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Automotive Waste Heat Recovery by Thermoelectric Generator Technology

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Abstract

Automotive exhaust thermoelectric generators (AETEG) are gaining significant importance wherein a direct conversion of exhaust waste heat into electricity allows for a reduction in fuel consumption. Over the past two decades, extensive progress has been made in materials research, modules and thermoelectric generator (TEG) system. Many prototypes using BiTe, $CoSb_3$ and half Heusler materials have been developed and tested for efficiency in different engines. The role of exhaust flow rate, temperature and heat exchanger type on the performance of AETEG is investigated deeply. This chapter reviews the progress made so far in the AETEG technology. Section 1 gives a brief introduction; section 2 gives a description of the technology and section 3, the construction details of a typical AETEG. The performance evaluation of AETEG is discussed in Section 4, application of TEG using engine coolant heat is discussed in Section 5 and TEGs for hybrid vehicles are described in Section 6. The parasitic losses due to AETEG and the conditioning of the power produced for practical applications using the maximum power point tracking technique are discussed in Sections 7 and 8, respectively. Finally, in Section 9, cost analysis and the challenges associated with the commercialization of AETEG is presented.

Keywords: thermoelectric generator, exhaust waste heat, power output, efficiency, parasitic losses

1. Introduction

Among the major contributors to the greenhouse gas emissions to the environment, automobiles make a substantial contribution to the extent of 16.4% [1]. According to the information

reported in energy technology perspective 2015, the number of light duty vehicles in the roads is expected to go up from present 900 million to 2 billion by 2050 [2]. With the global power sector moving towards clean technologies using renewable energy, the current 38% utilization of the global oil production for automotive use can increase to a significant extent. Though the advancement of electric vehicle (EV) technology is making a steady progress on one side (expected to reach 56 million passenger cars on road from the present 2 million by 2030), still it is far from making any drastic reduction in the emissions level due to transportation sector unless a radical innovation is made in the battery technology. Policies such as better urban planning that can increase the use of collective transportation and innovative technologies that can reduce the individual's vehicle need can make considerable contributions to the reduction of the CO_2 emissions. However, this requires substantial investment, and hence it is difficult to implement worldwide particularly in low and middle income countries. Implementing innovative technologies for improving automobile engine efficiency or innovations in the field of hybrid/low emissions vehicles can improve the fuel efficiency and thereby emissions can be reduced to a greater extent. Several recent developments in the engine, transmission and few ancillary systems of the vehicles show promising results. Converting a part of heat energy produced in the engine, released to the atmosphere via exhaust gas as waste heat into electricity by a thermoelectric generator (TEG) is one technology gaining a lot of attention in the past one decade though it is well explored long time back itself due to its inherent simplicity. This chapter discusses the various salient features and the progress made so far in this technology.

2. Electricity from automotive exhaust waste heat

In an internal combustion (I.C) engine, only one-third of the total heat produced in the fuel combustion is utilized for the propulsion of the vehicle while the remaining two-third goes as waste heat mainly through the exhaust gas and the engine coolant. The exhaust gas, usually at a higher temperature compared to the engine coolant which absorbs heat from engine walls, is let out in the atmosphere and the engine coolant is recirculated after cooling in the radiator. In some of the engines, particularly in diesel fuelled ones, to get better efficiency, part of the exhaust gas is cooled and mixed with air in exhaust gas recirculation (EGR) system to reduce the NO_x emissions. Turbo-charging is another technology utilizing the heat from the exhaust gas to improve the engine power. However, in all these technologies, only a small fraction of the exhaust gas or its energy is converted into useful work and remaining is let out to the atmosphere. Improving the engine performance by making use of this exhaust waste heat has been a subject of intense research in the field of energy recovery systems, exhibiting promising outcomes in the recent past.

Automotive exhaust thermoelectric generator (AETEG) technology involves converting the waste heat available in the exhaust gas into electricity that can be stored and utilized for various electrical inputs of a vehicle so that the fuel efficiency can be improved. The first such system was developed in 1963 by Neild [3] followed by Serksnis [4] in 1976. Later, Birkholz et al. in 1988 [5] and Bass et al. in 1990 [6] demonstrated AETEG using thermoelectric (TE) modules

made of Fe-based and BiTe materials, respectively. Although the earliest AETEG was developed more than 50 years ago, a surge in research activities in this field has been occurring only in the past 15 years, which is evident from **Figure 1** showing the number of publications on this subject over the past five decades. Such exponential increase in the research output in recent years is mainly due to some of the path-breaking outcomes in the thermoelectric materials' properties which improved the TE figure of merit (zT) value which was <1 over a long period to more than 1. In recent years, zT ≥2 were also reported in few materials, which were achieved by engineering the microstructure of materials in different length scales [7, 8].

The thermoelectric figure of merit (zT), a dimensionless parameter indicating the thermoelectric performance of the material is defined as $zT = [(S^2\sigma).T]/\kappa$ where S is the Seebeck coefficient (V/K), σ is the electrical conductivity (S/m), κ is the thermal conductivity (W/m.K) of the material and T is the absolute temperature (K). From the mid of last decade, almost all the major automobile manufacturers in the world are associated with R&D programmes involving design, development and testing of AETEG in collaboration with the TE device manufacturers and research institutes. However, the outcomes reported so far indicates that the improvement in the fuel efficiency obtained are of very low values and even negative in some cases due to the parasitic losses associated with the TEG [9, 10]. The commercialization of AETEG, which have been projected to be feasible with improvement in efficiency of >5%, is yet to be achieved. The major bottlenecks to achieve this target are non-availability of bulk TE materials with high zT and the high cost of the currently available modules. The main contributions to the high cost of AETEG at present mostly arise from the TE modules, which are still very high compared to the practically acceptable price of less than $1/Watt. The presently available commercial modules made of Bi_2Te_3 are mostly manufactured by processes involving substantial manual operations resulting in high cost when
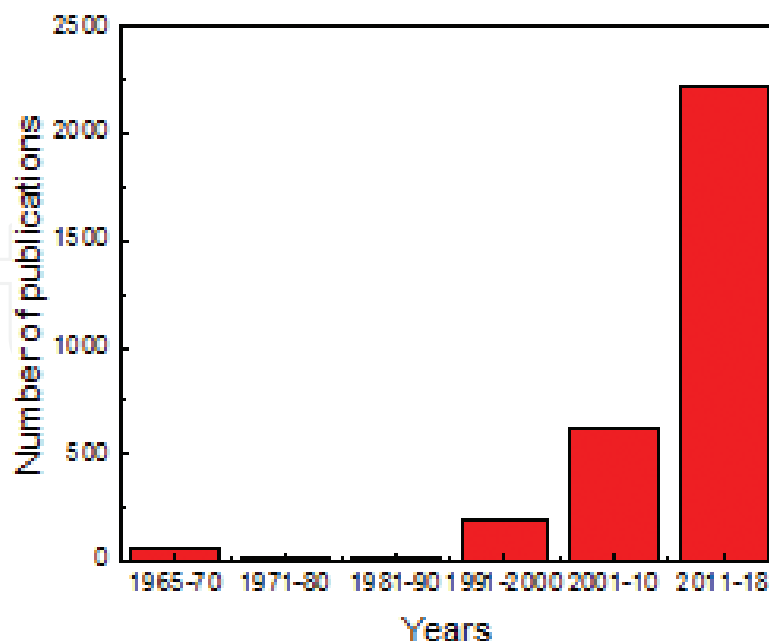

