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An experimental study on the balancing of heat exchanger surface temperature distribution and module output power in a TEG containing multiple thermoelectric modules via integrated PCM.

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Abstract

Thermoelectric modules are a promising technology for waste heat recovery and converting it into electrical energy without any moving parts. However, achieving equal power output of TEMs in thermoelectric generators formed with different row and column combinations of multiple TEMs is a significant problem. In this paper, a phase change material was used in the cold side heat exchanger along with the engine coolant to balance the power output of the TEMs in a TEG designed with a rectangular geometry and 3 layers, 24 TEMs. In addition, 10% by weight of Al₂O₃ and graphite nanoparticles were added to the PCM to increase its effectiveness. In experimental studies conducted with a propane-powered SI engine at full-load and in the 2000-4000 rpm range, it was observed that when PCM is used in EC_hex, the surface temperature of both sides of the heat exchangers distribution becomes homogeneous along the TEG plane, and consequently, the output powers of the TEMs become closer to each other. It was observed that the addition of nanoparticles to PCM contributed to both the convergence of TEM output powers along the TEG plane and the increase in the total output power of the TEG; this effect was more pronounced for graphite, increased with motor speed, and increased by 6.18% at 4000 rpm compared to using 100% PCM with 90% PCM + 10% graphite. Moreover, adding a nanoparticle to the PCM also increased the efficiency and fuel energy recovery rate of the TEG at five engine speeds.

Keywords: Exhaust waste heat recovery, SI engine, TEG, PCM/Paraffin, Power balance in TEMs

1. Introduction

In internal combustion engines (ICEs), a small portion of the fuel's chemical energy is used to produce useful mechanical output, while most of the leftover energy is wasted through hot exhaust gases, coolant, lubricating oil, and heat transfer from engine surfaces [1]. Among these loss paths, exhaust gas is particularly suitable for waste heat recovery because it carries thermal energy at relatively high temperatures and is continuously available during engine operation. Therefore, improving the overall efficiency of ICE-based systems requires not only better combustion performance and lower mechanical losses but also the recovery of part of the usable thermal energy discharged with the exhaust gases [2, 3]. Thermoelectric generators (TEGs) are widely researched because they can convert waste heat energy into electrical power without any moving parts [4-6]. TEGs, which have thermoelectric modules (TEMs), operate based on the Seebeck effect, in which the ΔT between the hot and cold sides of the module generates an electrical potential [7]. Therefore, the output performance of a TEG system is mainly dependent on the magnitude and stability of the temperature difference, as well as the uniformity of the temperature distribution over the modules [8-10]. Several approaches have been used in previous studies to improve the performance of exhaust-based TEGs, including heat exchanger optimization, finned and multi-channel structures, exhaust flow guidance, module placement and electrical connection strategies [11-14]. These studies show that high-temperature exhaust heat can be converted into electricity and used to supply auxiliary electrical loads in vehicles. However, automotive exhaust conditions are highly transient; temperature and flow rate of exhaust gases change with engine speed and load, causing nonuniform heat flux on the TEG surface. In multi-module TEG arrays, this leads to different temperature differences among modules and makes homogeneous electrical output difficult to maintain [15, 16]. Therefore, TEG performance improvement should not rely only on hot-side heat transfer enhancement. Cold-side management, inter-module temperature balancing, and electrical output homogenization in multi-row/column TEM arrays are also essential design requirements [17, 18].

The performance of thermoelectric generators largely related to the ΔT acting on the surfaces of the TEMs. Therefore, cold-side thermal management is a critical factor in maintaining TEG performance [19, 20]. Inadequate heat removal from the cold side can reduce the temperature difference throughout the TEMs even when sufficient heat is supplied to the hot side, thereby decreasing the open-circuit voltage and, under load conditions, the current, power output, and conversion efficiency [21, 22]. This problem becomes more severe in rectangular, large-area TEGs with multi-row and multi-column TEM arrays. The hot-side temperature varies gradually along the exhaust flow direction, while the cold side may experience nonuniform cooling due to fluid distribution, contact resistance, local heat accumulation, and heat exchanger geometry [23, 24]. As a result, TEMs mounted on the same TEG body can operate under different thermal conditions. This nonuniformity also affects system-level electrical performance. In series-connected TEM arrays, a low-temperature-difference module can limit the current and power of the entire array, whereas in parallel connections, voltage differences among modules can cause unbalanced power sharing [25]. This phenomenon is commonly described as temperature mismatch, electrical mismatch, surface temperature nonuniformity, or module-level power deviation [26]. Therefore, multi-module TEG systems should aim not only to maximize total power, but also to distribute temperature differences and electrical output as uniformly as possible. Improving cold-side effectiveness supports this aim by increasing the average temperature difference and reducing row/column-based performance variations [27]. Thus, in rectangular TEG systems, the cold-side heat exchanger should be regarded not only as a heat rejection component but also as a thermal interface controlling inter-module performance homogeneity [28]. Given the irregular and transient nature of exhaust waste heat in ICEs, cold-side thermal management becomes even more important. Although conventional water- or air-cooled systems can provide high heat removal capacity, their ability to passively damp temperature fluctuations and equalize surface temperature under transient heat loads is limited [29]. Therefore, integrating phase change material into the cold-side heat exchanger is a promising strategy for maintaining the temperature difference and homogenizing TEM output performance in TEG systems [30].

The literature on TEG performance enhancement can be classified into several major approaches. One major research direction is the design of exhaust-side heat exchangers. Finned, parallel-plate, multi-channel, chaotic, dimpled, splitter-column, and optimized flow-passage geometries have been used to enhance heat transfer from the exhaust gas to the hot side [31-34]. Although these configurations can increase the total TEG output, improved hot-side heat transfer alone does not ensure a uniform temperature distribution among the modules. Another group of studies has focused on cold-side cooling through air or water cooling, microchannel heat sinks, different coolant flow rates, alternative coolants, and low-thermal-resistance heat exchangers to reduce the cold-side temperature of TEMs [35-37]. These studies indicate that stronger cold-side heat dissipation generally increases the temperature difference and, as a result, the power output. However, changing the coolant velocity or flow direction may still be insufficient to fully suppress surface temperature fluctuations under transient operating conditions [38, 39]. A third line of research deals with the use of phase change materials (PCMs) in TEG systems. In these systems, PCMs are mainly used to moderate rapid thermal variations by storing or releasing latent heat during phase change [40-42]. This buffering effect is useful when the heat source varies with time, since it can delay overheating on the hot side, help preserve the ΔT across the modules, smooth sudden power variations, and support more stable electricity generation [43]. The main limitation, however, is the intrinsically low thermal heat conduction capacity of most PCMs. This limits the heat diffusion in the PCM volume and may even impede the temperature equalization process, particularly if the TEG has a huge surface area [44]. Therefore, several heat-conducting structures and additives such as metal foams, fins, graphite, expanded graphite, carbon nanotubes, graphene, and metal oxide nanoparticles have been used in PCMs for better heat spreading [45, 46]. The addition of Al_2O_3 has been shown to expedite melting and reduce the time to reach thermal equilibrium, while graphite-based additives are more suitable for fast and spatially homogeneous heat distribution in the PCM [47]. Accordingly, doped PCMs should be considered not only as latent heat storage materials but also as heat-spreading media that can contribute to surface temperature uniformity and inter-module thermal balance. Finally, another group of studies has

investigated module placement, electrical connection topology, and temperature mismatch in multi-TEM arrays [48-50]. Flow-direction-aligned module layouts can reduce mismatch losses, row- and column-based arrangements can affect pressure drop and power generation differently, and series, parallel, and hybrid electrical connections can show different performance characteristics under nonuniform temperature fields [8, 48]. Overall, TEG power generation is not governed only by thermoelectric material properties. Heat exchanger geometry, cold-side effectiveness, PCM phase-change behavior, dopant thermal conductivity, TEM layout, and electrical connection structure should be considered together as system-level parameters [51, 52]. Nevertheless, most studies have focused on total power improvement, general thermal stability, or individual heat-transfer enhancement. Experimental studies comparing the effects of pure and doped PCM fillers inside the EC_hex on module-level temperature difference, electrical output, and performance homogeneity in rectangular multi-row and multi-column TEG systems remain limited.

Ahmadi et al. [53] researched a PCM-assisted TEG system by placing aluminum boxes filled with three different PCMs on the hot-side, cold-side, and both-sides of the module, and compared these cases with a PCM-free system. Under a heater input of 100 W for 900 s, the hot-side PCM reduced temperature fluctuations and lowered the risk of module damage. After the heater was turned off, the system generated more than 1 V for 1800 s, while the cold-side temperature remained below 45 °C. Bijukumar et al. [48] studied temperature-gradient nonuniformity along the exhaust flow and the resulting mismatch losses in TEGs through experiments and simulations. The column-wise and row-wise arrangements of the 5×5 TEG array were compared with S, SP, and TCT connections. The results showed that SP-CWA and TCT-CWA generated 8.08% and 7.96% more power, respectively, than RWA. Borhani et al. [54] used RT35 paraffin on the cold-side and RT69 on the hot side, together with copper porous media with porosities of 0.80-0.95 and pore densities of 10-40 PPI, to numerically study the effects of PCM and porous media on TEG performance. The use of porous media on the cold side increased the electrical energy by 25.47%, whereas its use on the hot side decreased the power by 13.33%. Increasing PPI from 10 to 40 and decreasing

the porosity from 0.95 to 0.80 increased the output by 13.57% and 5.36%, respectively. Islam et al. [55] examined h-BN/MWCNT-reinforced lauric acid PCM/NePCM in a TEC1-12706-based TEG system. The LBM-0.8 sample provided the most favorable response, increasing the output voltage from 388 to 432 mV and keeping the heat sink temperature at about 54 °C. Meng et al. [51] evaluated finned PCM-TEG configurations through a mathematically validated model and showed that fins increased the temperature difference, with the dual-sided PCM design being recommended for practical use. In a 500 s simulation, the PCM-free TEG failed at 208 s, whereas all PCM-TEG designs continued operating, and the dual-sided design was recommended for practical use. Siviter et al. [9] experimentally and theoretically examined temperature-gradient mismatch losses in series- and parallel-connected TEG arrays. Compared with individual control, power losses were 9.22% for series connections and 12.90% for parallel connections, while the series connection provided higher electrical efficiency under constant temperature differences. Rajamony et al. [56] experimentally investigated graphene and graphene-silver nanoparticle-reinforced RT54HC PCM for TEG applications. The hybrid composite RT54-0.8GrAg enhanced the thermal heat conduction capacity of the PCM by 96% and increased the TEG voltage from 375 to 425 mV. The latent heat loss after 500 cycles was only 6.09%, indicating its potential for TEG and thermal management applications at 50-60 °C. Manikandan et al. [57] numerically studied a PCM-encapsulated heat sink for controlling the cold-side temperature of a TEG using COMSOL Multiphysics. By varying the PCM amount and heat input, they showed that the temperature difference and the voltage increased with phase change. At a PCM height of 3 mm, the TEG efficiency was enhanced by 36.7%, 33.8%, and 30% for heat flow of 0.1, 0.15, and 0.2 W, respectively. Subhash et al. [58] experimentally used two PCMs with different melting temperatures as thermal buffers on both sides of a TEG. PCM 42 and PCM 24 were placed into copper-wool-reinforced 3D-printed containers, and 50 °C was applied to both sides. The dual PCM-TEG structure generated a usable temperature gradient twice per thermal cycle, lasting about 16- and 45-min during heating and 25 min during cooling. Tang et al. [59] investigated SIC-based static reconfiguration in a 6×6 TEG array to reduce mismatch losses under nonuniform surface

