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Efficiency Enhancement of IC Engines using Thermo-electric Technology

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Abstract— This paper represents a potential approach for recovering wasted thermal energy from IC engines (internal combustion) such as Diesel engine and Gas engine generators. The wasted thermal energy recovery and turning it into usable electric energy is the main target of this paper. This potential or possibilities have been shown by using basic calculations of the state of the art Thermo-electric generator's efficiency and geometric parameters. A comparison of efficiencies in cases of diesel engine and gas engine shown here as well. Afterwards, the practical parameter consideration has been done to estimate its potential efficiency and application.

Keywords — Bangladesh, Bismuth Telluride (Bi_2Te_3), Diesel/Gas Engine, Thermo-electric generator (TEG), Thermo-electric module (TEM), Efficiency, Silicon Germanium ($Si_{0.7}Ge_{0.3}$), Wasted heat recovery.

1 INTRODUCTION

Among the different approaches for producing Electricity, Diesel generators and gas generators serves a large portion of electricity supply in developing countries such as our country Bangladesh. But due to limited efficiency of Diesel and Gas generators, a lot of thermal energy is wasted in this process. The amount of wasted heat, if salvaged, can offer us a promising amount of recovered energy. In this paper, the prospects of converting this wasted heat into electricity using a direct conversion method as an energy salvaging process has been discussed.

Thermo-electric (TE) generators are direct convertors of heat to electricity. The conversion process is carried out according to the principle of TE Seebeck effect, which was discovered in 1821. At first, thermocouples were used to measure temperature only. But discovering materials with more TE efficiency made the TE materials useful for refrigeration (TE cooler) and also electricity generation. [1]

In Bangladesh, among the electricity generations, 7.83% is HSD (High Speed Diesel) based, 21.18% is HFO (Heavy Fuel Oil) based and 62% is Gas dependent. Among the installed capacity 35.92% power is generated by reciprocating engines (gas/diesel). [2]

This paper discusses that, using thermoelectric modules with optimum parameters and design, about 7.6% of the thermal waste energy can be recovered. If calculated, about 483 MW power can be recovered in total in aspect of Bangladesh.

2 TEG overview

Thermoelectric generators (TEGs) are devices which are rugged, acoustically silent and containing no movable parts, can harvest electrical energy when a temperature difference is applied across the two sides or ends of the device. [3] The phenomenon of generating electricity gradient of a conductor due to a temperature gradient across it in open circuit condition is called the Seebeck effect. Another phenomenon known as Peltier effect is the opposite of Seebeck effect that absorbs or evolves heat when current is passed through the junction. The basic schematics of a thermocouple is shown in figure 1.

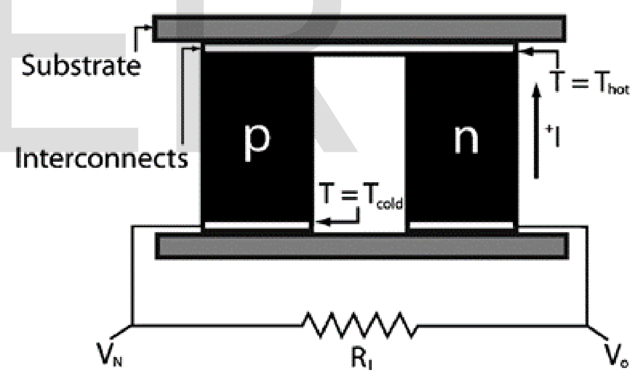

Figure 1: Schematic of a single thermocouple TEM operating in generation mode.

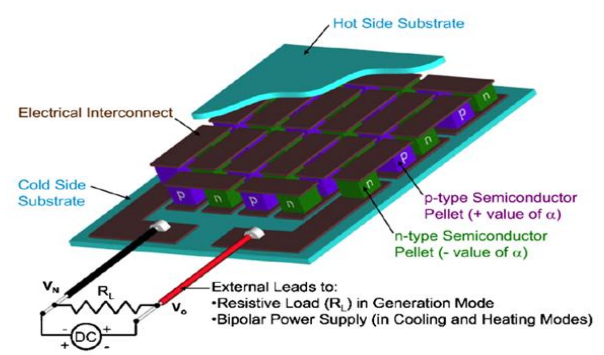

Figure 2: Cut-away view of a TEM. [4]

A set of thermos-couples are joined together to make a thermoelectric Module (TEM) (Figure 2).