Figure 1. Number of papers published in every decade from 1965 onwards on the subject of thermoelectric generator". [data sourced from www.isiknowledge.com using the key word of 'thermoelectric generator'].

it reaches the customers. In high-temperature modules (i.e., operating temperature > 400°C), the use of rare earth elements along with intricate assembling and packaging process escalates the overall cost tremendously. Incorporation of suitable diffusion barrier layers between TE elements and metal interconnects, sealing of the complete assembly in inert gas to prevent the degradation at operating conditions etc. are some of the essential requirements for modules operating above 400°C. In spite of all these hurdles, the emergence of low-cost abundantly available materials such as tetrahedrites ($Cu_{12-x}M_xSb_4S_{13}$), Mg_2Si and $MnSi_2$ showing promising features can give the required breakthrough for commercialization.

3. Automotive exhaust thermoelectric generator system

The TEG for automobile exhaust heat conversion mainly consists of four parts, namely, TE modules, a heat exchanger to capture the heat from the flowing exhaust gas and transferring it to the hot side of the modules, heat sink to remove the heat from the cold side of the modules and assembly components. **Figure 2** shows the schematic of typical TEG arrangement for automotive exhaust waste heat conversion. In the exhaust pipe attached to the engine, the TEG is usually integrated after the catalytic converter. This is because positioning TEG before the catalytic converter can lower the exhaust gas temperature which will affect catalytic converter's performance. It is always preferable that the location of the TEG in the exhaust pipe is as close as catalytic converter since as we move away from it the temperature drops significantly. In most of the prototypes tested either in simulated or in actual driving conditions, only a TEG in the exhaust pipe alone is used. However, it is not uncommon to use two TEGs, one at the regular exhaust line and another one in the exhaust gas recirculation system (EGR) to maximize the power output.

3.1. TE modules

TE modules which are the main functional part of the AETEG are made of several pairs of p and n-type legs/elements of the thermoelectric compounds, which are connected electrically in series and thermally in parallel. The choice of the appropriate materials for modules mainly depends on (a) the optimal temperature range where zT is maximum (b) easy availability and (c) mechanical durability at the operating conditions of the TEG. The efficiency of the TE module given by.

$$\eta_{TE} = \left[(T_h - T_c)/T_h\right] * \left\{ \sqrt{(1 + zT)} - 1 / \left[\sqrt{(1 + zT)}\right] + T_c/T_h \right\} \qquad (1)$$

where T_h, T_c are the hot and cold side temperatures of the module, T is the average temperature given by $(T_h + T_c)/2$, and zT is the figure of merit of the TE legs used.

To get the maximum efficiency in the modules, the operating temperature of the modules should be in the range where the zT of the leg materials is the highest.

Several materials with appropriate doping have been used in the modules which can be reliably employed in the typical exhaust gas temperature range which is 400–600°C for a diesel engine and 700–800°C for gasoline engine. **Table 1** gives the details of TE materials, modules and the performance of AETEG either in a simulated or actual road test conditions. In the temperature range of interest for AETEG, filled skutterudites, doped PbTe, and half-Heuslers
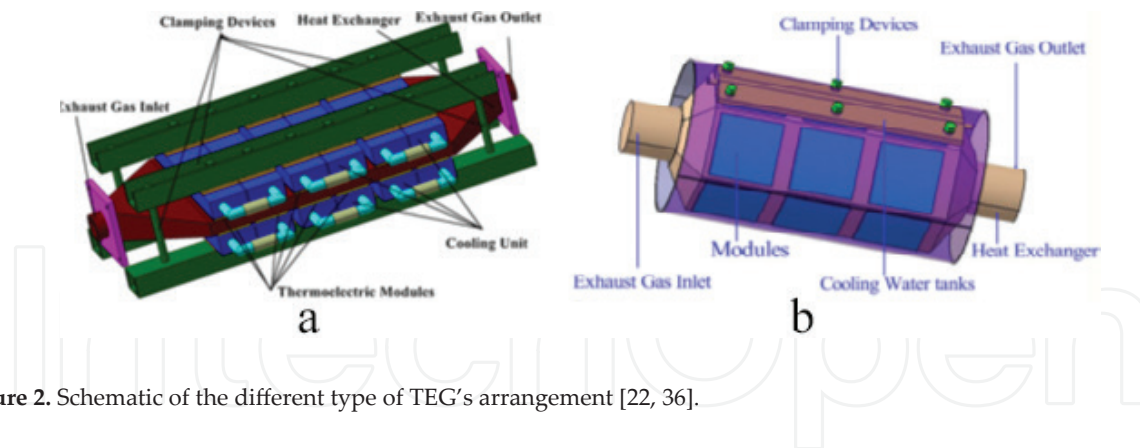
Figure 2. Schematic of the different type of TEG's arrangement [22, 36].

Sl. No	Materials	Module specifications	TEG performance	Ref.
1	Fe-based compound	—	—	[5]
2	BiTe	P_{max} ~35 W (at $\Delta T = 300°C$) $\eta_{max.}$ 4.5%	~125 W at 112.6 km/h speed	[9]
3	BiTe	5.3 × 5.3 cm P_{module}-13 W	1.0 kW	[12]
4	B and P doped Si_2Ge	20 × 20 cm P_{max}:1.2 W (at $\Delta T = 563$ K)	35.6 W	[13]
5	BiTe	6.2 × 6.2 × 0.5 cm (at $\Delta T = 563$ K)	42.3 W	[14]
6	Segmented Skutterudites and Bi_2Te_3 and commercial Bi_2Te_3 modules	Mod. Size:0.24 cm² P_{max}~18 W (at $\Delta T = 560°C$) $\eta_{mod.}$-6–8%	266 W at 60 km/h driving in 2 L engine.	[15]
7	Bi_2Te_3/Sb_2Te_3	$P_{nominal}$: 7 W at ΔT of 175°C	44 W using 12 modules	[16]
8	Bi_2Te_3	0.4 × 0.4 cm	75 W	[17]
9	Bi_2Te_3	4 × 4 × 0.42 cm	350 W (using 12 modules)	[18]
10	Skutterudites	—	700 W (steady state) 450 W (US06 driving cycle)	[19]
11	Half Heusler	5.26 W/cm² (under $\Delta T = 500°C$)	1 kW	[20]