temperature using experiments and simulation. By rearranging module positions without changing the electrical connections, SIC reduced the loss rate by 7.23% compared with TCT and increased output power by 8.62% and 7.37% compared with TCT and SP, respectively. Wang et al. [60] experimentally studied a hot-side PCM-TEG system under discontinuous and pulsed thermal boundary conditions. Erythritol PCM was evaluated at pulsed temperatures of 100, 130, and 160 °C. The PCM decreased hot-side temperature and voltage fluctuations and contributed to stabilizing power generation, although the maximum power and total recovered energy were lower than those of the PCM-free system. Aljafari et al. [61] experimentally investigated the graphene-doped and graphene-silver-doped RT54HC PCM in TEG applications. The 0.8 wt.% Gr: Ag hybrid PCM increased thermal conductivity by 96% and raised the TEG voltage from 375 to 425 mV compared with pure PCM. After 500 cycles, the composite showed low latent heat loss and was found suitable for 50-60 °C TEG applications.

To address the research gap mentioned above, this study experimentally investigates the effects of pure and modified PCM fillers integrated into the cold-side heat exchanger of a rectangular multi-row/column TEG system designed for exhaust waste heat recovery from a SI engine. The experiments were conducted at 2000, 2500, 3000, 3500 and 4000 rpm engine speed and three compositions of filler were compared, namely, 100% PCM, 90% PCM + 10% Al₂O₃ and 90% PCM + 10% graphite. The analysis included engine output parameters, exhaust gas and coolant flow rates, exhaust gas, coolant, and PCM temperatures, hot-side and cold-side temperatures at TEG/TEM measurement points, open-circuit voltages of TEM groups, and voltage, current, and power under load. Total TEG output power, TEG efficiency, and fuel energy recovery ratio were also evaluated as functions of engine speed. Thus, the study reveals not only the effect of different PCM compositions on total electrical power generation, but also their influence on the spatial uniformity of temperature difference and electrical output distribution in a multi-TEM array. In this respect, integrating pure and doped PCM fillers into the cold-side heat exchanger is proposed as an experimental approach to evaluate its potential for enhancing energy recovery and module-level performance homogeneity in ICE exhaust-based TEG systems.

1.1. Paper novelty and industrial relevance

In TEGs with TEM arrangements consisting of multiple rows and columns, the output power imbalance between TEMs reduces the total output power of the TEG, thus requiring the use of additional electronic circuits (DC/DC converter, current/voltage balancing module, etc.) to balance the power of the TEMs. While current studies generally focus on the use of electronic circuits to balance the output power of TEMs in such TEGs, there is a significant lack of studies focusing on design modifications to balance the output power of the TEMs. This paper minimizes the imbalance in the output power of the TEM groups due to temperature variation along the TEG plane by using PCM material in the cold-side heat exchanger of the TEG, thereby contributing to an increase in the total output power of the TEG. This can contribute to increasing the overall efficiency of systems with heat loss, such as internal combustion engine vehicles, industrial heating systems, and solar energy systems, by enabling the production of more useful energy from waste heat.

2. Material and Methods

2.1. Scope of Experimental Study and the TEG System

In this paper, experimental research was conducted on a three-layer TEG system designed to recover the thermal energy lost through the exhaust gases of an SI engine. The TEG system used in the experimental setup is based on the original TEG design developed and experimentally investigated by Gürbüz, et al. [62] for the recovery of exhaust waste heat of a gas-fueled SI engine. The system consists of a hot-side exhaust heat exchanger in the middle through which the exhaust gases pass, and cold-side heat exchangers (EC_hex) placed on two surfaces of this heat exchanger. The middle exhaust heat exchanger has dimensions of $127 \times 380 \times 38$ mm and is designed with two flow-guiding fins and a segmented body structure. The cold-side EC_hexs have dimensions of $427 \times 177 \times 25$ mm and have been rearranged in this study to be suitable for a phase change material (PCM/paraffin) application. Unlike the previous design, the engine coolant was routed

through EC_hex copper pipes, and the heat exchanger volume surrounding the copper pipes (approximately 0.6 L) was filled with PCM or nanoparticle-added PCM. With this arrangement, engine coolant flow was provided directly through the copper pipelines, while PCM was used as a heat storage and temperature equalization medium around the cold surface.

The TEG system utilizes a total of 24 commercial TEMs (TEG1-PB-12611-6.0 brand/model) BiTe/PbTe hybrid thermoelectric modules (TEM). Each TEM module measures 56×56 mm. The modules are placed between the Exh_hex and the EC_hex, with 12 modules in each of the top and bottom layers. Six independent TEM groups are formed, with four TEM modules connected in series from the exhaust inlet to the exhaust outlet, parallel to the exhaust gas flow direction. Thus, a total of 24 TEM modules are configured as 6 independent series connection channels, and the electrical output measurements of the TEG are performed through these independent series TEM groups. Open-circuit voltages were measured for each group, and voltage and current values were recorded under load. An electrical load test device was used, which could be connected to the output of the desired channel(s). The specifications of the TEMs used are given in Table 1.

Table 1. Basic specifications of the TEMs used

Technical Specifications	Value
Hot surface temperature	350 °C
Cold surface temperature	30 °C
Open circuit voltage	9.2 V
Resistance under load	0.97 Ω
Output voltage under load	4.6 V
Output current under load	4.7 A
Output power under load	21.7 W

In the EC_hex, approximately 0.6 L of PCM material remaining around the copper tubes was filled into the exchanger by melting the paraffin slightly above its melting temperature during the PCM filling process, taking care to avoid air voids. Two different nano-modified PCM mixtures were

prepared to improve the low thermal conductivity of paraffin. In this context, the experimental system was composed of three different working groups: pure PCM, 90% PCM + 10% Al₂O₃, and 90% PCM + 10% graphite. The nano-modifier ratio was determined as 10% by weight. In the mixture preparation process, the liquefied paraffin was mixed with the specified amount of nanoparticles for approximately 30 minutes using a magnetic stirrer to ensure a balanced distribution of the additives in the paraffin. The basic thermophysical properties of the paraffin used are shown in Table 2, and the basic properties of the Al₂O₃ and graphite additives are given in Table 3.

Table 2. Basic thermophysical of PCM/paraffin used in experiments

Properties	Value
Melting range	53.0 – 58.0 °C
Latent heat of fusion	170 kJ/kg
Kinetic viscosity (100 °C)	5.2 – 5.5 cSt
Specific heat	2 kJ/kgK
Solid density	880 kg/m ³
Liquid density	760 kg/m ³
Maximum operating temp.	89.85 °C
Flash point	199.85 °C

Table 3. Basic properties of Al₂O₃ and graphite nano modifiers used in the experiments

Properties	Alumina	Graphite
Chemical formula	Al ₂ O ₃	C
Average particle size	63 – 90 µm	75 µm
Physical structure	powder	powder
Purity	99.7%	90%
Density	3.9 – 4.1 g/cm ³	2.09 – 2.23 g/cm ³
Melting point	2050 °C	3000 °C

2.2. Experimental System and Test Procedure

In the experimental studies, a two-cylinder, four-stroke, liquid-cooled, SI engine with a total displacement of 505 cm³ and powered by propane fuel was used. Load and speed control of the experimental engine was provided by a dynamometer system (Go-Power D-100 brand/model). During the experiments, engine speed, effective torque, and effective power values were monitored and recorded on the digital display panel of the dynamometer. The intake air and propane fuel flow rates were detected using two thermal mass flowmeters (New-Flow TLF03A10111 and New-Flow TSF03A10111, respectively). In addition, a wideband lambda measurement system placed in the exhaust line was used to check the accuracy and stability of the mixture ratio. Experiments were conducted at full throttle (WOT) and at five constant engine speeds (2000, 2500, 3000, 3500, and 4000 rpm) for three different PCM compositions: 100% PCM, 90% PCM + 10% Al₂O₃, and 90% PCM + 10% graphite. In each experimental condition, the engine was first started and then allowed to cool until the coolant temperature reached approximately 82 °C. Then, the engine was run at a constant speed for at least 10 minutes at the specified experimental speed to allow the TEG system to reach a steady-state operating regime. Measurements were taken when the engine coolant temperature stabilized at approximately 85±2 °C, and the TEG system reached a steady state. After the tests were completed, the system was allowed to cool naturally. This ensured the repeatability of the initial conditions of the PCM in the next experimental setup. Data from each experimental set were evaluated by averaging approximately 300 seconds of recorded data.