To determine the performance of any thermoelectric device, a dimensionless parameter is used which is known as **figure of merit.** It is denoted as 'ZT' and it depends on the properties of the junction material of the TEG or TEM.

Equation for calculating figure of merit ZT,

$$ZT = \frac{\alpha^2 \sigma T}{\kappa}$$

Here, α = material seebeck coefficient
σ = material electric conductivity
T = Temperature of the hot side of TEM
κ = Thermal conductivity

According to Yang [5] we can get an overview of thermoelectric materials and their figures of merit. Bulk materials, such as bismuth telluride and lead telluride, identified in the 1960s and 1970s have ZT in the range of 0.5 to 1.0. These materials are most common in present-day applications, including demonstration vehicle waste heat recovery programs.

In recent times, carbon based thin film materials such as silicon carbon and boron carbon have been engineered which operates on a **quantum well** principle demonstrating their ZT ranging from 4 to 5 in the laboratory. Along with higher efficiency it comes with low cost due to its structure. But these materials are yet to be scaled up for practical applications**.** [6]

3 Present State of Art

New genre of nano-structured Thermo-electric materials have been developed, which are a bit more efficient than the traditional TEGs. These TEG's structure is referred as quantum wells (QW) and its composition consists of alternating layers of 10 nm thick silicon and SiGe films. Due to such confinement, all of the thermoelectric properties are improved which in turns, increases the thermoelectric Figure of Merit, ZT. This breakthrough has enabled the ZT of a QW material to reach a remarkable value of 4.1, whereas the conventional ZT of bulk TEG materials have remained around the value of 1 for 35 years. [7]

QW having ZTs greater than 3 can render a conversion efficiencies greater than 20%. Hence, QW materials which allows for much wider commercial applications, especially in case of waste-heat recovery from ICE engines, refrigeration, and air conditioning, where State of the art (SOTA) bulk thermoelectric modules were technically feasible yet economically unviable due to low conversion efficiencies. [7]

This nano-wired technology has been implemented commercially by Hayward California based startup ''Alphabet energy''. They have built a generator named E1 that uses exhaust fumes from industrial machineries and converts it into electricity using solid stated silicon nanowire based TE modules. [8]

4 METHODOLOGY

The purpose of this paper is to conduct a comprehensive study on implementing thermoelectric modules to recover wasted thermal energy in order to increase to overall efficiency in power production. We have considered reciprocating engine based power production since 35.92% of the power is generated by this type of engines. Moreover it is portable and transportation industries use a great deal of reciprocating engines, such as in, heavy duty trucks, SUVs, earth moving machines, ships etc. So, this study can also be applicable in those cases as well.

First, the TEMs have been designed and used theoretically according to SOTA TEG materials and a mathematical model has been established according to their parameters. Then, a MATLAB code have been developed from the mathematical model in order to calculate the efficiency of those TEMs. That enables to get an idea of what percentage of the wasted thermal energy can be potentially recovered from an ICE engine.

Different models of diesel and gas generators are then put into comparison according to their wasted thermal energy and potential recovery of energy using the TEMs, resulting an increase of overall efficiency. Then the prospects of wasted heat recovery from a diesel engine power plant of Bangladesh has been discussed as well as the optimization of TEM pellet geometry for further improvements. The possible practical result has been derived as well.

5 DESIGN

Physical Design: A TEM consists of an array of n and p-type pellets connected electrically in series and thermally in parallel between ceramic substrates. Bismuth Telluride (Bi_2Te_3) and Silicon Germanium ($Si_{0.7}Ge_{0.3}$) nanowire TEMs has been used as SOTA

The Hot side and cold side substrates are placed accordingly, then electricity is harnessed from the series connected P-N junctions. A heat sink is placed at the cold side of the TEG to enhance the efficiency. [4]

6 Mathematical Design: *TE Generator Equations*

The mathematical model has been developed according to Rafiee [1] and Cobble [9]**.** First of all, the Figure of merit, ZT of the TEG is calculated as follows:

$$ZT = \frac{\alpha^2 \sigma T}{\kappa} \quad (2.1)$$

Here α (V/K) is the material seebeck coefficient, σ (S/m) electrical conductivity and κ (W.m-1.K-1) is thermal conductivity.

