Case Studies in Thermal Engineering 12 (2018) 358–364

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Effect on TEG performance for waste heat recovery of automobiles using MgO and ZnO nanofluid coolants

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ARTICLE INFO

Keywords:
Nanofluid
Reynolds number
Circuit voltage
Thermoelectric generator
Conversion efficiency
Waste heat recovery

ABSTRACT

Present study deals with the theoretical analysis for the performance comparison of automotive waste heat recovery system with EG-W, ZnO and MgO nanofluidas coolants for TEG system. Effects on performance parameters i.e power output, conversion efficiency and circuit voltage of TEG system with exhaust inlet temperature, total area of TEG, Reynolds number and particle concentration of nanofluids for TEG system have been investigated. Theoretical performance analysis revealed enhancement in output power, conversion efficiency and voltage of the TEG system for MgO nanofluid, followed by ZnO and EG-W coolants. The power output and the conversion efficiency using 1% vol. fraction MgO nanofluid at an inlet exhaust temperature of 500 K, were enhanced by 11.38% and 10.95% respectively, as compared to EG-W coolants. The further increase in nanofluid concentration exhibited a progressive effect on output performance of the TEG system. Further analysis shows that there exists an optimal total area of TEGs for maximum output performance of the system. With MgO nanofluid as a coolant, total area of TEGs can be reduced by up to 33% as compared to EG-W, which would bring significant convenience for the arrangement of TEGs and reduce the cost of TEG system.

1. Introduction

In an Internal Combustion engine, only one third of chemical energy is converted to useful work [1]. A major component of this energy is wasted as heat from the exhaust gas. Various studies [1–4] have been done to recover this waste heat by use of thermoelectric generator (TEG). Thermoelectric generator is a solid state energy conversion device which produces voltage when a temperature difference is applied across its ends. Absence of moving parts, prolonged life [5] and compactness makes it a reliable device for converting heat to electricity. Though extensive research has been done, the nominal efficiency of TEG is a hindrance to its practical application. One of the ways by which the limited efficiency can be improved is by increasing the heat transfer at the cold side of the TEGs. Traditional heat transfer fluids like water and engine coolant have low thermal conductivity. Nanofluids on the other hand, have improved thermo physical properties due to presence of metal oxides, which have much higher thermal conductivity than base fluids. Due to improved thermal conductivity, nanofluids have been extensively used for the recovery of waste heat from the automobiles [6,7]. Li et al.[8] studied the performance of TEG system with graphene-water nanofluid as a coolant for cold side and reported that an increase of 11.29%, 21.55% and 3.5% in the voltage, power output and conversion efficiency respectively, with 5% vol. Concentration. Also, a similar performance analysis reported an increase in power output by at least 12.65% by use of Cu-EG nanofluid and Cu-EG/water as nanofluid [9]

With an experimentation for various oxide nanofluids, Xie et al. [9] concluded that, among all the various samples, EG-

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https://doi.org/10.1016/j.csite.2018.05.006
Received 17 April 2018; Received in revised form 8 May 2018; Accepted 10 May 2018
Available online 12 May 2018
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Nomenclature

