Applied Energy 210 (2018) 327–338

Contents lists available at ScienceDirect

Applied Energy

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

A dynamic model for thermoelectric generator applied to vehicle waste heat recovery

Song Lan, Zhijia Yang, Rui Chen*, Richard Stobart

Department of Aeronautical and Automotive Engineering, Loughborough University, LE11 3TU, UK

HIGHLIGHTS

- Developed a dynamic model of TEG system designed for vehicle waste heat recovery.
- Experimental validations are performed on both a TEM test rig and a TEG engine test bench.
- The model can be used as a basis for a model-based control design.
- The integration of TEMs with the HXRs is important for the overall power output.

ARTICLE INFO

Keywords:
Module-based
Dynamic model
Thermoelectric generator
Automotive waste heat recovery

ABSTRACT

Waste heat recovery using a thermoelectric generator (TEG) is a promising approach for vehicle original equipment manufacturers to reduce fuel consumption and lower CO_2 emissions. A TEG can convert otherwise wasted thermal energy from engines to electricity directly for use in the vehicle systems. This paper focuses on the development of a dynamic model of TEG system designed for vehicle waste heat recovery, which is made up of counter-flow heat exchangers (HXRs) and commercial thermoelectric modules (TEMs). The model is built from thermoelectric materials into a TEM and then into a TEG system. Compared to other TEG models, the tuning and validation process of the proposed model is more complete. Experiments are done on both a TEM test rig and a heavy-duty diesel engine, which is equipped with a prototype TEG on the exhaust gas recirculation (EGR) path. Simulations of steady-state operating points as well as the response to typical engine cycle test show good agreement with experimental data.

A TEG installed upstream of the after-treatment system in a heavy-duty truck has been modelled to predict the temperatures and power output in a dynamic driving cycle. The simulation results of temperatures show the model can be used as a basis to develop a control system for dynamic operation to ensure safety operation of TEG and efficient operation of the after-treatment system. A comparison of power output of the systems under different scenarios underlines the importance of integration of TEM with HXRs. Based on the simulation results, around 20% average power output increase can be expected by optimizing the thermal contact conductance and the heat transfer coefficient of hot side HXR.

1. Introduction

Driven by CO_2 legislation and fuel cost, car original equipment manufacturers have emphasised the efficiency of the engine and drivetrain. For the typical energy flow path of an internal combustion engine (ICE), approximately one third of the energy is discharged by exhaust gas. Interest in waste-heat recovery (WHR) has flourished in recent years [1–4]. Thermoelectric generator (TEG), as one of the WHR methods, has attracted substantial interest because of its advantages of silent operation and compactness. The performance of current TEG systems is largely decided by the thermoelectric modules (TEMs). Significant strides have been made in the materials of TEMs and recent work is beginning to translate those material improvements into TEG performance [4].

In the development of TEG for WHR, a number of modelling studies have been carried out to evaluate the performance [3,5–9] and optimize the design parameters [10–13]. However, only a few of studies [8,6,12,13,9] took the dynamics of the WHR systerm into account. In fact, the transient performance of TEG is important, especially in the application of vehicle WHR. First of all, the exhaust heat flow is often changeable during a normal operation of the car where start-up, shutdown, and engine load changes are a major concern. Yu et al. [8]

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* Corresponding author.
E-mail address: r.chen@lboro.ac.uk (R. Chen).

https://doi.org/10.1016/j.apenergy.2017.11.004
Received 26 June 2017; Received in revised form 25 September 2017; Accepted 1 November 2017

Nomenclature

Abbreviation

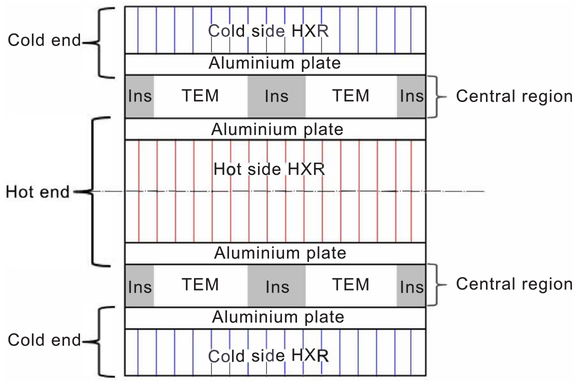
DOC	diesel oxidation catalyst
DPF	catalyst-diesel particulate filter
HXR	heat exchanger
ICE	internal combustion engine
MAE	mean absolute error
NRTC	non-road transient cycle
Nu	Nusselt number
Pr	Prandtl Number
Re	Reynolds number
TEG	thermoelectric generator
TEM	thermoelectric module
WHR	waste-heat recovery

Subscripts

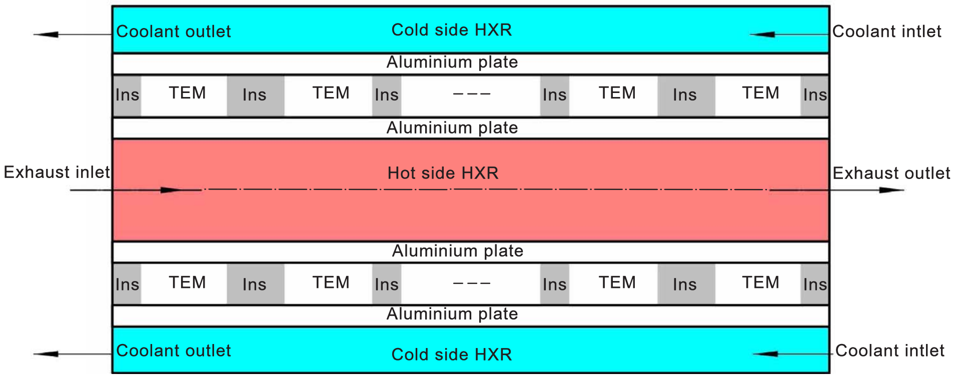
ap	aluminium plate
cd	cold end
col	coolant
cp	ceramic plate
ct	contact
cxr	cold side heat exchanger
exh	exhaust gas
gap	air gap
hd	hot end
hxr	hot side heat exchanger
in	gas-in & coolant-in
load	electrical load
n	n-type thermoelectric element
ocv	open circulate
out	output & gas-out & coolant-out
p	p-type thermoelectric element
tc	thermocouples

Symbols

$\dot{m}$	flow rate, kg/s
σ	electric conductivity, S/m
A	area, m^2
b	tuning constant
c	specific heat capacity, J/(kg K)
D	hydraulic diameter, m
F	clamping force, N
h	heat transfer coefficient, W/(m^2 K)
I	current, A
K	thermal conductance, W/K
k	thermal conductivity, W/(m K)
l	length, m
M	mass, kg
n	number
P	power, W
Q	heat flow rate, W
R	electrical resistance, Ω
S	Seebeck coefficient, V/K
T	temperature, K
U	voltage, V



(a) Front view of a TEG system.



(b) Side view of a TEG system.

Fig. 1. Structure of a TEG system.