In the experimental studies, temperature measurements were performed using K-type thermocouples. To determine the temperature distribution in the regions where thermoelectric modules (TEMs) are located on the TEG, a total of 14 K-type thermocouples were placed in contact with the upper and lower surfaces of the middle layer heat exchanger and the EC_hexs, where the exhaust gases pass. In addition, 4 more thermocouples were used to measure the TEG inlet and outlet temperatures of the exhaust gas and engine coolant.. Three temperature sensors

Here, P_{TEG} represents the total output power, and n represents the number of TEM groups. To evaluate the homogeneity of the electrical power distribution among the TEM groups, the average group power was first calculated using Eq.3. The percentage deviation of each TEM group from the average output power was calculated using Eq. 4.

$$\bar{P} = \frac{1}{n} * \sum_{i=1}^n P_i \quad (3)$$

$$D_i = \frac{P_i - \bar{P}}{\bar{P}} * 100 \quad (4)$$

Here, D_i represents the deviation from the average output power of the relevant TEM group. The TEG energy conversion efficiency is calculated as Eq.5, which is the ratio of the electrical power produced by the TEG to the waste heat transferred from the exhaust gas to the TEG system.

$$\eta_{TEG} = \frac{P_{TEG}}{\dot{m}_{exh} * c_{p,exh} * (T_{exh,in} - T_{exh,out})} * 100 \quad (5)$$

Here, η_{TEG} represents the TEG efficiency, $\dot{m}_{exh}$ the mass flow rate of exhaust gas, $c_{p,exh}$ the specific heat of exhaust gas, $T_{exh,in}$ the exhaust gas inlet temperature into the TEG, and $T_{exh,out}$ the exhaust gas outlet temperature into the TEG. The fuel energy recovery rate is calculated using Eq. 6 as the ratio of the electrical power produced by TEG to the fuel energy delivered to the engine.

$$\eta_{rec} = \frac{P_{TEG}}{\dot{m}_{fuel} * LHV} * 100 \quad (6)$$

Here, η_{rec} represents the fuel energy recovery rate, $\dot{m}_{fuel}$ the mass flow rate of fuel, and LHV the lower calorific value of propane. These calculations were used to compare the effects of different PCM compositions on TEG performance, which varies depending on engine speed.

3. Experimental Findings and Discussion

Figure 2 shows how the performance (brake power, brake torque, and brake specific fuel consumption) of the SI engine, operated with propane under wide open throttle conditions, varied versus engine speed. The SI engine has the highest brake torque with 29.08 Nm at 2500 rpm, the highest brake power with 9.72 kW at 4000 rpm, and the lowest brake specific fuel consumption value with 0.276 kg/kWh at 2500 rpm. It appears that the experiments conducted with TEG cover the engine speed range in which the SI engine achieves maximum brake torque and power, as well as minimum brake specific fuel consumption.

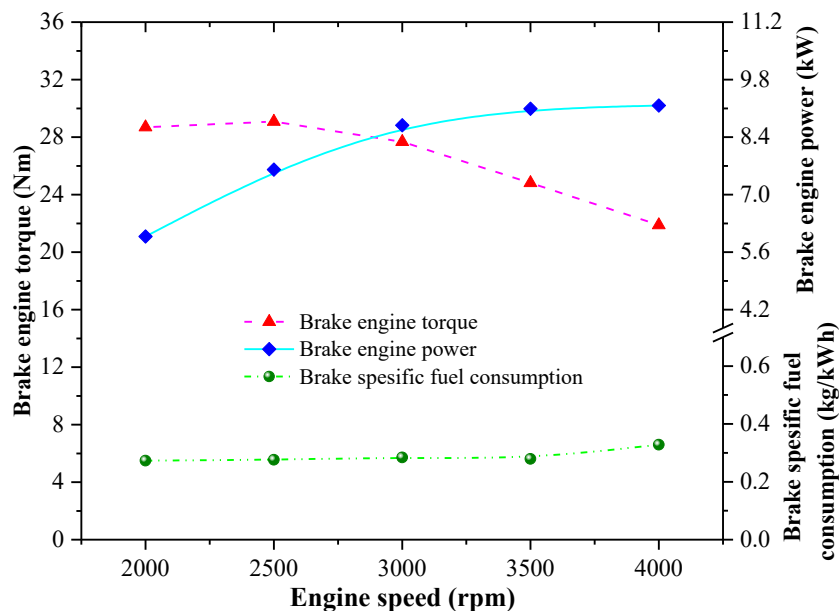


Fig.2. Variation of the effective/brake output parameters of the engine versus engine speed

In SI engine experiments conducted for different TEG arrangements, the engine's operating parameters were kept as constant as possible. This is because it is only in this case that it is possible to maintain a constant mass flow rate of exhaust gas and coolant in the SI engine. Fig.3 illustrates the variation of exhaust gas and coolant flow rates with engine speed for all TEG configurations. As can be seen, as engine speed raises, the flow rate of exhaust gas and coolant into the TEG also

increases; however, the mass flow of the engine coolant and exhaust gas are quite close to each other for different TEG arrangements.

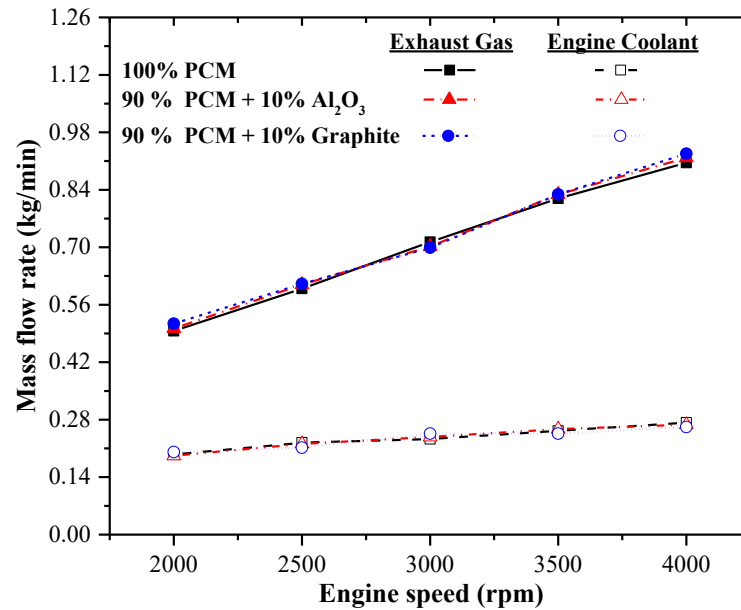


Fig.3. The variation of exhaust gas and engine coolant flow rates versus engine speed in different TEG arrangements

Fig.4 shows the variation of exhaust gas inlet and outlet temperatures in the TEG with engine speed in experiments conducted with different TEG arrangements. The variation and numerical values of exhaust gas inlet temperatures with engine speed are each quite close in all TEG arrangements under constant engine operating conditions. The exhaust gas inlet temperature at 2000 rpm is around 530 °C, increases gradually with engine speed, and reaches around 740 °C at 4000 rpm. However, the temperature of the exhaust gases from the TEG varied depending on whether only PCM or nanoparticle-added PCM was used in the EC_hex. In EC_hex, the addition of Al₂O₃ and graphite to PCM increased the heat transfer properties of PCM, resulting in greater heat transfer to the EC and thus increasing the heat flux on the TEMs. As a result, the use of nanoparticle-added PCM lowered the exhaust gas exit temperature from the TEG and reduced the temperature difference between the inlet and outlet temperatures of the exhaust gas. It should be noted that this positive effect is even greater when graphite is added to PCM. This is a consequence

of graphite having a higher heat transfer coefficient than Al_2O_3 . The temperature difference of the exhaust gases between the inlet and outlet of the TEG when adding Al_2O_3 or graphite in the PCM reaches its peak at approximately 20 °C at 4000 rpm. When compared to using only PCM, this difference increases to approximately 44 °C.

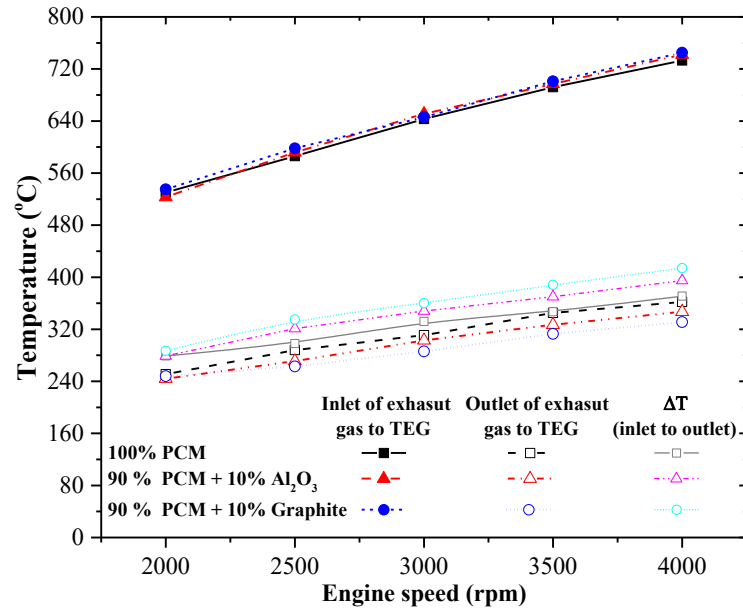


Fig.4. The variation in exhaust gas temperature with engine speed in different TEG arrangements

Fig.5 illustrates the variation of EC inlet and outlet temperatures in the TEG with engine speed in experiments conducted with different TEG arrangements. The variation and numerical values of EC inlet temperatures with engine speed are each quite close in all TEG arrangements under constant engine operating conditions. The EC inlet temperature at 2000 rpm is approximately 71 °C, increases gradually with engine speed, and increases to approximately 78 °C at 4000 rpm. It is not possible to say the same for the outlet temperature of the EC from the TEG. Because, just like exhaust gas, the outlet temperature of the EC from the TEG varied according to whether only PCM or nanoparticle-added PCM was used in the EC_hex. When nanoparticles are added to PCM, the heat transfer coefficient increases, resulting in increased heat transfer from the nanoparticle-added PCM to the EC. This noticeably increases the exit temperature of the EC from the TEG at all engine speeds compared to using only PCM. This increase is an average of 1.9 °C for all speeds

with Al_2O_3 addition and an average of 5 °C with a graphite additive. Consequently, the exit temperature of the EC from the TEG at 2000 rpm is 81.5 °C with only PCM, while it rises to 85.5 °C with 90% PCM + 10% graphite. At 4000 rpm, the exit temperature is 89.7 °C with only PCM, while it rises to 95 °C with 90% PCM + 10% graphite.

