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Thermoelectric materials and heat exchangers for power generation – A review

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ABSTRACT

Around 60–70% of the fuel energy in an internal combustion engine is lost as waste heat through engine exhaust and coolant. Hence, waste heat recovery techniques can be used to increase the efficiency of the engine. Thermoelectric systems are widely used for converting heat energy to electric energy. A considerable attention of researchers has been drawn by the thermoelectric generator, for the waste heat recovery from engine exhaust. The thermoelectric generator is one of the promising green energy source and the most desirable option to recover useful energy from engine exhaust. A high-efficiency heat exchanger, which is an integral part of the thermoelectric generator, is necessary to increase the amount of heat energy extracted from engine exhaust at the cost of acceptable pressure drop. The present work is a summary of thermoelectric materials, and heat exchanger studies on heat transfer rate, thermal uniformity, and pressure drop. The heat exchangers with different internal structures enhance heat transfer rate and thermal uniformity, which increase the power output and the conversion efficiency of the thermoelectric generator. The presence of flow-impeding inserts/internal structures results in an adverse increase in pressure drop and has a negative effect on the performance of waste heat source.

1. Introduction

For any country, thermal energy is an important resourceful entity for the economic development [1]. The level of energy consumption increases with the economic development and population in a country [2]. Increasing fuel costs is forcing industries and governments to increase the power efficiency [3]. With petroleum prices increasing and the environmental problems caused by greenhouse gases, the issue is becoming more and more serious [4]. The Internal Combustion engine (ICE) has been a primary power source for automobiles, locomotives, long-haul trucks, and ships over the past century [5]. High capacity diesel engines are widely used for power generation. But in reality, about two third of the input energy of Internal Combustion engine is wasted through exhaust gas and cooling water of the engine [1]. Only 30% of the engine power is converted into useful work and is used to drive a vehicle and its accessories load [6]. For current Internal Combustion engines, the proportion of fuel energy converted into useful work at medium and high loads is about 30–45% for a diesel engine or 20–30% for a petrol engine [4]. This also depends on the engine operating conditions [7]. It is difficult to increase the efficiency of ICE to an excess of 42%, [8]. Diesel engines are more efficient than gasoline engines and are therefore preferred for professional use where fuel economy and cost is an important factor [9]. A considerable amount of energy is released into the atmosphere in the form of the exhaust gas [7]. A serious and concrete effort should be made towards conserving waste energy through waste heat recovery techniques [1].

Waste heat is heat generated by a process of fuel combustion or chemical reaction, which is then expelled in the ambient and is not reused for useful and economic purposes. If the waste heat can be recovered, a considerable amount of fuel can be saved [1]. It has been identified that waste heat recovery technologies can be used to save energy [2]. If this portion of waste heat can be recovered, energy efficiency will be improved, and vehicles all over the world could save lots of energy and global warming will be reduced [6]. A simple exhaust gas heat recovery system helps to maintain the temperature of the diesel engine at the desired range of > 70 °C in cold climates with subzero temperatures [9]. Depending on the temperature level of the exhaust stream and the proposed application, different heat exchanger devices, thermoelectric material, heat pipes, bottoming cycle, turbocharger, and combustion equipment can be employed, to facilitate the use of the recovered heat [1,3,4]. The high-temperature stage is used to generate electricity or mechanical power, and the low-temperature stage is used

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Nomenclature

A	area [m^2]
h	average heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
I	current [amp.]
P	power output [W]
R	electrical resistance [Ω]
T	temperature (K)
V	voltage [volt]
ZT	figure of merit [dimensionless]
ΔT	temperature difference [°C]

Greek symbols

σ	electric conductivity [$\Omega^{-1}\,m^{-1}$)]
κ	thermal conductivity [$W\,m^{-1}\,K^{-1}$)]
η	efficiency [%]
ρ	electric resistivity [Ωm]
γ	thermal uniformity coefficient [dimensionless]
π	Peltier coefficient [V]
τ	Thomson coefficient [V/K]
α	Seebeck coefficient [$\mu V\,K^{-1}$]

Subscripts

c	electronic component/ electric contact
g	generator
H	hot side
i	measurement position
j	junction
l	lattice component
L	cold Side
m	mean
OC	open circuit
th	thermal

for the process of feed water heating or space heating. The heat recovery systems are to be selected on the basis of temperature level [10]. The engine manufacturers have increased thermal efficiency by implementing different techniques such as enhanced fuel/air mixing, variable valve timing, and turbocharging [5]. It is predicted that even if only 6% of the heat contained in exhaust gas is converted into electric power, this would mean reduction of fuel consumption by 10% due to the decrease in mechanical losses from the resistance of the alternator drive [8]. Fuel reduction of up to 6% can be achieved, depending on the waste heat recovery technology and the driving cycle [11].