Table 1. Materials, modules specification, and performance of some of the AETEGs fabricated and tested in engine exhaust.

are some of the compounds showing promising results. However, the cost factor associated with these compounds because of the rare elements used makes it difficult in lowering of per Watt cost and the large-scale mass production. Apart from this, unlike the stationary or space

applications where the TEGs showed very high durability, in the case of automotive application, the modules and materials are subjected to highly fluctuating thermal and mechanical conditions which can affect its longevity. As mentioned earlier, TE legs are electrically connected in series. Hence, the failure of either a leg or the joint between leg and metallic electrodes/interconnects can result in to a complete electrical breakdown of the module. The reliability of the modules, which is affected owing to such failures occurs predominantly due to thermo-mechanical stresses created at the interface by the coefficient of thermal expansion mismatch between TE elements and interconnects. Using a fault management system which can cut off the failed module from the rest can overcome this problem in AETEG. However, such arrangement makes the system more complicated and costly. The development of a particular material system-specific design using multiphysics simulations and experiments can help in improving the reliability of the leg-interconnect joints and the interface. Another problem severely affecting the durability of the module is the loss of materials from the TE legs by sublimation under prolonged exposure to high temperatures. Coating the surface with a stable thin layer of materials with comparable thermal coefficient of expansion (CTE) or casting the space between the TE legs with highly tortuous, extremely low thermal conductivity (<0.01 W/m·K) aero-gel could reduce the sublimation loss. However, all these processes substantially add up the overall cost of the modules.

3.2. Heat exchanger

The heat exchanger is an essential element of in AETEG which determines its overall performance. Since its primary function is to extract heat from flowing exhaust gas, an optimum design and sizing are critical for delivering the maximum power output. The efficiency of the TEG (η_{TEG}) which is given by $\eta_{TEG}=\eta_{HE}\times\eta_{TE}\times\varepsilon$ where η_{HE} is the heat exchanger efficiency, η_{TE} is the conversion efficiency of the cluster of TE modules and ε is the ratio of heat transfer from modules hot side to the cold side. An ideal heat exchanger should have low weight and high η_{HE} without causing severe backpressure to the flow of the exhaust gas. The back pressure will increase the parasitic losses in the vehicle.

Thermal efficiency (η_{HE}) of the heat exchanger mainly depends on three factors: (a) type, (b) internal geometrical shape and (c) materials of construction. The types of heat exchangers are classified according to the heat transfer mechanisms and the number of fluids. Construction type and flow arrangements are some of the other parameters used for further classifications. In automotive TEG, the type of heat exchangers used are mostly indirect, contact type with direct heat transfer between different medium such as gas and solid in the hot side and solid and liquid in the cold side of the system. According to the construction type and geometrical shape classification, the heat exchangers used are mostly either box type or tubular with extended surfaces such as fins or heat pipes depending upon the space available for the integration into the vehicle [10, 11, 21].

The choice of the materials for the heat exchanger fabrication is determined by their thermal conductivity, density, and fabricability. Since most of the heat exchangers are with extended surfaces, its shell outer temperatures are significantly influenced by the thermal conductivity of the materials used. The density of the materials used decides the overall heat exchanger weight and the parasitic loss associated with it. Materials which are easy to fabricate by

multiple manufacturing routes could bring in design flexibility and result in reduction of overall AETEG cost. Stainless steel, aluminum and brass are some of the heat exchanger materials used so far and tested in both diesel and gasoline engines.

The heat transfer from the exhaust gas to the outer shell of the heat exchanger where the TE modules are placed occurs by the combination of the convection and conduction mechanisms. The thermal resistance (R) for the convective heat transfer is given by R = 1/(h.A) where h is the heat transfer coefficient and A is the area of the heat transfer surface. Any internal arrangement which enhances the heat transfer area (A) increases the convective heat transfer which subsequently improves the hot side temperature (T_H). The thermal resistance for the convection mostly occurs in the boundary layer. Various kinds of fins with different shapes, dimensions, and arrangements are customarily set in the heat exchanger inside wall to enhance the turbulence resulting in the breakdown of the boundary layer. **Figure 3** shows some of the most commonly used internal arrangements in box type heat exchangers. Fishbone and inclined plate fin arrangements are some of the shapes showing high heat transfer rate from the exhaust gas with acceptable level of back pressure [22, 23]. Serial plate arrangement with the plate's direction perpendicular to the gas inlet showed the highest back pressure. Such arrangement gave backpressure as high as 190 kPa in a shell of 280 × 110 × 30 mm with inlet and outlet of 40 mm diameter [23]. An open shell metal foam filled plate heat exchanger also showed a very high efficiency of heat recovery 83.5% [24]. However, the high tortuosity of the foam structure creates an unacceptable levels of back pressure.

The temperature distribution in the heat exchanger along the exhaust flow direction usually tends to be lower in the downstream than the gas inlet region due to the heat loss to the TE module located close to the inlet [25]. Such nonuniformity in the temperature distribution reduces the power output of the modules placed beyond certain specified length in the downstream. Computational analysis carried out using different exhaust and coolant flow arrangements such as co-flow/parallel flow and counter flow suggest predicted a different overall power output [26]. However, it must be noted that a detailed experimental validation of these analyses only can confirm the preferred configuration that can maximize the overall power output.
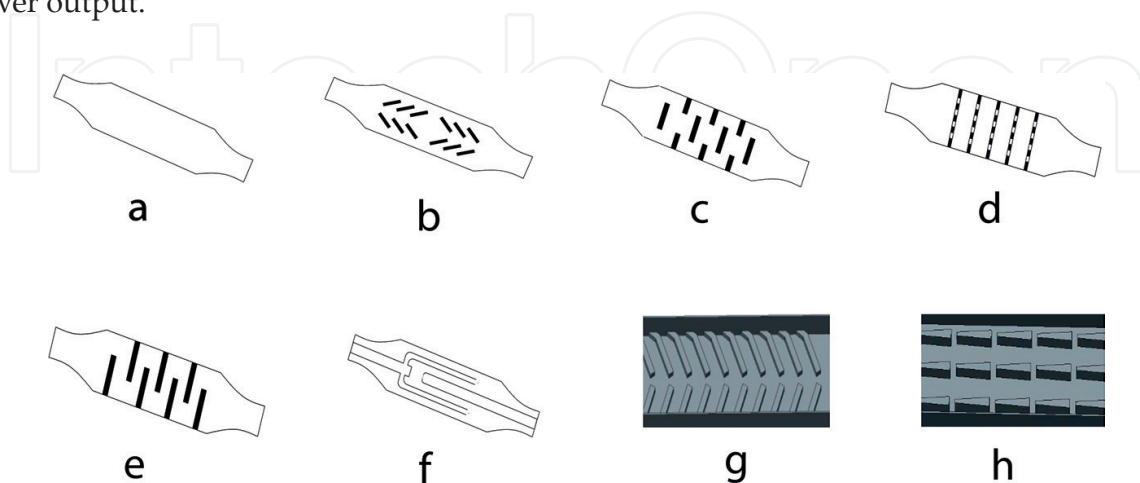

Figure 3. Different shapes of the internal arrangement for heat exchangers used in automotive TEG. (a) Empty cavity, (b) inclined plate, (c) parallel plate structure, (d) separate plate with holes, (e) serial plate structure and (f) pipe structure, (g) fish bone structure, and (h) accordion shape [23].