m_f	Mass flow rate of exhaust gas
m_c	Mass flow rate of coolant
N_x	Number of TEG module in X direction
N_y	Number of TEG module in Y direction
α_p	Seebeck coefficient for P- type material
α_n	Seebeck coefficient for N- type material
I	Current
T_h^i	Temperature of hot side TEG module
k_{pn}	Electrical conductivity of P-N junction
T_l^i	Temperature of cold side TEG module
R_{pn}	Resistance of P-N junction
Q_l^i	Heat transfer per unit area from cold side
l	Length of TEG module
b	Width of TEG module
h	Height of TEG module
λ_p	Thermal conductivity of P- type leg
λ_n	Thermal conductivity of N- type leg
h_f	Heat transfer coefficient for cold side
h_f	Heat transfer coefficient for hot side
h_c	Heat transfer coefficient for cold side
Ar	Area of TEG
T_{fav}^i	Average exhaust side temperature
T_{cav}^i	Average coolant side temperature
T_f^i	Initial exhaust temperature
T_f^{i+1}	Exit exhaust temperature
C_{pf}	Specific heat capacity of exhaust gas
C_{pc}	Specific heat capacity of coolant
C_{pf}	Specific heat capacity of nanofluid
T_c^i	Initial coolant temperature
T_c^{i+1}	Exit coolant temperature
Q_h^i	Heat transfer per unit area from hot side
V_i	Discretized voltage of TEG module
V_{total}	Voltage for TEG system
R_{eq}	Total resistance of the TEG modules
R_l	Load resistance
I_o	Initial current
P	Power output
ρ_{nf}	Density of nanofluid
Nu_{nf}	Nusselt number of nanofluid
Pe_c	Peclet number of nanoparticle
Re_{nf}	Reynold's number of nanofluid
Pr_{nf}	Prandlt number of nanofluid
Φ	Volume fraction of nanofluid

MgOnanofluid possess higher thermal conductivity of 40.6% and low viscosity at 5% vol. concentration. Also it is observed that, thermal conductivity dropped up to 5% of the initial value, when nanofluid was kept for 24 h which indicates its stability. The enhanced thermal transport properties of EG-MgO nanofluid is because of nanoparticles interactions and its lower viscosity [10,11]. MgO nanoparticles with water and propylene glycols base fluid have also shown improved heat transfer properties [12,13]. Most of the studies use Maxwell's equation for predicting thermal conductivity. At lower concentration the model holds true but anomaly was seen at higher concentration of nanofluid [14]. Jang et al.[15] concluded that the anomaly was due to different particle size, particle clustering, nanolayering and brownian motions which are neglected in Maxwell equations. Jeong et al. [16] studied the effect of particle shape on the thermal conductivity and viscosity of ZnO nanofluid and investigated that an increase of 12% in thermal conductivity at 5% vol. fraction for spherical ZnO nanoparticles. Saleh et al. [17] obtained a minimum 14% increase in thermal conductivity of nanofluid at 5% vol. concentration with particle size between 18 and 23 nm by using ZnO-EG nanofluid for heat pipe. A part from thermal properties in base fluids, MgO nanostructures has been investigated for antibacterial properties [18] and optical properties of ZnO especially core-shell structures are under intensive research [19].

In the present work, TEG based waste heat recovery system is studied with nanofluids (ZnO and MgO) and EG-W(50/50) as coolants. The governing equations have been formulated and solved using EES. Various performance parameters and temperature distribution of the TEG modules, with different inlet temperature of exhaust gas, concentration of nanofluid, mass flow rate variation (Reynolds Number) and total area of TEGs have been analyzed. Further comparative study analysis between ZnO, MgO nanofluids and EG-W has been discussed for maximum performance and optimum total area of TEG.

2. Mathematical modeling and simulation

The configuration of TEG system with Bi_2Te_3 material properties and its dimensions for P and N type are shown in Table 1. Conservation of energy forms and the basis of the model have been developed with the following assumptions:

Table 1
Parameters of thermoelectric material.

Semiconductor Parameters	Value
Seebeck coefficient of P-type leg	$2.037 * 10^{-4}$ V/K
Seebeck coefficient of N-type leg	$1.721 * 10^{-4}$ V/K
Resistivity of P-type leg	$1.314 * 10^{-5}\Omega m$
Resistivity of N-type leg	$1.119 * 10^{-5}\Omega m$
Length of P- and N-type leg	5 mm
Width of P- and N-type leg	5 mm
Height of P- and N-type leg	5 mm
Thermal conductivity of P-type leg	1.265 W/m K
Thermal conductivity of N-type leg	1.011 W/m K