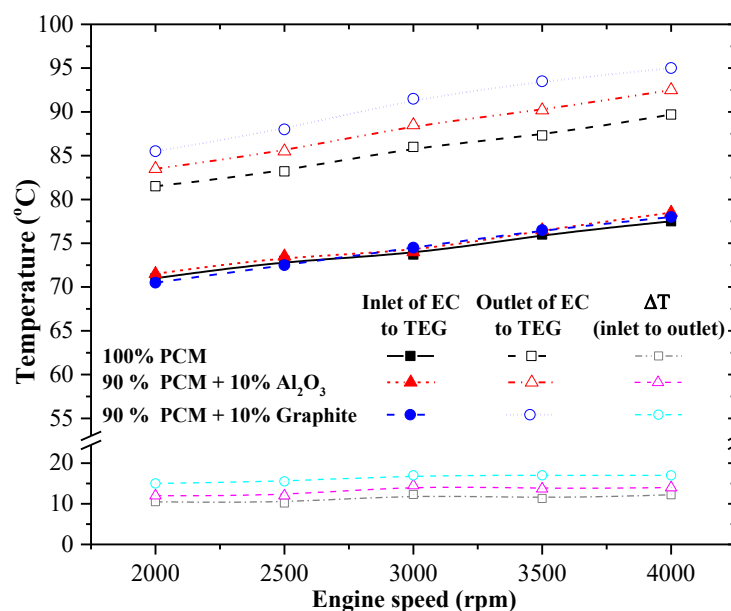


Fig.5. The variation of EC temperature with engine speed in different TEG arrangements

The variation of PCM or nanoparticle-added PCM temperature versus engine speed in different TEG arrangements is given in temperature measurements, which were performed at three different regions on the EC_hex (TEG inlet, outlet, and midpoint) along the passage line of exhaust gases through the TEG (Fig.6). The heat transfer from Exh_hex to EC_hex via heat flow between the hot and cold surfaces of the TEMs increased the temperature (up to 195 °C) of the PCM or nanoparticle-added PCM in direct contact with the surface of EC_hex, causing it to transition from solid to liquid phase and resulting in heat transfer along the horizontal plane of EC_hex. In areas with locally high temperatures, a pressure relief line is used in the EC_hex to prevent the PCM from increasing pressure by transitioning to the gas phase and potentially causing a fire. For all TEG arrangements, the temperatures of the PCM or nanoparticle-added PCM decreased from point 1 (where the exhaust gas input the TEG) to point 3 (where they output). Temperatures at all measurement points varied depending on whether PCM alone or PCM with added nanoparticles

was used in EC_hex and increased slightly with the use of nanoparticles. This varied depending on engine speed and experimental conditions but averaged around 4 °C between PCM and 90% PCM + 10% Al₂O₃, and an average of 8 °C between PCM and 90% PCM + 90% graphite. It should be noted that during the experiments, the temperatures of the PCM or nanoparticle-added PCM decreased with increasing engine speed for all TEG configurations at all measurement points. This situation can be attributed to the shortening of the time required for heat transfer due to the increasing flow rate of exhaust gas with increasing engine speed and the increase in the rate of heat transferred to the EC due to the increase in the EC mass flow rate passing through the EC_hex with increasing engine speed. However, this will further contribute to an increase in ΔT between the TEM surfaces with increasing motor speed, and thus an increase in the output power of the TEMs.

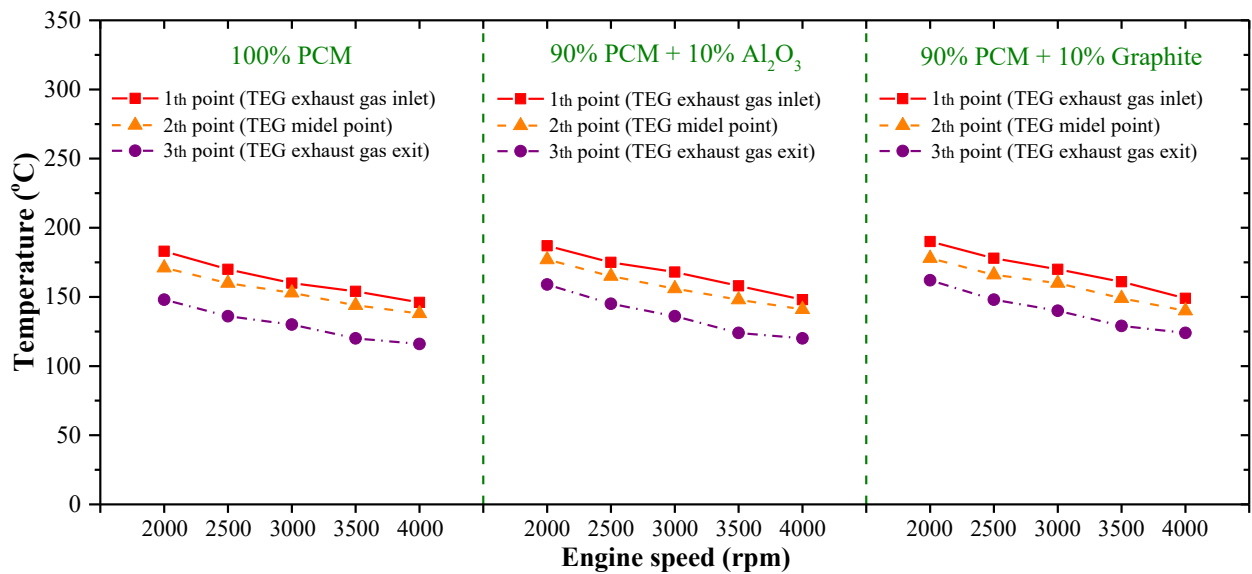
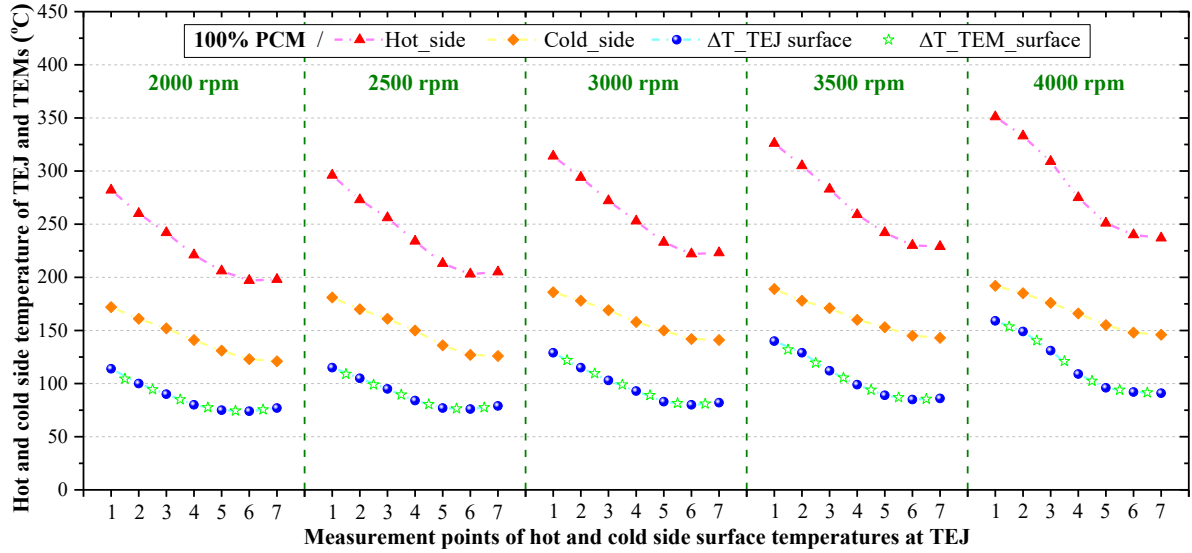


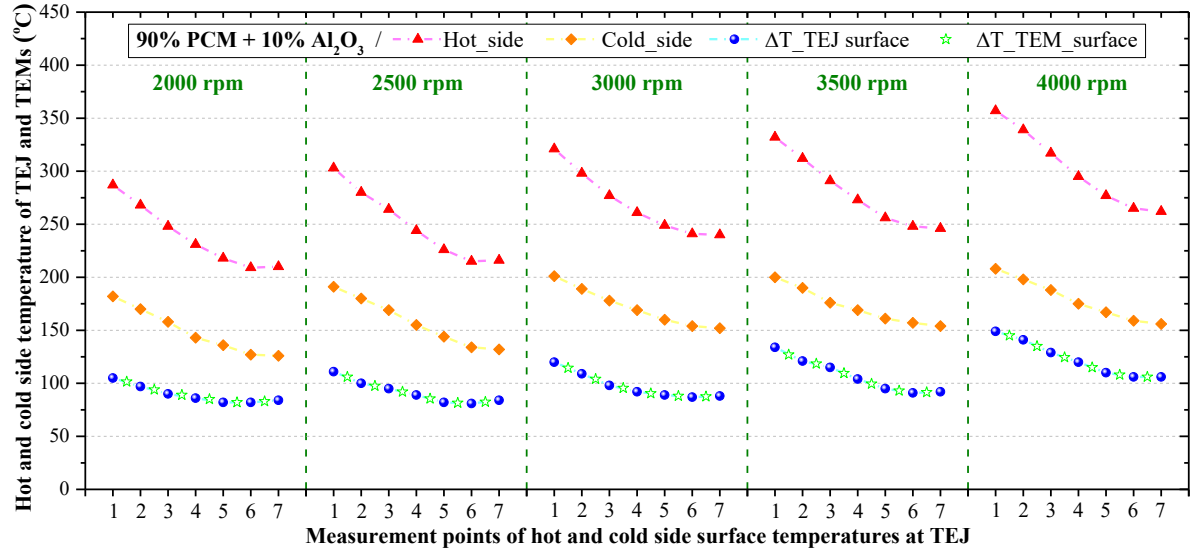
Fig.6. The variation of PCM or nanoparticle-doped PCM temperature versus engine speed in different TEG arrangements

Both side (hot and cold) surface temperatures of TEG and TEMs at the measurement points [(a) 100% PCM, (b) 90% PCM + 10% Al₂O₃, and (c) 90% PCM + 10% Graphite] are given in Fig.7. In all three TEGs, the hot side heat exchanger (Exh_hex) surface temperatures decrease from the inlet to the outlet plane of the TEG (from 1 to 7) at all engine speeds. Between measurement points