2. Thermoelectric material

2.1. Thermoelectric module-Seebeck effect

A thermoelectric (TE) module consist legs of n-type and p-type semiconducting materials connected thermally in parallel and electrically in series. Material structures and compositions are used to classify thermoelectric materials. Some of the main classifications are Clathrate, Chalcogenide, Half-Heusler, Skutterudite, Silicide, and Oxide. Thermoelectric material properties are highly temperature-dependent and face multiple challenges in application, such as specific materials choice. The figure of merit ZT describes thermoelectric material performance. It depends on the thermoelectric material properties such as, Seebeck coefficient α, thermal conductivity κ, and electrical conductivity σ, and $ZT = \alpha^2\sigma T/\kappa$ where T is the material temperature. A thermoelectric couple is a pair of n-type and p-type legs, and a thermoelectric module generally has several couples. These couples and their electrical interconnects are covered by an electrical insulator, typically a ceramic [12]. Thermoelectric conversion efficiency can be improved by maximizing the Seebeck coefficient and by lowering the electrical resistivity and thermal conductivity [13]. Heavily doped semiconductors can be used as thermoelectric materials and can be grouped into three technologies depending on the temperature range of the operation. Those based on Bismuth Telluride materials, Lead Telluride and Silicon-Germanium alloys [14]. The variation of the Seebeck coefficient and the electrical conductivity as a function of the reduced Fermi energy, serves for the optimization of the power factor, $\alpha^2\sigma$ [15]. Materials based on Bismuth Telluride have the highest figure-of-merit ($3.4 \times 10^{-3}\ K^{-1}$) but are restricted to operate below 250 °C. Lead Telluride has the next highest averaged figure-of-merit ($2.0 \times 10^{-3}\ K^{-1}$) over an operating temperature range of up to 500 °C. Finally, Silicon Germanium has the lowest figure-of-merit ($0.8 \times 10^{-3}\ K^{-1}$) but is able to operate for long lengths of time at temperatures around 1000 °C [16–20]. The complex structures helped to improve the ZT with various approaches mainly by Clathrates, Skutterudites and Zintl phase. The substructure approach and incorporating nanostructures opened up a new opportunity. The superlattice materials show ZT up to 2.5 at room temperature, but are not suitable for mass production [21]. Nanostructures have been demonstrated to be a powerful tool to achieve record thermal efficiencies [22]. The recent understanding of phonon scattering and the energy filtering led to the development of Nanocomposites which are showing the promising route to develop materials of higher ZT [21]. The Tellurium based glasses with high copper concentrations are confirming Chalcogenide semiconducting glasses for high-performance thermoelectric materials [23].

2.2. Thermoelectric material preparation

A dip coating procedure is used to prepare the graded thermoelectric material of n-type β-$FeSi_2$/Bi_2Te_3 by using $Sn_{95}Ag_5$ as bridge material. It is observed that the maximum power output is approximately 2.5/3 times that of monolithic material β-$FeSi_2$ at the same temperature difference [24]. A complex sol-gel method is used to prepare $La_{1-x}Sr_xCuO_{3-\delta}$ polycrystalline samples. The transport properties of the samples are modified by changing La atoms for strontium atoms [25]. A silicon molding process can be used to fabricate Bi–Sb–Te system thermoelectric elements of 300 m height and 40 m cross-sectional width [26]. A cylindrical explosive consolidation is used to prepare three-phase powder mixtures of Bi–Te–Se and Bi–Te–Sb. [27]. A cryogenic grinding method is used to prepare Bi_2Te_3 nanosized powders with an average particle size of about 70 nm, in the state of liquid nitrogen. Cryogenic grinding can produce much finer and good sinterability Bi_2Te_3 powders [13]. The thermal conductivities (κ) of the materials prepared by spark plasma sintering could be evaluated from the following expression [28]:

$$\kappa = \kappa_l + \kappa_c \qquad (1)$$

Here, the lattice component (κ_l) values are directly obtained by the measurement of thermal (κ) and electrical (σ) conductivities of the materials by spark plasma sintering, whereas the electronic components κ_c are calculated by Wiedemanmn– Franz law $\kappa_c = L\sigma T$, [28]. Fabrication methods such as superlattice, plasma treatment, segmented element, nanocomposite and nanostructure to improve ZT value of thermoelectric materials have been introduced [29]. Device efficiency and commercial feasibility of the most promising thermoelectric materials are governed by fabrication costs and coupled thermal and electrical transport factors [30].