- Heat transfer attains a steady state on both sides of TEG.
- Heat rejected from exhaust gas is equal to heat gained by the hot side of TEG.
- Heat transfer due to thermal radiation is neglected
- The contact resistances between the TEG - exhaust gas and TEG - coolant is neglected.
- Heat transfer in the ducts is neglected

The fluid flow for hot and cold fluid TEG system is in parallel configuration. All the TEGs are assumed to be divided into N_x and N_y computational units. X - direction have N_x rows, which are marked by the alphabet i [0, N_x] and Y - direction have N_y rows marked by the alphabet j [0, N_y]. Based on the above nomenclature, computing unit can be represented by the coordinates in the same plane as (i, j) as shown in Fig. 1.

The governing equations for the heat transfer process using basic laws of thermodynamics are as follows:

$$Q_{i,h} = N_y\left[\alpha_{pn} I T_{i,h} + k_{pn}(T_{i,h} - T_{i,l}) - \frac{I^2 R_{pn}}{2}\right] \tag{1}$$

$$Q_{i,l} = N_y\left[\alpha_{pn} I T_{i,l} + k_{pn}(T_{i,h} - T_{i,l}) + \frac{I^2 R_{pn}}{2}\right] \tag{2}$$

Eqs. (1) and (2) have been taken into account Joule effect, Peltier effect and heat conduction loss of TEGs. Various electrical properties of P-N junction are defined as follows.

$$\alpha_{pn} = \alpha_p - \alpha_n \tag{3}$$

Where,

$$k_{pn} = \frac{l\,b(\lambda_p - \lambda_n)}{h} \tag{4}$$

$$R_{pn} = \frac{h(\rho_p - \rho_n)}{l\,w} \tag{5}$$

Newton's cooling law describes the heat flux for the hot and cold side of TEGs by,

$$Q_{i,h} = N_y h_f Ar(T_{i,fav} - T_{i,h}) \tag{6}$$

$$Q_{i,l} = N_y h_c Ar(T_{i,l} - T_{i,cav}) \tag{7}$$

Due to steady state assumption, heat gained by the hot side of TEGs, $Q_{i,h}$ must be equal to the heat lost by the exhaust. Similarly phenomenon happens with the cold side of TEGs $Q_{i,l}$ and the coolant. Mathematically,

$$Q_{i,h} = C_{pf} m_f(T_{i,f} - T_{i+1,f}) \tag{8}$$

$$Q_{i,l} = C_{pc} m_c(T_{i+1,c} - T_{i,c}) \tag{9}$$

The initial and boundary conditions of the present modeling are,

$$T_f^1 = 500\,K \quad T_c^1 = 298\,K \tag{10}$$

All the thermoelectric modules in the system are connected in series. Thus the output voltage provided by all TEGs in a column is given by,

$$V_i = N_y \alpha_{pn}(T_{i,h} - T_{i,l}) \tag{11}$$

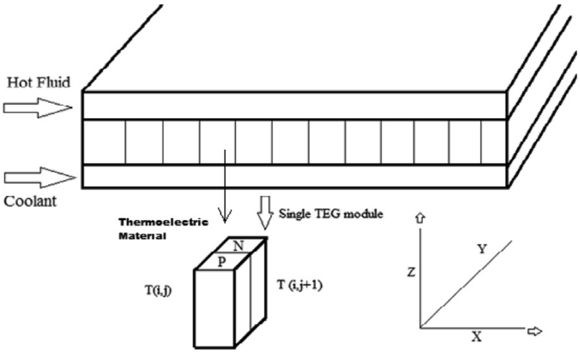

Fig. 1. Mathematical model and arrangement of TEG system.