Using heat exchanger made of high thermal conductivity materials can improve the uniformity of the hot side surface to some extent. For example, in a study using steel and brass, Deng et al. observed better temperature uniformity in brass heat exchanger due to its higher thermal conductivity (κ_{brass}-109 W/m·K) [22]. Similarly, in a study using three-dimensional model to optimize heat exchanger parameters, Kempf et al. showed that by using silicon carbide in the heat exchanger better temperature uniformity can be achieved compared to stainless steel of 444 (SS 444) grade [25]. However, from the fabrication point of view, it will be highly cost-effective and easy to use SS than silicon carbide. The silicon carbide components are in general fabricated either by slip casting or gel-casting followed by sintering at above 2000°C. Such processes can adds up the TEG's cost significantly. The brass has higher density than SS which will increase the overall TEG's weight and the parasitic loss associated with it.

3.3. Heat sink or cold side heat exchanger

The AETEGs can be operated either at the maximum power (P_{max}) or maximum efficiency. In automotive exhaust application, it is always preferable to maximize the power output as it reduces the engine load which will improve the overall fuel efficiency. The P_{max} of a AETEG not only depends on hot side temperature (T_H) but the temperature difference (ΔT) between the hot and the cold side of the module. Hence, to maximize the power output, the cold side temperature (T_c) of the TE modules should be as low as possible. In most of the AETEGs designed, fabricated and tested in the laboratory testing conditions, the cold side temperature was controlled by using a water-cooled heat sink. However, in actual vehicles, it can be connected to the engine coolant circuit.

In the heat sink, the coolant flow is usually in the same (co-flow) or opposite (counterflow) direction to the exhaust gas flow as described in the previous section. Cross-flow and counter cross-flow arrangements are also used in few cases. The output power and the conversion efficiency of the AETEG for the various coolant flow arrangements mentioned above depends on the specific geometrical design of the cold side heat exchanger also. In the co-flow arrangement, the ΔT decreases along the streamwise direction of the exhaust gas flow as more sensible heat is absorbed and transferred to the cold side of the module tends to increase the coolant temperature. On the other hand, in counterflow arrangement, the ΔT decrease is lesser along the streamwise direction. However, to get the maximum power output in the TEG whether co-flow or counter-flow is preferable depends on the temperature and flow rate of the exhaust gas which in turn depends on the type, capacity and operating conditions of the engine.

The output power and the conversion efficiency of the AETEG for the various coolant flow configurations mentioned above depends on the specific geometrical design of the heat exchanger and heat sink combination. Su et al. performed simulation studies on different configurations of cooler design for TEG system viz., plate-shaped, stripe-shaped and diamond-shaped designs [27]. They further validated the simulation outputs with experiments and concluded that diamond-shaped design gave the highest power for a given engine speed among the three configurations for the cold side of the TEG system. They also observed that the temperature of the cold side is relatively uniform ensuring that the deviation in ΔT between the individual modules is minimal.

The cold side heat exchanger in TEG system in actual vehicle can either be a separate TEG coolant circulation system or integrated to the existing engine coolant circuit (integrated cooling

system). While the separate system requires additional space and increases the overall weight of the vehicle, connecting the existing engine coolant circuit avoids these complexities. However, the cooling pump capacity and radiator size may have to be increased to accommodate the additional heat coming from the cold side of the TEG so that the overheating of the coolant can be prevented. In a combined simulation and experimental studies carried out in a 2.0 L 4 cylinder engine, Deng et al. observed that under certain vehicle operating conditions, temperature of the integrated cooling system increases and exceeds the boiling point of coolant [28].

3.4. Assembly components

The heat transfer between hot side heat exchanger and the cold side heat sink through TE modules depends on how well various components of the AETEG are assembled so that thermal contact resistance will be minimal between various interfaces. The thermal contact resistance depends on many factors: the applied contact pressure, surface roughness, the interface materials and its hardness are some of the important parameters to list. The assembly components are responsible for enforcing sufficient force over the modules sandwiched between the heat exchanger and the heat sink. The ΔT across the hot and cold side of the TE module increases typically with contact pressure as it generates more area of physical contact at the microscopic level resulting in more heat conductance through the interfaces. **Figure 4** shows the curve showing the typical variation of ΔT with applied contact pressure in a TEG with and without interface materials. [29].

In the absence of any interface materials, it can be seen that the ΔT remarkably increases with applied pressure. With the use of thermal grease at the interface, the ΔT is almost invariant. However with graphite, the most common interface material in AETEG, the ΔT was significantly
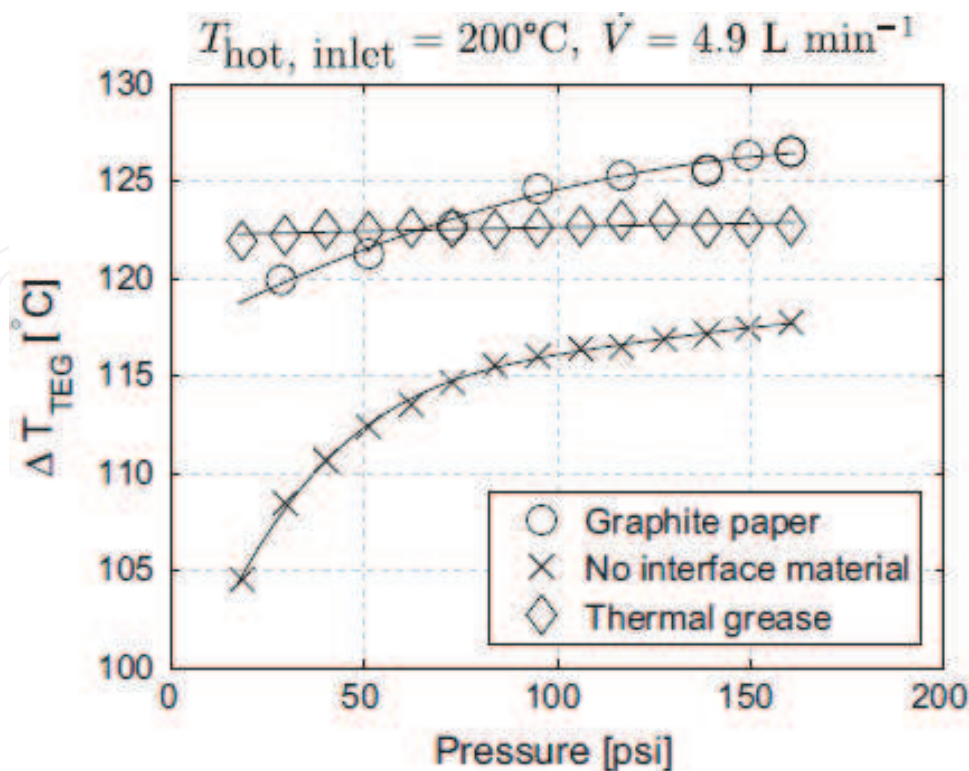