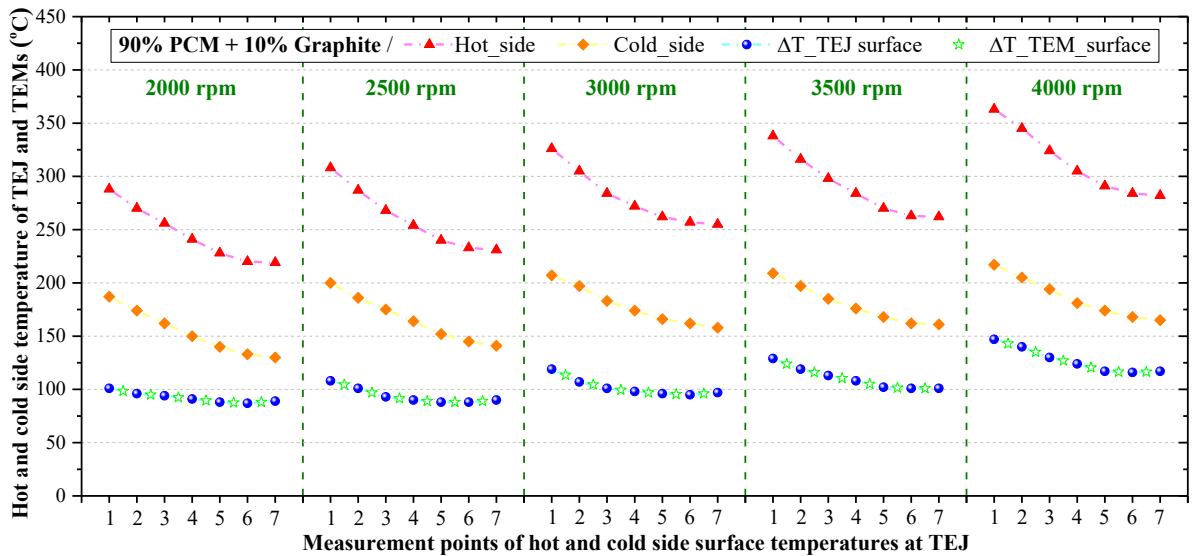
6 and 7, a slight decrease or increase or staying constant is due to the increased heat transfer effect caused by the accumulation of exhaust gases in the exit throat. The Ec_hex surface temperatures also exhibit a similar variation curve, but the rate of decrease is slower. This is due to the use of PCM or nanoparticle-added PCM, which has no flow effect other than heat transfer via mass generated during the solid-to-liquid phase transition in Ec_hex . The most significant effect of this is the reduction in the heat transfer effect due to the higher surface temperatures of Ec_hex corresponding to the inlet plane of the exhaust gases to the TEG and the redirection of hot exhaust gases towards the outlet of Exh_hex , thereby increasing the surface temperatures of Exh_hex at the outlet region and consequently the ΔT acting on the surfaces of the TEMs. As a result of this, in the TEG with rectangular geometry, the ΔT temperature differences affecting both sides of the TEM groups listed from 1 to 6 from the inlet plane of the exhaust gases towards the outlet plane become closer to each other/become more balanced. Another important issue to consider here is the effect of adding nanoparticles to the characterization of PCM. When Al_2O_3 or graphite is added to PCM, the heat transfer rate of PCM increases. In this case, compared to using only PCM, the surface temperatures of Exh_hex decrease at the inlet area of the exhaust gases to the TEG, but the Exh_hex temperatures increase towards the outlet area of the exhaust gases from the TEG, and therefore, the ΔT temperature difference acting on the hot and cold surfaces of the TEMs also increases. The range of measurement points 3-4, i.e., the region where the 3rd row TEM group is located, can be defined for this transformation. In other words, the effect of the nanoparticle added in PCM on the surface temperatures is the midpoint of the long side of the rectangular TEG. Finally, a comparison between adding Al_2O_3 or graphite to the PCM clearly shows that graphite, having a higher heat conductivity coefficient than Al_2O_3 , makes the temperature distribution of surfaces of Exh_hex and Ec_hex more homogeneous along the exhaust gas flow throughout [Fig. 7 (b) and (c)]. The discussed findings are clearly seen in the ΔT_TEM curves presented in Fig. 7 (a), (b) and (c), which will actually characterize the output performance (open circuit/load voltage, load current and output power) of the TEM groups.



(a)



(b)



(c)

Fig.7. Hot_side and cold_side surface temperatures of TEG and TEMs at the measurement points [(a) 100% PCM, (b) 90% PCM + 10% Al_2O_3 , and (c) 90% PCM + 10% Graphite]

Fig. 8 illustrates the variation in the open-circuit voltage of the TEM groups with motor speed, which is also an indicator of the heat flux on the TEMs as a function of the ΔT between the hot and cold sides of the TEG heat exchanger surfaces. As shown in the figure, with only PCM use at all five engine speeds, the open-circuit voltages of the 1st and 2nd TEM groups in the inlet stage of the exhaust gases to the TEG are higher at all speeds compared to 90% PCM + 10% Al_2O_3 and 90% PCM + 10% graphite. However, after the 3rd TEM row, named according to the flow plane of the exhaust gases from the TEG, the open-circuit voltage of the TEM groups increases with 90% PCM + 10% Al_2O_3 and 90% PCM + 10% graphite. This is due to the increased cold-side surface temperature as a result of the improved heat transfer effect of the nanoparticle additive to the PCM. Thus, the heat transfer effect from the hot exhaust gases to the surface at the TEG inlet is reduced, thus causing the hotter exhaust gas to move towards the through-outlet of the TEG. Consequently, the open circuit voltage of the TEM groups decreases in the inlet region of the exhaust gases into the TEG, while the open-circuit voltage of the TEM groups increases in the outlet region. However, to numerically evaluate the impact of this effect on the output power balance between the TEM groups and the total output power of the TEG, examining the output performance of the TEM groups under load will yield more accurate results.

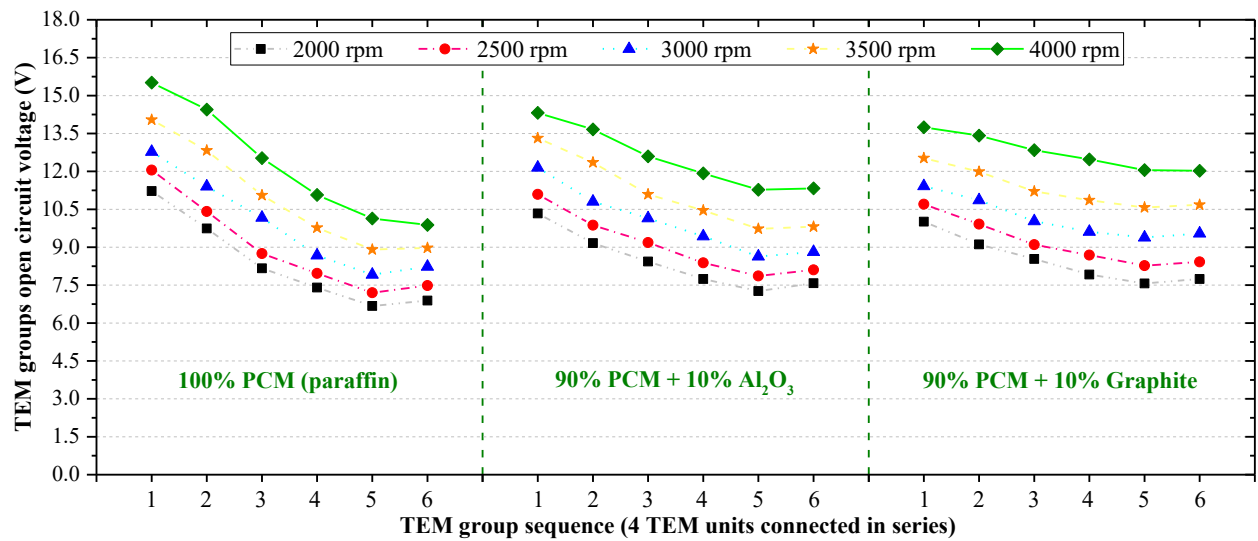


Fig.8. The variation in the open circuit of TEM groups in different TEG arrangements

In the experiments, the output power of each node was optimized by connecting a DC load device to 6 electrical nodes provided by serially connecting a total of 4 TEMs on the lower and upper layers in the same row. Fig.9 shows the curves of an example test performed with a DC electronic load device. As seen in the figure, the TEM provides the optimum load current and therefore the highest output power when the load resistance and the internal resistance are close to each other; at this point, the internal resistance is also quite low. This point also corresponds to a moment when the load current and voltage are optimal together and thus bring the output power of the TEM to its maximum value.

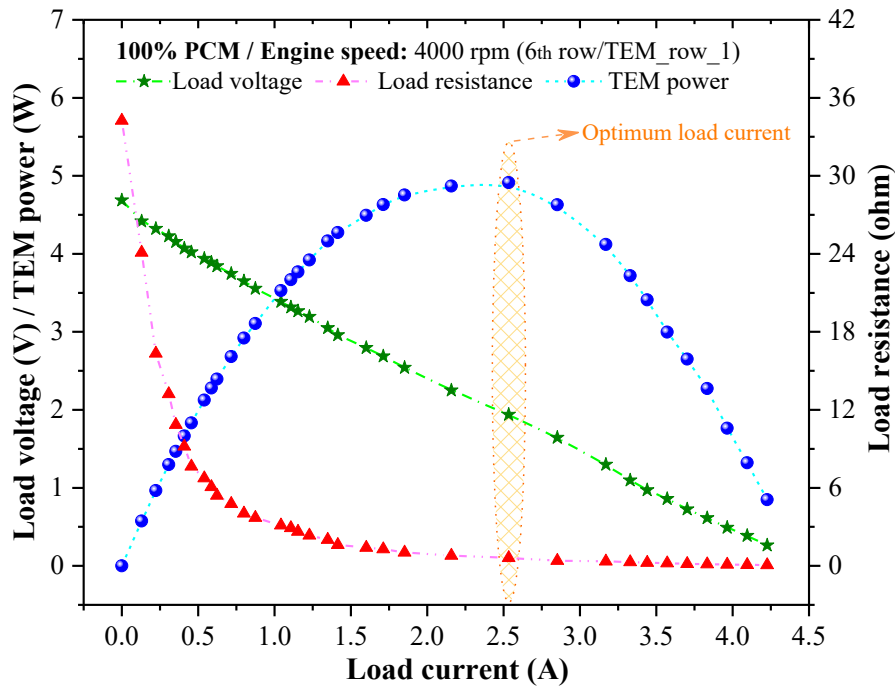


Fig.9. An example loads resistance test result [1st TEM in 1th row TEM group for 100% paraffin at 4000 rpm]

Output performance of TEM groups under electrical load/resistance in different TEG arrangements [(a) load voltage, (b) load current, and (c) output power of TEM groups] is given in Fig.10. Firstly, in all three TEG arrangements, with the increase in motor speed, the increase in the ΔT temperature difference between the hot and cold surfaces of the TEM (Fig. 7) increased the load current and voltage of the TEM groups, and consequently, the power outputs also increased. The increases in

TEM groups with engine speed for different TEG configurations had similar characteristics, but the numerical value and change characteristics of the power outputs according to the order of the TEM groups varied depending on the use of PCM or PCM with added nanoparticles in EC_hex. At TEG using only PCM, the output performance (load current, load voltage, and output power) of the 1st and 2nd TEM groups is higher than that of others at all motor speeds. However, by adding Al₂O₃ or graphite to the PCM, the performance of the 3rd TEMs groups is almost equalized, and the output performance of the 4th, 5th, and 6th TEM groups has become higher. This also decreased the difference in output performance between the TEM groups numbered 1 through 6, meaning the power outputs were balanced/brought closer together. Here, another noteworthy finding emerges with the addition of Al₂O₃ or graphite into the PCM. The output performance among TEM groups numbered 1 to 6 has become more balanced with 90% PCM + 10% graphite compared to 90% PCM + 10% Al₂O₃. In fact, while the output performance of TEM groups 1 and 2 is higher with 90% PCM + 10% Al₂O₃, the output performance of 90% PCM + 10% graphite becomes higher from TEM group 3 onwards, resulting in a more balanced output performance among TEM groups numbered 1 to 6. This chain of events stems from the fact that the graphite added to the PCM has a more advanced heat transfer characteristics property than Al₂O₃, resulting in an raise in the ΔT temperature difference between the hot-side and cold-side of the TEMs (3rd row and onwards) positioned towards the exhaust gas outlet plane in the TEG, and consequently an increase in load voltage, load current, and output power.