The total output voltage of the system, thus can be calculated as,

$$V_{total} = N_y \alpha_{pn} \sum_{1}^{N_x} (T_{i,\,h} - T_{i,\,l}) \tag{12}$$

Total electrical resistance in the circuit is addition of resistance of P-N junction and load resistance.

$$R_{eq} = N_x N_y R_{pn} + R_l \tag{13}$$

Total current is then given by Ohm's law

$$I_c = V_{total}/R_{eq} \tag{14}$$

The suitable hot side heat transfer coefficient has been taken as 80 W m^2 K^{-1} [20]. The heat transfer coefficient for cold side of TEGs and nanofluid coolants can be calculated by evaluating Nusselt number of nanofluid for laminar or turbulent conditions [21,22].

$$Nu_{nf}(la\min ar) = 0.4328\,\mathrm{Re}_{nf}^{.333}\mathrm{Pr}_{nf}^{.4}(1 + 11.285\varphi^{.754}Pe_d^{.218}) \tag{15}$$

$$Nu_{nf}(turbulent) = 0.0059\,\mathrm{Re}_{nf}^{.9238}\mathrm{Pr}_{nf}^{.4}(1 + 7.6286\varphi^{.6886}Pe_d^{.001}) \tag{16}$$

$$Nu_{nf} = h\,D/k_{nf} \tag{17}$$

Inlet condition of the hot fluid and cold fluids temperature (EG-W and 1% vol. fraction of nanofluids) are 500 K and 298 K respectively. Mass flow rate and the other fluid properties are listed in Table 2. Using above mentioned conditions the model was solved using (EES). The iterative method was used to solve the problem in which an initial current I_o was assumed to obtain the temperature distribution of the TEG system to find the current I.

Power output, a critical parameter to evaluate the performance of TEG can be calculated as,

$$P = \sum_{i}^{N_x} (T_{i,\,h} - T_{i,\,l}) \tag{18}$$

Thermoelectric conversion efficiency, an equally important parameter is defined by the ratio of total power output and heat captured at hot side of TEG can be obtained as,

$$\eta_{convs.} = \frac{P}{\sum_{0}^{Nx} (Q_{i,\,h})} \tag{19}$$

The numerical code has been validated with theoretical result [20]. With the comparison for temperature gradient of hot and cold side fluid of TEM system, for the same geometry and operating conditions($T_{fi} = 500\,K, T_{ci} = 298\,K,\ m_c = m_a = 0.03\,kg/s$, *1% vol. concentration* of *nanofluid*), similar trend has been observed and showed maximum 3% and 2% deviations between the predicted and theoretical data.

3. Results of TEG system performance

Variation of circuit voltage and total power output of TEGs for coolants EG-W, ZnO, MgO nanofluids with 1% vol. fraction are shown in Fig. 2. The inlet temperature of exhaust is 500 K and coolant mass flow rate is 0.03 kg/s. A gradual decrease in hot side TEG temperature is observed for all coolants, due to continuous heat transfer between exhaust gas and hot side of the TEGs. Comparing coolants with same mass flow rate, MgO nanofluid has a higher cold side heat transfer coefficient as compared to other coolants. Thus it causes lower cold side temperature of TEGs. Also with MgO nanofluid, the temperature gradient between the hot side and cold side of TEGs is higher, followed by ZnO nanofluid and EG-W. The temperature gradient across TEGs is directly proportional to power and voltage developed. Thus from the analysis it is observed that MgO nanofluid has 11.38%, 10.95% higher power output and voltage, respectively compared to EG-W as coolant. However, Fig. 3 shows the variation of power output and voltage with different exhaust inlet temperature, with same mass flow rate and 1% vol. concentration of MgO, ZnO nanofluid and EG-W as coolants. It is observed that for all mentioned coolants, power output increases with exhaust inlet temperature. The reason is that, with increasing exhaust

Table 2
Coolant Properties.