Figure 4. Variation of differential temperatures with contact pressure using different interface materials [29].
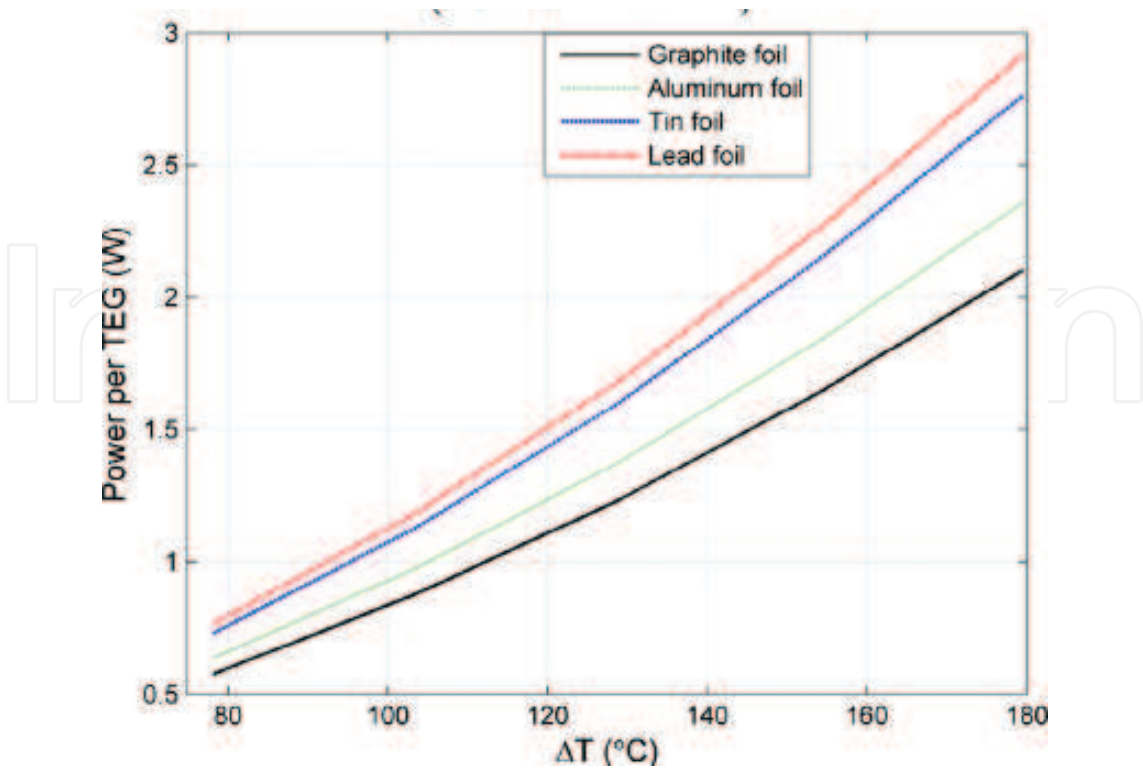
Figure 5. Estimation of the power per modules as a function of ΔT with different interface materials [28, 30].

higher than the other two for a given contact pressure particularly above 60 psi. The appropriate choice for the interface materials is the one with low hardness and high thermal conductivity. Such material will deform while applying pressure, make good contact between module and heat exchanger surfaces, and decrease the thermal contact resistance. **Figure 5** shows the comparison of the estimated power per Bi_2Te_3 modules as a function of ΔT in an investigation carried out using different interface materials [30]. Among the graphite, aluminum, tin and lead foils, the softest material lead is estimated to give lesser thermal contact resistance.

4. Performance evaluation of the AETEG

The AETEGs are usually tested for their performance by three different methods viz. (a) using a laboratory built test rig with hot gas or air as the heat source (b) in a simulated driving condition using laboratory test rig with gasoline or diesel engine and dynamometer and (c) in actual road driving test. While most of the performance tests reported so far were carried out by first or second methods, testing in actual driving conditions are very few. Such real driving conditions of a vehicle can give more realistic assessment of issues associated with this technology and its commercial feasibility.

4.1. TEG evaluation in test rig with a heat source

This test method is the ideal way of validating the design of an AETEG optimized by analytical and numerical methods. It is also a simple method to evaluate TE module reliability under the typical engine operating conditions. In AETEG, apart from the module efficiency, the power

produced is determined by multiple factors such as (1) location of the TEG in the exhaust line, (2) exhaust gas flow rate and temperature, (3) locations and arrangement of modules in the TEG, (4) area of coverage of the modules in the heat exchanger/s, (5) heat sink temperatures, (6) thermal conductance at various interfaces, and (7) scheme of the modules electrical connection. Several multiphysics simulations, combining fluid mechanics, heat transfer, and thermoelectric phenomena, have been carried out to predict the influence of some of the above mentioned factors on the performance and power output of the TEG. However, the experimental validation of these predictions is very limited [31, 32]. **Figure 6** shows the image of a test rig designed and developed by this author used for evaluating the AETEG performance using hot air/gas [33]. Testing of the TEG in this test rig offers complete performance details, that is, the efficiency of the TE modules, heat exchanger, and heat sink, which will be useful for further optimization of the design before evaluating their performance in the actual engine using established driving conditions. The test rig consists of the following sub systems:

- Heat source

- Heat exchanger

- Flowmeter

- Pressure transmitter

- Differential Pressure transmitter

- Data Acquisition and Integration unit

The hot air source is a blower and heater combined unit where a high pressure blower of 4000 lpm output capacity draws in air and passes it to air heater which can heat up the air up to 400°C. The pressure of the hot gas is measured at inlet and outlet of heat exchanger using
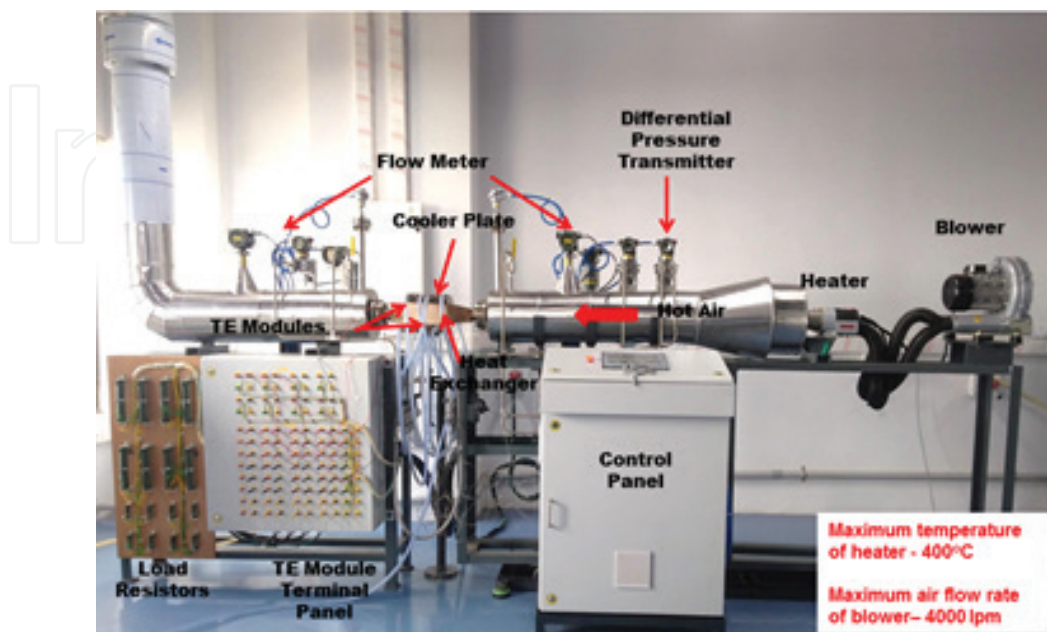

Figure 6. Photo image of the AETEG and the test rig developed at CAEM, ARCI.

a pressure transmitter and the back pressure due to the heat exchanger is measured by the differential pressure transmitter. The inlet and outlet temperatures of the hot air of the heat exchanger are measured using RTD sensors and K-type thermocouples are used for recording the temperatures on surface of heat exchanger. The data acquisition and integration unit collects the current and voltage signals from TE modules and also the pressure and flow rate signals and displays them in the display panel.

4.2. AETEG evaluation in test rig with engine exhaust

The performance evaluation of AETEGs using the engine exhaust gas has been carried out by many research groups. This method uses a test rig consisting of either a petrol or diesel engine coupled to a dynamometer to apply variable load. The testing can be carried out either in the steady state or transient condition using various engine speed and torque combinations which allows the generation of exhaust gas of different flow rates and temperatures. IC engines of different sizes ranging from 0.8 L [34] to 14 L [12] have been used in this method. In most of the works, while the heat exchanger and heat sink designs are different, the overall configuration of the AETEG prototypes is similar to one another.

The earliest attempt of building an AETEG and testing in an engine exhaust was carried out by Neild in the year 1963 [3]. Subsequently, Serksnis [4] and Birkholz [5] developed a similar system for exhaust waste conversion. Takanose and Tamakoshi developed a TEG and demonstrated it in a passenger car exhaust [35]. The system generated 100–130 W of power under various driving conditions. During the same period, Bass and his coworkers developed a 1 kW unit using 72 units of HZ-13 modules and tested in a 1.4 L Cummins diesel truck engine [12]. The BiTe modules made by Hi-Z Technology Inc. USA were arranged in a nickel steel support structure with an octahedral cross-section through which exhaust gas flows close to its internal surface. The modules cold side was cooled using an aluminum heat sink. The TEG initially generated power output of 400 W. Subsequently with several modifications in the design which resulted in better heat transfer at hot side, the TEG generated 1068 W under the engine operating condition of 300 HP and 1700 RPM. Ikoma and his co-workers from Nissan Motor Corporation, Japan developed a SiGe based AETEG fitted to the exhaust of a gasoline engine [13]. The system was made using 72 modules arranged between the rectangular cross section exhaust pipe made of SS 304 and aluminum water-cooled jacket. The TEG produced the maximum power of 35.6 W under the engine condition of 60 km/h hill climb with overall power generation efficiency of 0.1% [13]. Matsubara and his team from Science University of Tokyo, Japan [15] developed a prototype TEG and tested in a 2.0 L Toyota Estima engine using in-house manufactured segmented modules (skutterudites/Bi_2Te_3) and 4 HZ-14 modules made by Hi-Z Technology Inc., USA. The TEG produced an output power of 266 W under 60 km/h speed which is only half of the rated capability of the system. In both the abovementioned works, it was highlighted that the effectiveness of the heat exchanger and loss of heat at the various contact surfaces critically influence the power produced in the TEG.

The first qualitative assessment of the effect of AETEG system on the vehicle fuel efficiency and parasitic losses was carried but by Thatcher et al. in a 1999 model GMC Sierra light-duty pickup truck [9]. The study also emphasized the importance of the cold side temperature on the overall power output of the TEG. A 330 W capacity system built using 16 units of HZ-20 modules manufactured by Hi-Z Technology Inc., USA. The TEG produced 117 W under the

engine speed of 112.6 km/h with the hot side and coolant side of temperature around 300 and 80°C, respectively. Decreasing the cold side temperature to 15°C increased the power output to 229 W, which showed that decreasing the cold side temperature of the module appears to be more beneficial, unlike increasing the hot side temperature which may have the adverse effect on the module durability.

In a project partially funded by Swedish energy agency, with partners from Scania CV AB, Titan X, Eberspächer Exhaust Technology GmbH & Co. Germany, Swerea IVF, Gothenburg and KTH, Stockholm, a TEG system using Bi_2Te_3-based commercial modules has been designed, developed and tested in experimental hot gas test bench as well as in an actual engine exhaust [11]. The 224 modules which can be used up to 330°C are arranged in 14 modular TE units consist of hot exhaust gas and cooling water channels with counter cross-flow arrangements. At the input gas parameters of 300°C temperature and 1000 kg/h flow rate, the TEG delivered power output of 416 W. In a similar work using 1.2 L gasoline engine, a TEG designed to a nominal power of 225.6 W has produced the maximum power of 189.3 W at the engine operating conditions of 80 Nm torque, 2600 RPM speed [10]. The TEG was fabricated using 24 numbers of commercial Ferrotech SCTB NORD thermoelectric modules (Code Name TMG-241-1.4-1.2) made of BiTe-based compounds with the maximum power rating of 9.4 W. The increase in overall engine efficiency was close to 0.2%.

