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Research Paper

Modeling and fabricating a prototype of a thermoelectric generator system of heat energy recovery from hot exhaust gases and evaluating the effects of important system parameters

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HIGHLIGHTS

- A thermoelectric module with a low thermal conductivity is more effective.
- System efficiency could be improved by using liquids on the cold and hot side of TEG.
- The thermal conductivity of the heat sinks has no significant effect on efficiency.
- The good results have been yielded, especially at temperatures lower than 100 °C.

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ABSTRACT

The heat lost through smokestacks has an adequate energy recovery capacity. A new and effective method of recovering this energy is the use of thermoelectric generators, which directly convert thermal energy to electricity. Some of the advantages of thermoelectric generators include their environmental friendliness and also their lack of moving or rotating parts, which makes them operate without noise and extends their service life. This paper deals with the general modeling of a thermoelectric generator system, including the modeling of the cooling system for the cold side of thermoelectric generator, system of heat transfer from smokestack to the hot side of thermoelectric generator and also the modeling of the thermoelectric modules themselves. In continuation, for validating the obtained equations, an experimental prototype of this thermoelectric generator is fabricated and the empirical results including the nominal voltage, current and power of the manufactured system are compared with the theoretical results. This comparison shows the validity of the presented modeling and the good agreement between the theoretical and practical results, especially at low temperatures. Based on the calculations, the highest error was 4.6 percent for a temperature difference of lower than 100 °C. Additionally, for the same temperature difference, the highest theoretical and practical output powers for this module were 3.4 W and 2.8 W, respectively. Considering the matching of these results, the effects of some important parameters on the output power of the considered thermoelectric generator are also investigated, and the significant influence of the thermal conduction coefficient of thermoelectric modules is demonstrated.

1. Introduction

Petroleum-based and fossil fuels have been utilized extensively in transportation systems throughout the world; although for reasons such as the depletion of oil resources, environmental problems, and the regulations and limitations set by governments for reducing the consumption of fossil fuels, alternative fuels and vehicle powertrain systems are getting better in quality and more efficient [1].

Many of the existing commercial and environmental problems can be solved and socioeconomic benefits can be gained by improving the conditions of consumed fuels. Some of these issues are as follows:

- Despite the increase of energy efficiency in many developed countries these countries still depend on foreign countries for the fuel they need; and a substantial amount of this imported fuel (almost half of it) is utilized in vehicles and trucks [2].

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Nomenclature

A	area (m^2)
b	space between the fins (m)
C_p	specific heat (J/kg · K)
D	diameter of a circular tube (m)
f	fanning friction factor
h	heat transfer function ($W/m^2 \cdot K$)
I	current (A)
K	thermal conductance (W/m · K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu_D	Nusselt number
n	number of fins
P	electrical power (W)
Pr	Prandtl number
Q	heat flow (W)
R_b	thermal resistance of heat sink base (W/K)
R_i	internal resistance (Ω)
R_L	load resistance (Ω)
R_{hS}	heatsink thermal resistance (W/K)
Re_D	Reynolds number
r	radius (m)
T	temperature (K)
T_b	bulk temperature of the exhaust gas
TE	thermoelectric
TEG	thermoelectric generator
T_C	cold junction temperature in a thermoelectric module
T_h	hot junction temperature in a thermoelectric module
t_b	heat sink base thickness
t_f	fin thickness
u_m	mean fluid velocity
V_O	output voltage (v)
W_f	fin width (m)

Greek symbols

α	seebeck coefficient
ΔT	temperature difference
η_f	fins efficiency
ρ	density

Subscripts

b	base
c	cold side
f	fins
h	hot side
i	input
L	load
m	mean
o	output

- Almost one-third of carbon emission in the world is produced by various vehicles. Inefficient and fuel-guzzling vehicles are major causes of increased carbon production; and the increase of carbon dioxide along with other greenhouse gases is a key factor in global warming [3].
- Equipped with systems such as accident.
- Navigation systems, future and next-generation vehicles should be able to produce on-demand power; which requires more fuel consumption.

Almost all personal vehicles and light trucks are equipped with engines that run on gasoline or diesel. The energy consumption of a gasoline-burning internal combustion engine has been shown in Fig. 1 [4]. As is observed, 70% of the energy contained in fuel is lost, as heat, from the exhaust pipe or in the cooling process and the rest is converted to mechanical work and energy.

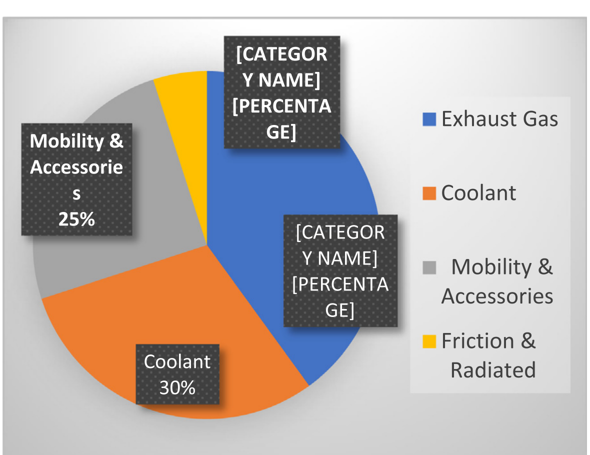

Fig. 1. Energy consumption of a gasoline-burning internal combustion engine.

A portion of this produced work is used to overcome friction in the power transmission system of a vehicle and its other equipment such as cooling pump, fuel pump, etc. Consequently, only 20–25% of the initially produced energy is used to drive the vehicle. Moreover, this remaining energy has to overcome the following:

- inertia generated during the acceleration or uphill movement of vehicle,
- aerodynamic drag force
- friction between vehicle tires and road surface

There are three major ways of reducing fuel consumption in vehicles [5]:

- Increasing the overall efficiency of power systems (engine, power transmission system, etc.) in order to produce more work from the consumed fuel, reducing the amount of work needed to move a vehicle by lowering its weight
- Reducing the friction between vehicle tires and road, etc and
- Recovering the energy dissipated from a vehicle.

1.1. Energy recovery from exhaust pipes

A considerable amount of unused heat (about 40% according to Fig. 1) is dissipated via the exhaust pipe of a vehicle. Here, the notion of fuel consumption improvement means to increase the overall efficiency of a vehicle's power transmission system which has lost a great deal of energy through the discharged exhaust gases. According to the book of "Vehicle Electronics and Electricity" published in 1999, the average electricity consumption of an automobile is 600 W [6]; which imposes an extra load on the engine to provide this power. If the heat lost through a vehicle's exhaust pipe can be utilized to generate the electricity needed by the vehicle, a substantial amount of load can be removed from vehicle engine. One method of converting the dissipated heat to electricity is the use of thermoelectric (TE) converters.