Parameters	Value
Inlet temperature of cold fluid	298 K
Inlet temperature of hot fluid	500 K
Specific heat capacity of EG-W	3340 J/kg K
Specific heat capacity of exhaust gas	1020 J/kg K
Heat transfer coefficient of exhaust gas	80 W m^2/K
Mass flow rate of exhaust gas	0.03 kg/s
Mass flow rate of cold fluid	0.03 kg/s

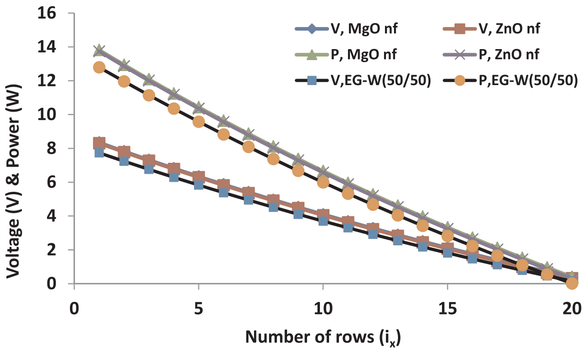

Fig. 2. Variation of voltage and power of TEMs.

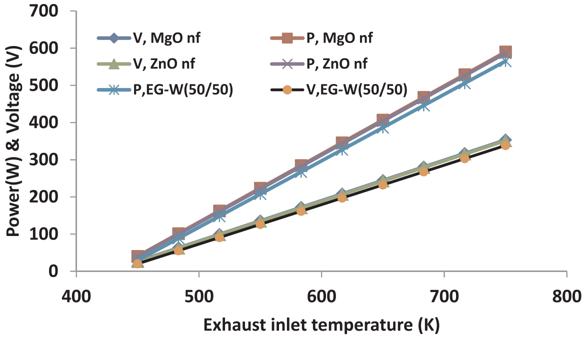

Fig. 3. Variation of voltage and power for TEG system.

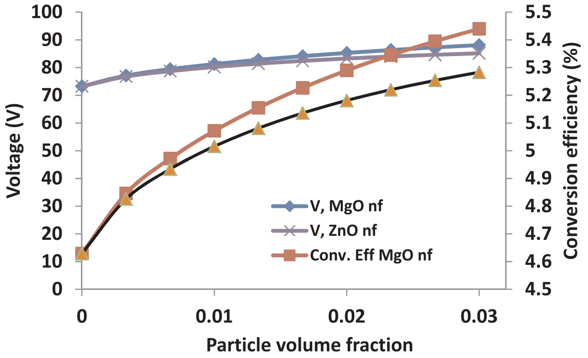

Fig. 4. Variation of voltage and conversion efficiency for TEG system.

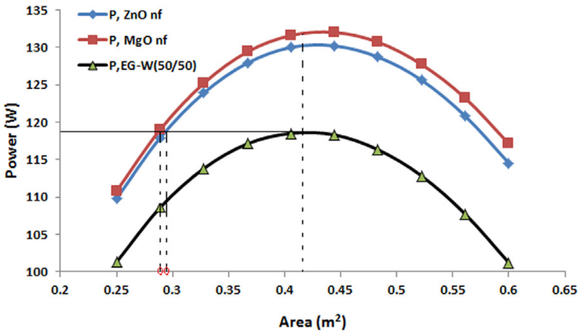

Fig. 5. Variation of power with total area of TEG system.

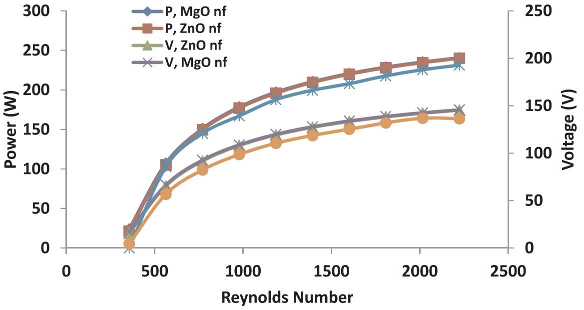

Fig. 6. Variation of power and voltage of TEG system.

inlet temperature, heat transferred on the hot side of TEGs increases while the condition on the cold side remains same. This results in a higher temperature gradient across TEG modules. At an exhaust inlet temperature of 650 K, the increase in power output and voltage for MgO nanofluid are 5.28% and 5.16% respectively, compared to EG-W as coolants and followed by ZnO nanofluid.