For example, if a recording is created for output power at 4000 rpm, the output power of TEM groups numbered 1 to 6 with only PCM is 19.78 W, 17.41 W, 13.59 W, 11.01 W, 9.38 W, and 8.99 W, respectively, while with 90% PCM + 10% Al₂O₃ it is 16.89 W, 15.51 W, 13.73 W, 12.56 W, 11.61 W, and 11.84 W, respectively, and with 90% PCM + 10% Al₂O₃ it is 15.88 W, 15.03 W, 14.26 W, 13.66 W, 13.14 W, and 13.17 W, respectively.

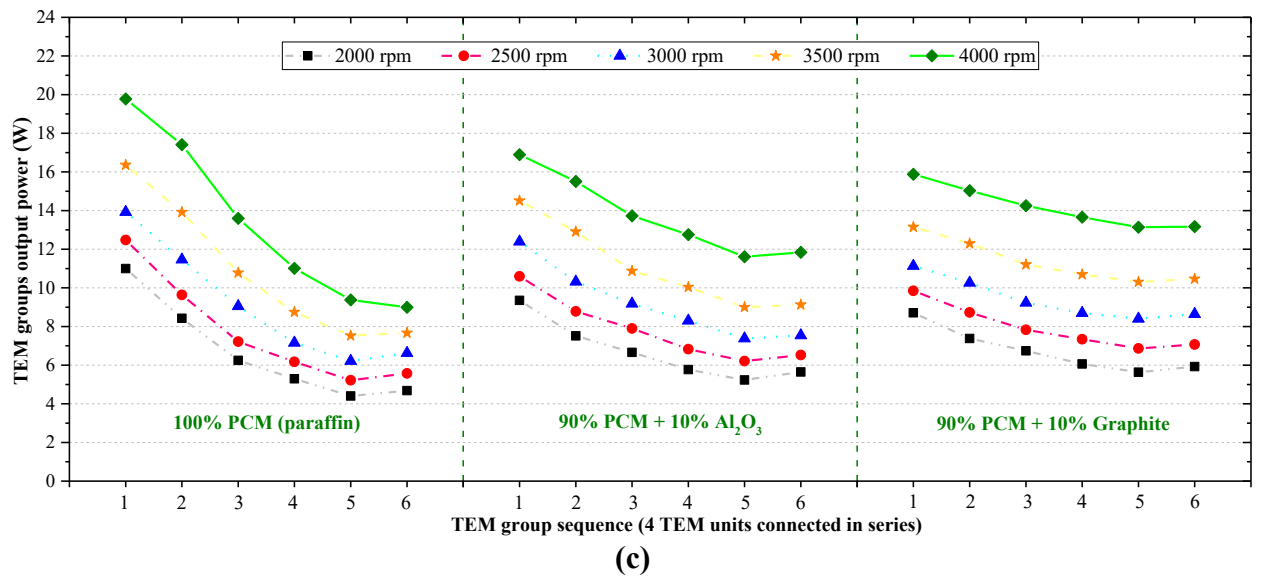
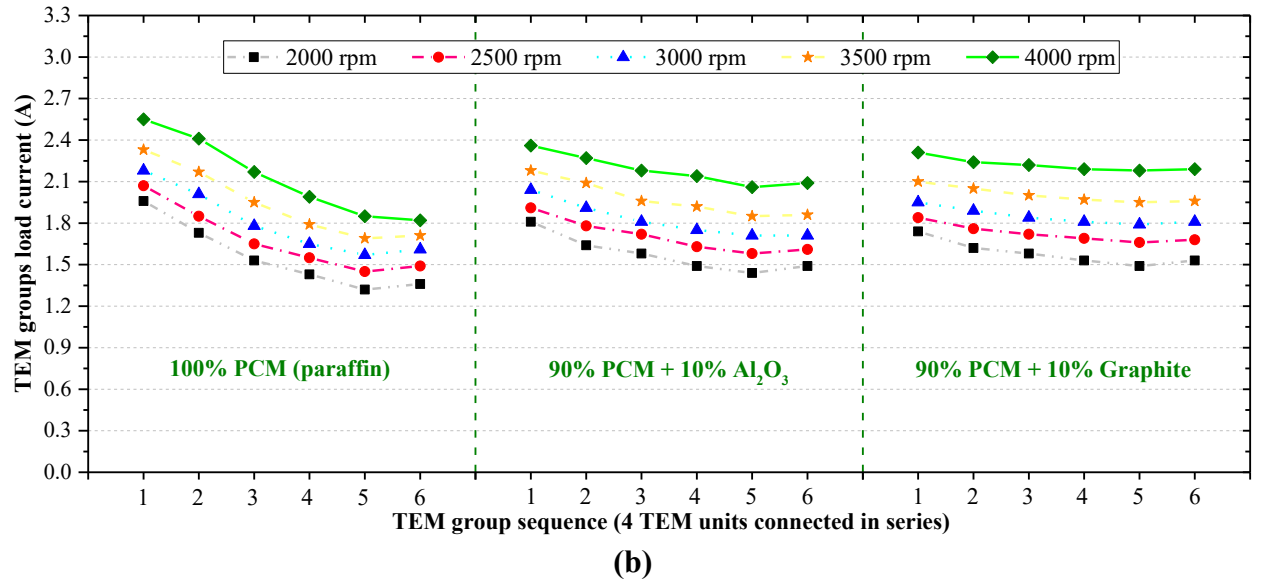
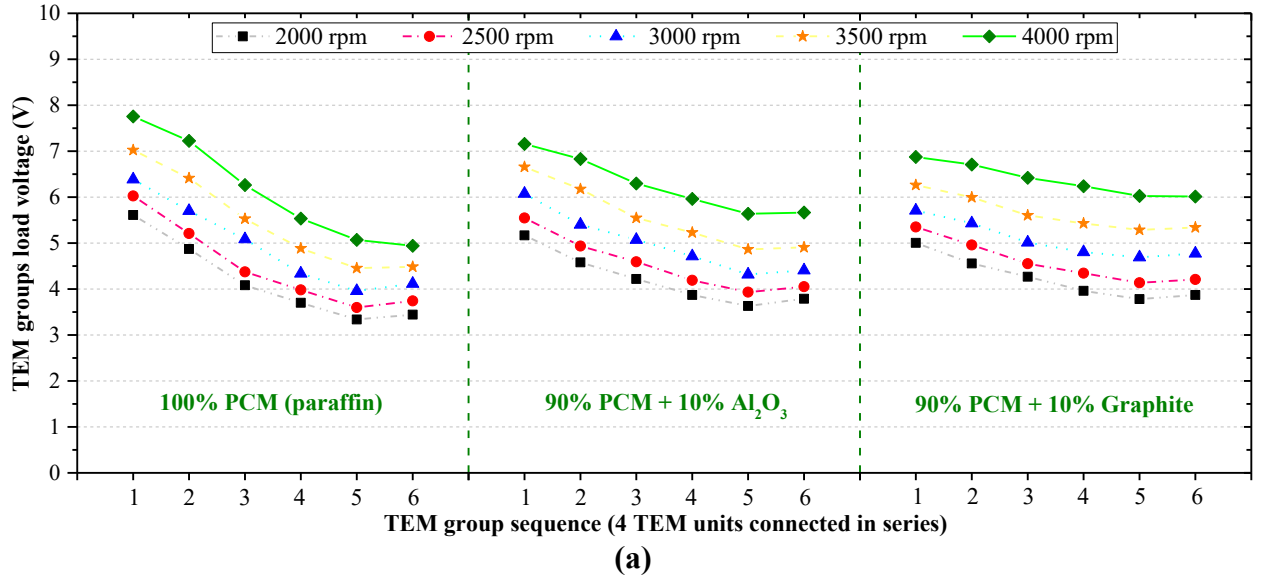
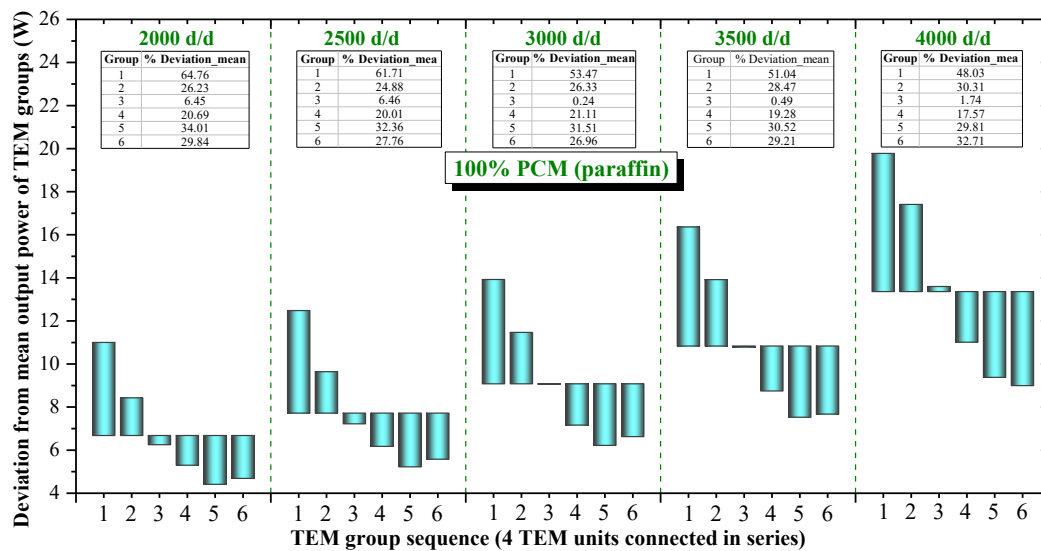


