 January 2018
Received in revised form
2 August 2018
Accepted 8 August 2018
Available online 9 August 2018

Keywords:
Thermoelectric generator
Internal combustion engine
Waste heat recovery
Pulsating flow
Heat transfer

ABSTRACT

Using thermoelectric generator (TEG) for waste heat recovery on internal combustion engines is a promising solution for efficiency improvement. This study investigates the behavior of TEG during engine operation. It distinguishes the effect of the engine flow properties on the TEG performance. Three test rigs have been designed and built to investigate this effect. The results confirm that there are two main engine exhaust gas properties that affect the TEG performance, namely: engine exhaust gas composition and engine exhaust gas pulsation.

An analytical model has been developed to identify and quantify the effect of each parameter on the convective heat transfer coefficient between the exhaust gas and the thermoelectric module, hence on the TEG performance. Test results show a difference in the TEG output power up to 30% between hot air and real engine test at perfectly similar TEG inlet temperature and mass flow rate. The model identifies that 5–12% of this difference is related to the gas composition whereas another test rig proves that the engine exhaust pulsating flow is responsible for the remaining difference (88–95%). Further studies will be conducted to improve the TEG design thanks to this pulsation effect behavior.

1. Introduction

In 1893, the German scientist Rudolf Diesel built the first prototype of a compression ignition (CI) engine that bears his name. These CI engines have a wide field of application and are characterized by their high efficiency in energy conversion. However, and despite all the improvements already achieved, 35% of engine efficiency [1] is no longer enough to face the increasing demand and consumption of fossil fuels. In Diesel engines, around 30% [2] of fuel energy is wasted as heat in the exhaust manifold. Thus, various methods were suggested for its recovery such as: turbo-compounding [3], turbo-charging [4] and Rankine cycles [5]. Among all these, thermoelectric generator (TEG) is starting to attract significant attention. A TEG is a technology which directly converts thermal energy into electrical energy thanks to the Seebeck effect of some materials. Despite its low thermoelectric conversion efficiency (3–5%) [6], it has already found its potential in many niche applications [7] due to its quiet, compact and emission-less operation. A possible solution to increase the efficiency of a TEG is using an intelligent algorithm used for mutli-objective optimization systems. The state of art of this kind of algorithms is resented by Cui et al. [8]. This system is used for energy management and optimization in petrochemical industries where in the work of Han et al. [9] showed up to 15% of energy saving efficiency.

The Seebeck effect, discovered by Thomas Johann Seebeck in 1821, is the fundamental operating principle of TEG [10]. The energy conversion efficiency of a thermoelectric material is a function of the dimensionless figure of merit (ZT) that depends on the material Seebeck coefficient ($V{\cdot}K^{-1}$), the thermal conductivity ($W.m^{-1}.\ K^{-1}$), the electrical conductivity (Siemens/m) and the temperature (K). During the last years, many researchers have focused on the physical properties of thermoelectric materials and the manufacturing techniques of thermoelectric modules (TEM). Either by comparing different thermoelectric materials properties

---

* Corresponding author. French Alternative Energies and Atomic Energy Commission, District of Pays de la Loire, Bouguenais 44340, France.

E-mail address: Ali.nour-eddine@ec-nantes.fr (A. Nour Eddine).

https://doi.org/10.1016/j.energy.2018.08.065
0360-5442/

Nomenclature

A	Contact area (m^2)
C_p	Specific heat ($J.kg^{-1}.K^{-1}$)
D_h	Characteristic length (m)
e	Thickness (m)
h	Heat transfer coefficient ($W.m^2.K$)
I	Generated current (A)
k	Thermal conductance of n-type and p-type ($W \cdot K$)
$\dot{m}$	Mass flow rate ($kg.s^{-1}$)
P_{elec}	Generated electrical power (W)
P_{th}	Thermal power (W)
P_{max}	Maximum output power (W)
q_s''	Cooling rate ($J.s^{-1}$)
Q	Heat (W)
r	Perfect gas constant ($J.Kg^{-1}.K^{-1}$)
rpm	Engine rotational speed ($round.min^{-1}$)
R	Electrical resistance (Ω)
R^2	Coefficient of determination
T	Temperature (°C)
V	Voltage (V)
Z	Factor of merit ($1.K^{-1}$)
ZT	Figure of merit