Zhang et al. reported the development of high temperature, high power density TEG yielding 1002.6 W power when tested in a Caterpillar diesel engine exhaust [20]. The TEG was fabricated using modules made of half-Heuslers compounds of p-type (peak ZT of 1.0 at 500°C) and n-type (peak ZT of 0.9 at 700°C) compounds. Heat exchanger with 0.2 mm thick nickel fins and aluminum cold plate with coolant flow perpendicular (cross flow) to the exhaust was used to create the temperature difference between hot and cold side of the modules. The exhaust gas of 550°C with a flow rate of 1728 kg/h generated a temperature difference 339°C of between hot and cold side. The efficiency of the individual module was around 2.1%. Liu et al. investigated an automotive TEG designed, fabricated and tested in test rig with 2.0 L naturally aspirated engine with a dynamometer and in actual road test condition in a 3.9 L engine [36]. The TEG was made of 60 modules, a brass heat exchanger and aluminum water tank as the heat sink. The maximum power output of 335.8 W under the temperature difference of 235°C with the conversion efficiency of 0.9% was obtained in the test rig. Interestingly, combining the four of the same TEGs into a single system for road test could able to generate only 390 W power as under this test conditions the exhaust heat from engine appeared to be inadequate and could able to create a temperature difference of 133°C only.

AETEG's have been investigated for the performance both in gasoline and diesel engines of various capacities and vehicles. Whether it is advantageous to use this technology for a particular kind of engine is a debatable topic. The amount of waste heat and the temperature of the exhaust gas usually is higher in the spark ignition (S.I) engine compared to compression ignition (C.I) engine. The maximum exhaust gas temperature for gasoline engines is about 700–800°C and for diesel engines is about 400–500°C at the exhaust manifold. A study carried out by Wojciechowski et al. in a single point injection 0.9 L Fiat spark ignition (gasoline) engine and 1.3 L diesel engine using BiTe-based AETEG suggests that it is more beneficial to use in spark ignition engine [16]. For a given engine power, the high output of gas flux from the diesel engine results in a low hot side temperature and hence the energy produced is lesser.

5. Automotive TEG for engine coolant waste heat conversion

Similar to the exhaust waste heat conversion, the heat in the engine coolant can also be utilized to generate power using the TEG, as nearly 30% of the energy from the fuel combustion accounts for this loss. However, the important point to be noted here is that the waste heat available in the coolant is of low grade in nature. Unlike exhaust gas, in this case the temperature and flow rate are lesser and need better heat capturing technique. Kim and his coworkers demonstrated TEG for engine coolant heat conversion using a 2.0 L passenger car engine [17]. The TEG was made of 72 BiTe modules with the hot and cold side blocks used to recover and dissipate the heat from the coolant. The cold side block was integrated with heat pipes which enhances its efficiency. Under the engine idle condition, the maximum output power of 0.4 W/module was generated which increased to 1.04 W/module under 80 km/h driving mode. The higher power obtained in the driving mode can be attributed to the lesser cold side temperature rather than hot side temperature, which shows an improvement of only 5°C. Under driving mode, the cold side temperature decreases by 25°C due to the arrangement of the heat pipes which showed better cooling performance than the radiator.

6. TEG for hybrid and electric vehicles

Hybrid vehicles consume relatively less fuel than the petrol or diesel vehicle by efficiently combining a conventional I.C engine power with the electric motor/s. The power to the drive comes from either downsized engine, motor or both depending on the driving conditions. The improvement in fuel efficiency mainly comes from operating the engine in an optimized condition with less idling, regenerative breaking, and dual power sources. Depending on the kind of the power source, the hybrid vehicles can be classified as serial hybrid, series–parallel hybrid, and plug-in hybrid. In some hybrid systems, the engine is automatically shut off during idling and restart when accelerated by integrated starter generator (ISG) thereby reducing the fuel consumption. The regenerative braking system converts the kinetic energy from the moving vehicle into electrical energy and stores it in a battery. At present, though the hybrid cars consume less fuel than conventional vehicles, there are still CO_2 emissions, the level of which may have to be reduced further to meet the futuristic goal of the allowable limit. Though, unlike in conventional I.C engines, not much work has been carried out in AETEG for the hybrid vehicles. The computational and experimental work carried out so far suggests that a notable improvement in fuel efficiency can be achieved using TEG in hybrid cars [37, 38]. Since in hybrid vehicles, the engines used are downsized, the exhaust flow rate and the temperature are expected to be low and hence using heat pipe-assisted TEG will be more suitable to maximize the power output [39].

7. Parasitic losses by TEG in vehicle

The overall effect on the fuel efficiency of the vehicle due to the incorporation of AETEG in the exhaust line not only depends on the power it produces but also on the parasitic losses associated with it during driving which has been estimated to contribute to a notable extent. The parasitic losses mainly comes from three sources viz. power required for pumping coolant into

heat sink, exhaust blow-down power loss, and the rolling resistance [31]. The dominant among these three is the rolling resistance loss due to the weight of the TEG system which tends to increase with the vehicle speed.

The coolant pumping power (P_{cp}) is given by $P_{cp} \approx \rho_f \chi Q / \eta_{cp}$, where ϱ_f is the density of the coolant, χ is the loss coefficient for coolant flowing through the TEG loop, Q is the coolant flow rate, and η_{cp} is the coolant pump efficiency. The loss coefficient χ depends on Reynolds number of the fluid flow. In a typical AETEG where the coolant circuit is connected to engine coolant loop, the flow rate through the TEG will be low relative to the flow through engine coolant jacket. However, as the capacity of the TEG increases, the χ through it also will be significant.

The exhaust blow-down power, which is the power required for the engine to drive the gaseous products of the combustion through the exhaust system can change because of the flow resistance introduced by the TEG system's heat exchanger. The blow-down power can be both positive and negative depending on the power gains obtained due to AETEG. If the power produced helps to decrease the shaft power, the net blow-down power will decrease. The blow-down power given by $P = \Delta p \cdot V_F$ is calculated from pressure drop across the TEG's heat exchanger (Δp) and the volumetric flow rate of the exhaust gas (V_F). For a given engine running at a speed (ω), the volumetric flow rate of exhaust is given by $V_F = (\pi \cdot \omega \cdot N_p \cdot S \cdot b^2)/8$ where N_p is the number of pistons, S is the piston stroke and b is the piston bore [25].

The rolling resistance is due to the weight of the AETEG system produces power loss given by $P_R = \mu_R W_T \nu / \eta_R$, where μ_R is the rolling resistance coefficient, W_T weight of the TEG system, ν is the velocity of the vehicle, and η_R driveline efficiency which is normally constant at around 0.9 [31]. An estimation in a 1.5 L car fitted with TEG tested under new European driving cycle showed that the weight penalty of TEG could be as high as 12 W/kg [47]. Therefore, the TEG requires very stringent design criteria in terms of the heat exchanger materials and TE module materials.