The effects of different concentrations on circuit voltage performance and conversion efficiency of the TEG system at exhaust inlet temperature 500 K with a coolant mass flow rate of 0.3 kg/s have been shown in Fig. 4. The result revealed that the conversion efficiency and voltage for different concentrations of nanofluids are higher than that of EG-W. The performance parameters gradually increase, with the increase in concentration of nanofluid. 3% vol. fraction of MgO nanofluid as coolant has 20.33% higher circuit voltage and 0.81% higher conversion efficiency, compared to EG-W coolants followed by ZnO nanofluid, for the TEG system. The reason is the enhanced heat transfer coefficient of MgO nanofluid than EG-W, resulting in a higher temperature difference and hence higher performance.

The effect on total area of TEMs with power output has been shown in Fig. 5 at an exhaust inlet temperature of 500 K and mass flow rate of exhaust and coolant at 0.03 kg/s. The optimal total area of TEGs exists for maximum output of the TEG system, which is 0.43 m^2 for EG-W and 0.2867 m^2 and 0.2925 m^2 for MgO nanofluid and ZnO nanofluid respectively with 1% vol. concentration. Thus with the application of nanofluid the optimal area of TEG system decreases with a range of 30–33% with comparison to EG-W coolants for waste heat recovery through TEG system. Possible reason is that, due to the enhanced heat transfer coefficient by using nanofluid coolant, TEGs tend to recover more waste heat energy as compared to EG-W. Thus, the optimal value of the TEGs area shrinks as compared to the EG-W as coolant. Due to decrease in total area, less number of TEMs is required to obtain peak power output. This would result in lower number of TEGs, their appropriate placement and thus save cost of the system. Also it is observed that for the same total area of TEG system the enhancement in power output for the system are about11.38% and 9.86%for MgO, ZnO nanofluids respectively. The enhancement in power output is due to their conductivity and higher heat transfer coefficients.

Distribution of circuit voltage and power output of TEG system with Reynolds number (coolant mass flow rate range 0.016 kg/s-0.1 kg/s) at an inlet exhaust temperature of 500 K and 1% vol. fraction of nanofluids have been shown in Fig. 6. It is observed that with increase in Reynolds number power output and circuit voltage gradually increases. At a Reynolds number of about 2200, MgO nanofluid has 3.52% higher power output, 4.01% higher voltage, compared to EG-W coolant and followed by ZnOnanofluid for TEG system. The possible reason of this may be the enhanced thermal conductivity and the viscosity of the fluid by addition of nanoparticles due to their large aspect ratio. The increase in thermal conductivity results in higher heat transfer, which further results in increase in performance of the system.

4. Conclusions

The theoretical analysis presented here investigates and compares the performance of TEG based waste heat recovery system with EG-W, MgO nanofluid and ZnO nanofluid as coolants. The outcome of the present analysis are summarized as follows:

- Compared to EG-W, MgO nanofluidcoolant attains a lower temperature at cold side and a wider temperature gradient across TEGs under same mass flow rate condition, which effectively improves power output and circuit voltage of the TEG system.
- Among all mentioned nanofluids, for the same power output of TEG system, MgO nanofluid decreases the optimal total area of TEGs upto 33% as compared to EG-W followed by ZnO nanofluid. Reduction in TEG system area will also lead to reduction in cost of the overall TEG system.
- For the same area of TEG system, the power output is enhanced by 11.38% and 9.86% for MgO nanofluid and ZnO nanofluidsin comparison to EG-W as coolant. Also, for same area of the TEG system, the optimal concentration of ZnO nanofluid coolant is about7% with 20.57% enhancement in power.

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