Greek symbols

α	Seebeck coefficient ($V \cdot K^{-1}$)
η	Thermal efficiency
λ	Thermal conductivity ($W.m^{-1}.K^{-1}$)
λ_{inox}	Inox thermal conductivity ($W.m^{-1}.K^{-1}$)
μ	kinematic viscosity ($kg.m^{-1}.s^{-1}$)
σ	Local conductivity ($Siemens.m^{-1}$)
Φ	Heat flux (W)
ω	Uncertainty

Subscripts

ai	Air inlet
ao	Air outlet
c	Heat exchanger cold side
cond	Conductive
conv	Convective
gi	Gaz in
h	Heat exchanger hot side
in	Inlet
inox	Thermal conductivity of the Inox
I	Internal
L	Load
n	n-type
out	Outlet
p	p-type
s	Surrounding
wil	Wall inner layer
wol	Wall outer layer
∞	Infinity

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Abbreviations

ICE	Internal combustion engine
OP	Operating points
RTG	Radioisotope thermoelectric generator
TE	Thermo electric
TEG	Thermo electric generator
TEM	Thermo electric module

[11], working on new fabrication techniques [12], or studying the compatibility with a chosen application [13]. In addition to the improvement of the thermoelectric material and module, the global system analysis and optimization present also a great area of improvement for higher performances. Thus, the heat transfer from the heat source up to the module has been in the scope of many studies. This involved several domains such as: the effect of Joulean electrical resistive losses and conduction heat losses which was numerically investigated by Chen et al. [14] in early 2000, the effect of surface–to-surrounding convection heat transfer losses which was numerically investigated by Rabari et al. [15], the effect of decreasing the contact resistance investigated by Tae Young et al. [16] and recently proved by the experimental validation of the effect of the clamping pressure on a TEG prototype designed for automotive engine application [17]. Several authors investigated the effect of this heat transfer such as Tang et al. [18] that showed an 11% power loss in the modules due to thermal imbalance. This justify the recent studies that aims to identify the best adaptable type heat exchanger for TEG configuration [19]. The direct relation between the heat transfer and the TEG performance is well proven in the literature, which means an extensive understanding and improvement of the heat transfer between the fluid and the surface of the heat exchanger is required in any future TEG application. Despite investigating several parameters affecting the heat transfer, none has mentioned the effect of the oscillatory flow which is inherent to engine exhaust port and which proven that have an effect of the heat transfer, hence it can have an effect of TEG performance.

The use of oscillatory flows to enhance heat transfer is a broad area which has also received much attention in the recent years. One of the early studies of this kind is reported by Siegel et al. [20], where they have demonstrated that heat transfer explicitly depends on the frequency of the pulsations. A wide literature survey on oscillatory flow is reported by Cheng and Zhao [21]. They have investigated two different groups of oscillatory flow: pulsating flow and reciprocating flow. The researchers showed and enhancement on heat conduction when high frequency and low amplitude oscillations [22], and convective heat transfer enhancement in a low frequency large tidal displacement oscillating flow [23]. Several researches aimed to determine the underlying mechanism for the observed heat transfer enhancement in an oscillatory flow. Li et al. [24] have investigated heat transfer in oscillating flows at low frequencies and large amplitudes by numerical simulations. They found that the heat transfer enhancement in an oscillatory flow may be the cause of intra cycle oscillations that promote fluid mixing. Bouvier et al. [25] have experimentally investigated the heat transfer in an oscillating flow inside a cylindrical tube. The Fourier's transforms of temperature measures at several radial positions showed that predominant frequencies are not the same in the wall and in the fluid, as if the wall acts as a low pass filter with respect to the thermal solicitation imposed by the heated oscillating flow on the fluid temperature signal. Thus, establishing a non-dimensional correlation including frequency effect within a Nusselt correlation has been attempted by Akdag et al. [26] through cycled-averaged Nusselt number. They showed an increased global heat transfer with increasing both the frequency and the amplitude