Fig.10. Output performance of TEM groups under electrical load/resistance in different TEG arrangements [(a) load voltage, (b) load current, and (c) output power of TEMs groups]

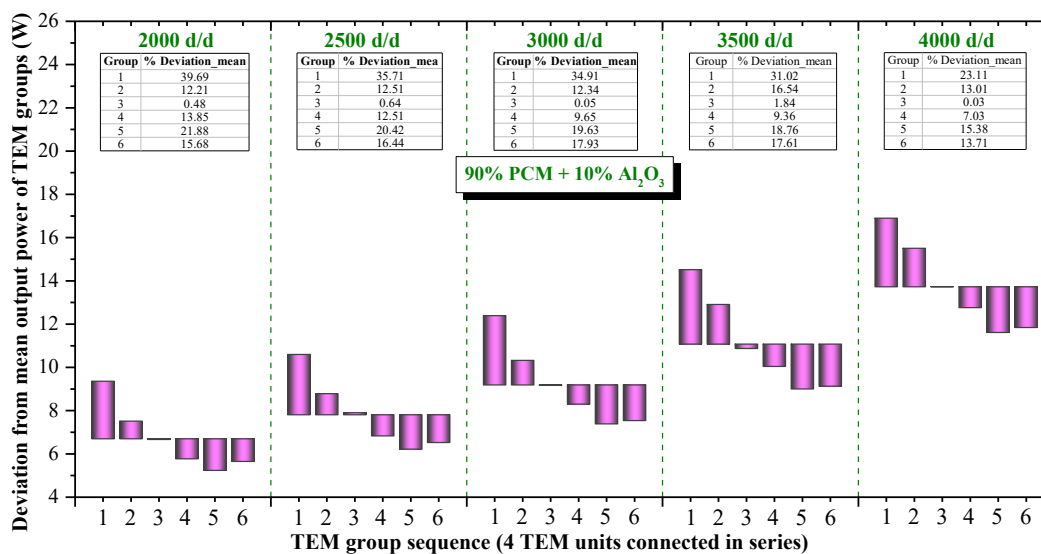
Fig.11 presents a floating column graph showing the deviation of each TEM groups from the average calculated from the average of 6 TEM group, as well as tables showing the percentage deviations from the average [(a) 100% PCM, (b) 90% PCM + 10% Al₂O₃, and (c) 90% PCM + 10% graphite]. As can be seen in Fig.11, at all three TEG arrangements, the deviation of the TEM groups' output power from the average power of the TEG groups decreases from the 1st to the 6th TEM group. On the other hand, it is seen that the deviation of the TEM groups' output power from the average power of the TEM groups decreases with engine speed for all three TEG configurations. Here, a comparison of different TEG arrangements provides important evidence of how adding nanoparticles to the PCM balances the power output of TEM groups. At all engine speeds, it is seen that the deviation of the output-power of each TEM group from the mean TEM group output power is significantly declined with the addition of Al₂O₃ nanoparticles to the PCM.

For example, at 2000 rpm, where the highest deviation rate occurs, the deviation of the output power of the 1st TEM group with 100% PCM from the mean TEM output power is 64.76%, while with 90% PCM + 10% Al₂O₃, it decreases by 38.72% (25.07 units) to 39.69%. At 4000 rpm, where the lowest deviation rate occurs, the deviation of the output power of the 1st TEM group using 100% PCM from the mean TEM output power is 48.03%, while with 90% PCM + 10% Al₂O₃, it decreases by 51.88% (24.92 units) to 23.11%. For other engine speeds and TEM groups, differences were observed between these two values. When graphite is added to PCM, the output power of the TEM groups is observed to be more balanced/closer to each other compared to both 100% PCM and 90% PCM + 10% Al₂O₃. For example, at 2000 rpm, where the highest deviation rate occurs, the deviation of the output power of the 1st TEM group with 100% PCM from the mean TEM output power is 64.76%, while with 90% PCM + 10% graphite, it decreases by 54.96% (35.59 units) to 29.17%. At 4000 rpm, where the lowest deviation rate occurs, the deviation of the output power of the 1st TEM group with 100% PCM from the mean TEM output power is 48.03%, while with 90% PCM + 10% Al₂O₃, it decreases by 75.18% (36.11 units) to 23.11%. For other

engine speeds and TEM groups, differences were observed between these two values. In an example comparison between 90% PCM + 10% Al_2O_3 and 90% PCM + 10% graphite, the deviation of the output-power of the 1st TEM group with 90% PCM + 10% Al_2O_3 from the mean TEM output power is 23.11%, while with 90% PCM + 10% graphite, it decreases by 48.42% (11.19 units) to 11.92%. The addition of graphite and Al_2O_3 increased heat transfer from PCM to EC, contributing to the balancing of the output-power of the TEM groups. Furthermore, the higher heat transfer coefficient of graphite compared to Al_2O_3 enhanced this contribution to balancing the output-power of the TEM groups.



(a)



(b)

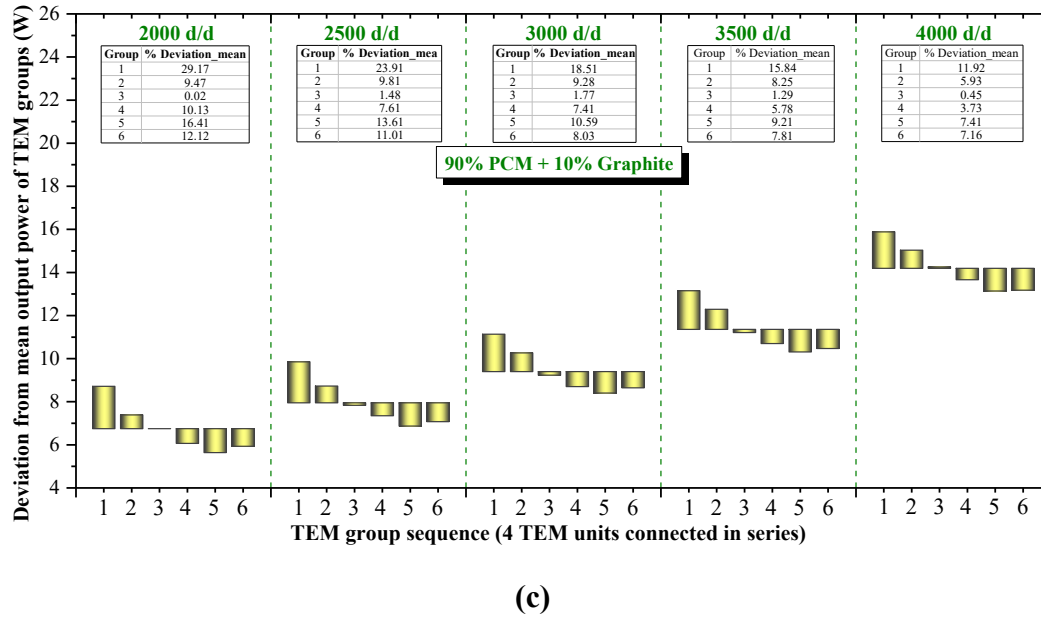


Fig.11. Deviation from mean output power of TEMs groups [(a) 100% PCM, (b) 90% PCM + 10% Al₂O₃, and (c) 90% PCM + 10% graphite]

The change of the total TEG output power with motor speed, obtained by stacking the output power of 6 TEM groups for all TEG configurations, is shown in Fig.12. For all three TEG configurations, the output power of the TEG increases with engine speed. Furthermore, compared to using only PCM, it has been observed that the output power of the TEG raises when nanoparticles are added to the PCM. This increase is less pronounced at lower speeds but increases with higher speeds. Furthermore, with nanoparticles added to the PCM, the balancing in the output powers of the TEM groups, which are sorted towards the inlet to the exit of the exhaust gases at the TEG, is more clearly seen in this stack graph. For example, at 4000 rpm, the output power of the 1st TEM group when using only PCM is 19.778 W, while the output power of the 6th TEM group is 2.2 times lower at 8.992 W. However, at the same engine speed, with 90% PCM + 10% Al₂O₃, the power of the 1st TEM group is 16.893 W, while the power of the 6th TEM group is 1.4 times lower at 11.939 W. Moreover, with 90% PCM + 10% graphite, the power of the 1st TEM group is 15.878 W, while the power of the 6th TEM group is only 1.2 times lower at 13.171 W. Similar variations are observed within other engine speeds and TEM groups. However, it should also be noted that the effect of adding nanoparticles on the power output balancing of TEM groups

increases with engine speed. On the other hand, it is also worth mentioning the increase in the total output power of the TEG with nanoparticles added to the PCM. This effect is quite small at low speeds but increases significantly with engine speed. For example, at 2000 rpm, compared to using only PCM, the TEG output power increases by only 0.05% with 90% PCM + 10% Al_2O_3 , while this increases up to 0.98% with 90% PCM + 10% graphite. On the other hand, at 4000 rpm, compared to using only PCM, the TEG output power increases by 2.71% with 90% PCM + 10% Al_2O_3 , while this increases up to 6.18% with 90% PCM + 10% graphite. Increases in TEG output power with nanoparticle addition to PCM in the 2000-4000 rpm range vary between the values offered. Of course, it should be mentioned that the effect of graphite addition to the PCM on the output-power of the TEG is higher than that of Al_2O_3 at all engine speeds.