8. Power conditioning and maximum power point tracking

In AETEG, the output voltage changes dynamically in a nonlinear way over a wide range with the fluctuation of flow rate and temperature of exhaust gas. Therefore, a proper power conditioning circuit similar to the ones used in photovoltaic power system with a maximum power point tracking (MPPT) control is essential between the TEG and the load. A number of different power conditioning circuits for AETEG to step-up or step-down the voltage have been proposed. Some of the prominent circuits are DC-DC converters such as Ćuk converter, SEPIC converter, and Boost-buck cascade converter. MPPT is an algorithm used to operate a power system at its maximum power capability under various operating conditions. Different MPPT techniques such as load matching method, incremental conductance technique, ripple correlation, perturbation and observation (PAO) method has been developed. The PAO method is the most commonly used one due to its simplicity and system independence.

In automotive exhaust waste heat conversion, MPPT can be used, for example, between the TEG system and a battery pack so that power flow is regulated to obtain the maximum power transfer. Eakburanawat et al. proposed an MPPT technique based on feedback from battery current alone assuming constant battery voltage [40]. However, all practical batteries have a significant change
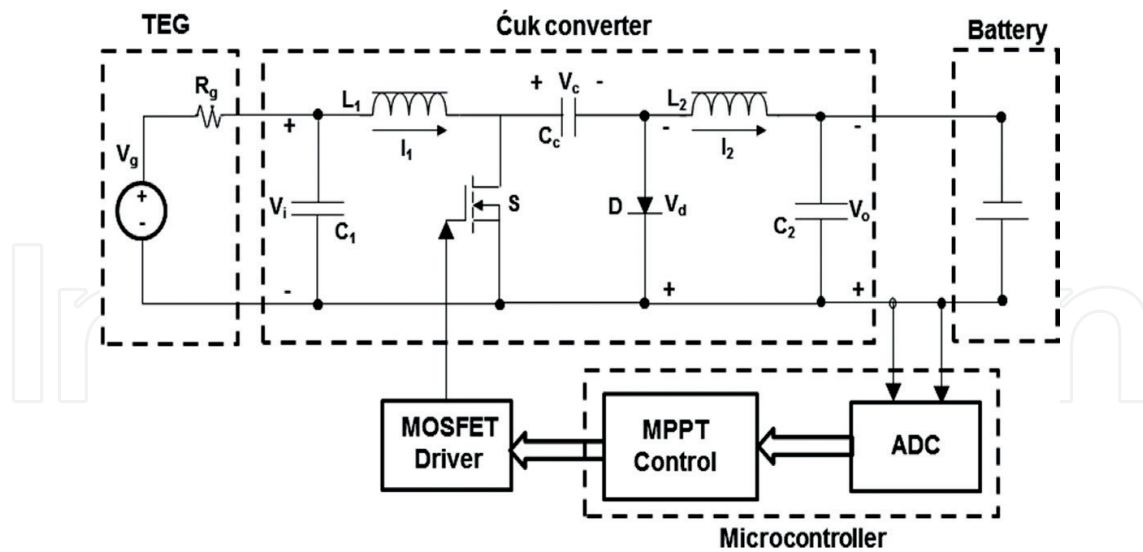
Figure 7. Schematic of power conditioning system based on battery voltage and current [40].

of terminal voltages, especially during charging, which should not be neglected. Later, Yu et al. proposed the MPPT technique based on the measurement of TEG power which is derived from its terminal voltage and current [41]. However, such maximization has not taken into account the power converter loss, which should not be a constant value. Subsequently, the same group has proposed a DC-DC Ćuk converter-based power regulation system with the MPPT technique which considers both the terminal voltage and current of the battery to maximize the TEG output power instead of using terminal voltage and current [42]. **Figure 7** shows the schematic of power conditioning scheme proposed based on battery voltage and current. The variation of battery voltage and power converter loss is also taken into account in this system.

Fang et al. proposed a novel MPPT scheme which involves the aggregated dichotomy and gradient (ADG) method for rapid tracking the maximum power in an automotive TEG [43]. They carried out the steady state and transient tracking experiments under various load conditions of dynamometer and compared the ADG method with traditional methods like single gradient method (SGM), single dichotomy method (SDM) and perturbation and observation method (PAO). The results showed that the ADG had better tracking accuracy and speed compared to the traditional methods.

9. Cost analysis of automotive TEG

Though the TEG for automotive exhaust application envisaged improving the overall fuel efficiency, the final task of implementation on commercial scale mainly depends on the cost–benefit it offers over the lifespan of a vehicle. At present, both technological and cost factors of AETEG are not in favor for such commercial realization. The major cost components in the AETEG come from modules, heat exchangers for hot and cold side, power conditioning unit with control systems, and so on. Various cost analysis studies carried out in passenger automobiles under different operating conditions suggest that the cost of the existing TE modules alone must be reduced

up to 40% by using low-cost materials with higher zT [44]. In an analysis carried out in conventional vehicles operated in Korea, Bang et al. reported that the application of TEG in mid-size sedan and the medium-duty truck can save 0.15 and 1.04 kL fuel, respectively, at a driving speed of 80 km/h. Such fuel savings show that the economically acceptable costs of the TEG system for these two vehicles are 744 $/kW (mid-size sedan) and 2905 $/kW (medium duty truck) [45]. A comprehensive cost analysis of the real application scenario of automotive TEG using skutterudites module by Hendricks et al. suggests that the heat exchangers cost most often dominate the overall AETEG cost, and it is necessary to bring down from the current 10$/W to l $/W or lesser [46]. They observed that the minimum system cost is coinciding with the maximum power point which is governed by factors such as exhaust temperature, ΔT between the hot and cold side of the module, zT of the materials, thermal conductance between the hot and cold sides, heat exchanger cost factor and the parasitic losses. The rolling resistance arising due to the weight of the TEG alone would attract the penalty of a significant fraction of the power produced. In a 1.5 L engine family car tested under new European drive cycle incorporating an AETEG showed a power loss of 12 W/kg [47]. The additional load for the coolant pump for circulating the coolant to the cold side heat exchanger would further add up to the power loss. Employing low-density materials in both the heat exchanger/s and TE modules would considerably reduce the AETEG cost by decreasing its weight and parasitic losses associated with it.

10. Summary

Hydrocarbon-based fuels will continue to be a primary source of energy for transportation for the next few decades. Improving the efficiency of the vehicles by even few percentages will have a tremendous effect on the fuel savings and controlling the emissions. Automotive TEG is one potential technology which can increase the vehicle fuel efficiency. Though the technique is known for several decades, significant progress has been made in materials, modules, and systems over the past 20 years only and as of today it is far from commercialization. The high cost and low efficiency of the currently available modules make the overall cost of the TEG much higher than $1/W barrier apt for implementation this technology in vehicles. The high zT observed in several low-cost materials in recent years need to be translated into reliable high-power output modules. An innovative design which reduces the overall weight of the AETEG with improved efficiency is a key necessity to make this technology commercially successful.

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