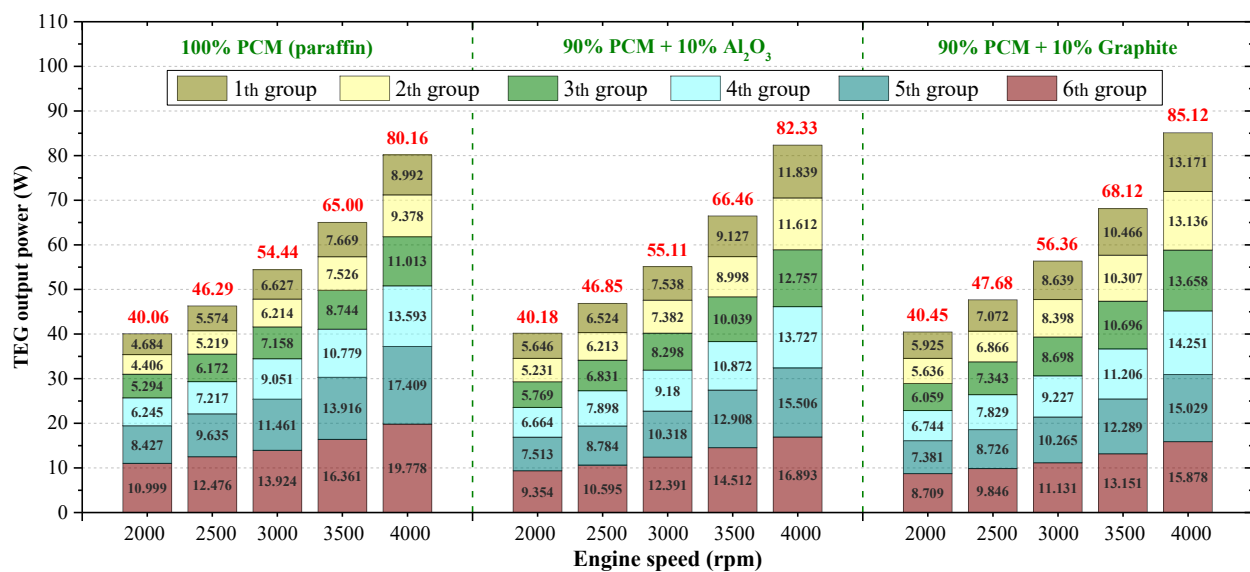


Fig.12. The variation of the TEG output power versus engine speed in different TEG arrangements

Fig.13 illustrates the variation of the TEG efficiency versus engine speed in different TEG arrangements. TEG efficiency, an indicator of how much of the waste heat in the exhaust gases of the TEG is converted into electrical output power, decreases slightly for all three TEG configurations as the engine speed is increased from 2000 rpm to 3000 rpm, and shows a noticeable

upward trend with further increases in engine speed. However, the TEG efficiency increased at all five engine speeds due to the higher TEG output power achieved by adding particulate matter to the PCM. This upward trend, however, reached higher values with increasing engine speed. For example, at 2000 rpm, the TEG efficiency with PCM alone was 2.161%; with 90% PCM + 10% Al_2O_3 it increased to 2.166% (only a 0.005-unit increase); and with 90% PCM + 10% graphite, it reached 2.198% (0.037-unit increase), while at 4000 rpm, the TEG efficiency with PCM alone was 2.298%, increasing to 2.364% (0.066-unit increase) with 90% PCM + 10% Al_2O_3 and to 2.456% (0.150-unit increase) with 90% PCM + 10% graphite. The increase in TEG efficiency is higher with the addition of graphite to the PCM because graphite has a higher heat conduction coefficient than Al_2O_3 , which allows for greater heat transfer rate to the EC in EC_hex, increasing the ΔT between the cold and hot surfaces of the TEMs, thus both balancing the output-power of the TEMs and increasing the total output-power of the TEG.

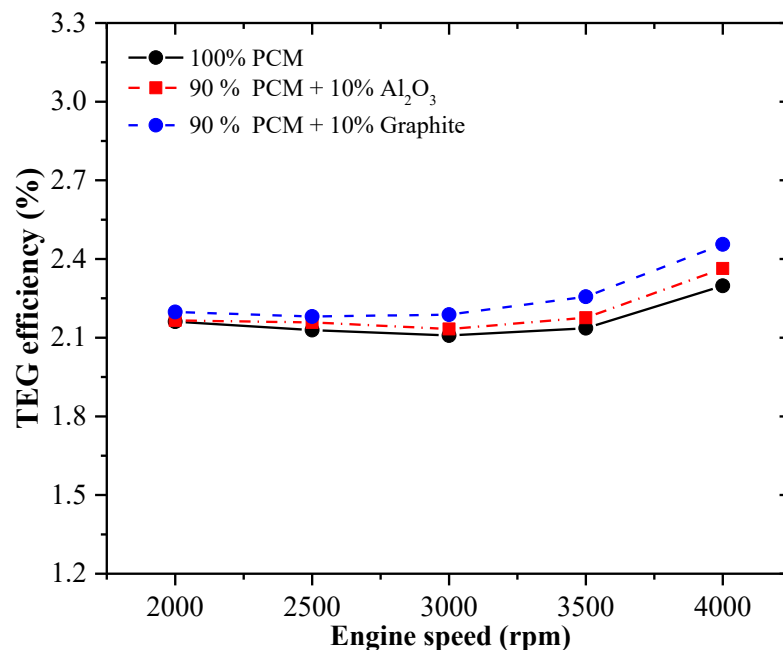


Fig.13. The variation of the TEG efficiency versus engine speed in different TEG arrangements

The variation of the fuel energy recovery rate versus engine speed in different TEG arrangements is given in Fig.14. In all three TEG arrangements, the fuel energy recovery rate increases with

engine speed. Furthermore, the higher output power achieved in the TEG with a nanoparticle additive to PCM also increased the fuel energy recovery rate. This increase was even higher with the graphite additive compared to the Al_2O_3 additive to PCM. At 4000 rpm, where the highest fuel energy recovery rate is obtained, the fuel energy recovery rate is 0.215% with PCM alone, while it increases by 2.79% (0.006 units) to 0.221% with 90% PCM + 10% Al_2O_3 , and by 6.51% (0.014 units) to 0.229% with 90% PCM + 10% graphite. The increases in fuel energy recovery rate observed with the addition of nanoparticles to PCM occur at other engine speeds as well.

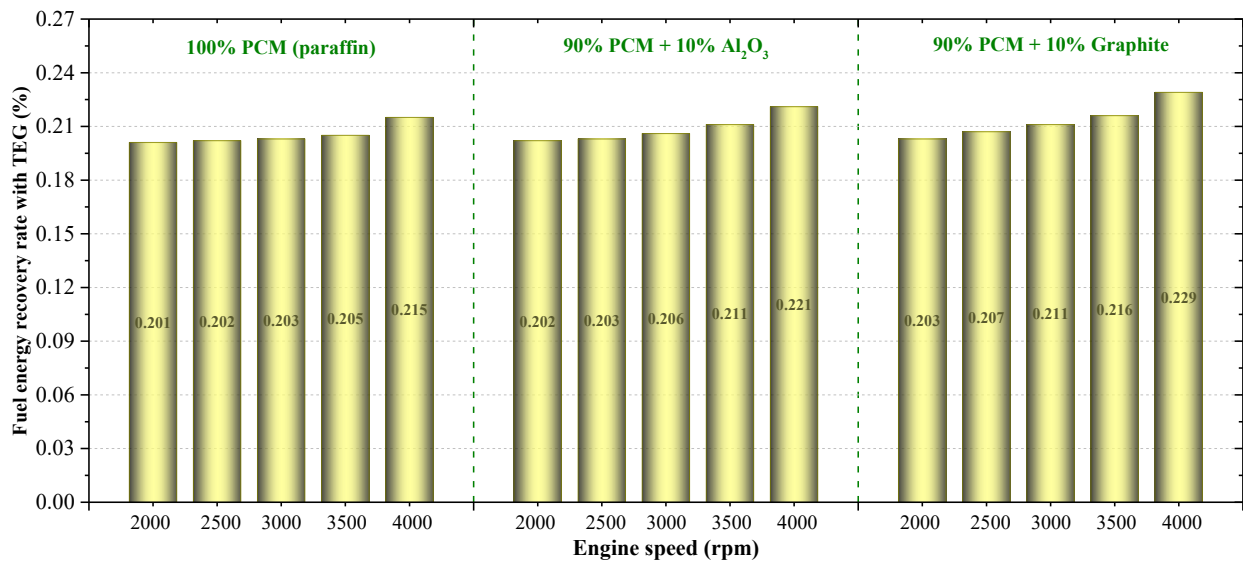


Fig.14. The variation of the fuel energy recovery rate versus engine speed in different TEG arrangements

4. Conclusion

The overall results of the paper, which investigated the effects of using PCM/paraffin or nanoparticle (Al_2O_3 and graphite) added PCM in the cold side/EC_hex to balance/approximate the output performance (load current, load voltage, and output power) of TEM modules in a three-layered TEG consisting of 24 TEMs ($6 \times 2 = 12$ on one side and a total of $12 \times 2 = 24$) designed to convert the exhaust waste heat of a propane-fueled SI engine into electrical energy, is summarized as follows:

- The engine produced a maximum torque of 29.08 Nm at 2500 rpm, a maximum power of 9.72 kW at 4000 rpm, and a minimum specific fuel consumption of 0.276 kg/kWh at 2500 rpm.
- The exhaust gas inlet temperature increased from approximately 530 °C at 2000 rpm to approximately 740 °C at 4000 rpm; the TEG output power also increased with increasing engine speed.
- The addition of nanoparticles increased the coolant outlet temperature compared to 100% PCM. The average increase was 1.9 °C for the Al₂O₃ additive and 5 °C for the graphite additive.
- At 4000 rpm, the coolant outlet temperature reached 89.7 °C with 100% PCM, while it reached 95 °C with 90% PCM + 10% graphite.
- The addition of nanoparticles increased the PCM temperature compared to 100% PCM. The average increase was approximately 4 °C for 90% PCM + 10% Al₂O₃ and approximately 8 °C for 90% PCM + 10% graphite.
- At 2000 rpm, the deviation of the first TEM group from the average TEM group power decreased from 64.76% with 100% PCM to 39.69% with 90% PCM + 10% Al₂O₃ and to 29.17% with 90% PCM + 10% graphite.
- At 4000 rpm, the deviation of the TEM group 1 from the average power was reduced to approximately 11.92% with graphite-doped PCM.
- At 4000 rpm, the total TEG output power increased by 2.71% with 90% PCM + 10% Al₂O₃ and by 6.18% with 90% PCM + 10% graphite compared to 100% PCM.
- At 4000 rpm, the TEG efficiency increased from 2.298% with 100% PCM to 2.364% with 90% PCM + 10% Al₂O₃ and to 2.456% with 90% PCM + 10% graphite.
- The fuel energy recovery rate at 4000 rpm increased from 0.215% with 100% PCM to 0.221% with 90% PCM + 10% Al₂O₃ and to 0.229% with 90% PCM + 10% graphite.

Overall, the study concludes that the use of nanoparticle-modified PCM is an effective passive thermal management method for homogenizing temperature distribution in multi modules TEG

systems, reducing power imbalance between TEM groups, and improving overall energy recovery performance. Among the tested configurations, 90% PCM + 10% graphite exhibited the best overall performance in terms of temperature homogenization, balancing of TEM power outputs, total TEG output power, conversion efficiency, and fuel energy recovery. Future studies should further evaluate the system's applicability under real vehicle conditions by investigating the nanoparticle rate, PCM filling ratio, cold-side heat exchanger geometry, and long-term thermal cycle stability.

5. References

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