Electrical resistivity of the material ρ (Ωm) can be Obtained from electrical conductivity:

$$\rho=1/\sigma \qquad (2.2)$$

The thermal conductivity is sum of the component carrier (electron) and phonon which are respectively, $\kappa_{electron}$ and κ_{phonon} :

$$\kappa = \kappa_{electron} + \kappa_{phonon} \qquad (2.3)$$

According to The Wiedmann-Franz law the carrier thermal conductivity is given as:

$$\kappa_{electron} = L.\sigma.T \qquad (2.4)$$

Where, L is the Lorenz number (2.445×10-8W.S-1.K-2). [9]

Although there are several methods for calculating, the basic equations have been used in this paper. [9]

The temperature difference between the hot and cold side of the TE generator is:

$$\Delta T=T_H - T_C \qquad (2.5)$$

Where, T_H is the hot side and T_C is the cold side temperature in Kelvin.

The open circuit output voltage is:

$$V_{OC}=\alpha.\, \Delta T \qquad (2.6)$$

So the output current is calculated as:

$$I= V_{OC} / (R + R_L) \qquad (2.7)$$

Here, R is the TE generator's internal resistance and calculated as:

$$R= \rho l / A \qquad (2.8)$$

Here l is the length and A is the cross sectional area of the TE pellet.

R_L is the load resistance which is set 1.323393R, for optimum efficiency. [9]

The output power is:

$$P=I_2.R_L \qquad (2.9)$$

The input heat to the TE generator is calculated as follows:

$$Q_H = \alpha.I.T_H - 0.5R.I_2 + K.\, \Delta T \qquad (2.10)$$

Where K is:

$$K= \kappa A / l \qquad (2.11)$$

So the TE pellet waste heat is:

$$Q_C = Q_H - P \qquad (2.12)$$

And the TE pellet efficiency is:

$$\eta = P / Q_H \qquad (2.13)\ [1]$$

7 MATLAB CODE CALCULATION

A MATLAB code is developed in order to carry out these calculations for specific temperature differences and TEM parameters. In this case, parameters for the TEG pallets are given as below.

In this paper, bismuth telluride (Bi_2Te_3) nanowires of (6×6×1) mm pellet has been used for the TE generator of the generator coolant system or radiator. Its seebeck coefficient is ovsereved to be 287 μV/K at 327 Kelvin (58.9 ^{o}C). It has high electrical conductivity of 1.1×10^5 S/m and very low lattice thermal conductivity of 1.20 W.m-1.K-1. Its melting point is about 858 Kelvin (584.85 °C) and it's useful in temperature about 350 Kelvin (76.85 °C). [10], [11]

To design the TE generator for the exhaust system, the $Si_{0.7}Ge0._{0.3}$ - 1at%P (99.999999999% purity) with 10 mm in diameter and 0.3 mm thick has been selected. Its seebeck coefficient is 326.6 μV/K at 1000 Kelvin (726.85°C). It has the electrical conductivity of 49079.75 S/m and the lattice thermal conductivity of 4.4 W.m-1.K-1. The melting point is about 1563 Kelvin (1289.85°C) and it's useful in temperature about 1000 Kelvin (726.85°C). [12]

For our calculation, we have chosen W18V32 generator [13], Wartsila (origin in Finland), a very similar type of generator (W20V32) that is used in Meghnaghat powerplant of Orion group, Bangladesh. [14]

Bi_2Te_3 was use at the radiator side of the Generator where temperature of the high side is of the water jacket/ radiator, 96^{o}C (369K) and room temperature 27^{o}C (300K) is considered as cold side temperature. [15]

7.1 Matlab code for efficiency calculation of Bi_2Te_3

From the Matlab code designed for calculating the efficiency of the Bi_2Te_3 TEM, the result obtained is illustrated in figure 3 in a graphical form, where the change of efficiency with the corresponding temperature and the optimum operational zone is indicated. The curve in the graph appears to be a straight line although it is non-linear. The slope of the curve is quite low, hence it appears almost linear.

The Calculated Efficiency was 5.936% for a temperature difference 69^{o}C and power calculated for each pallet was 0.3807 Watt.

The thermal energy dissipated at the water jacket/radiator along with the charged air circuit (High temperature (HT) and Low Temperature (LT)) was (1512 + 1440 + 1193) KW = 4145 KW. [15]

With 5.936% efficiency, (4145 × 5.936%) KW = 246.04 KW electricity can be produced form the coolant waste heat.

The number of the TEG pallets required,

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$$\frac{Total\ Power\ dissipated}{power\ produced\ by\ each\ TEG\ pallet} = \frac{4145}{0.3807} = 10887.8 \approx 10888$$

For each pallet being (6x6x1) mm, the dimension of the TEM containing 10888 TEG pallets will be,

$$\{10888 \times (.006 \times .006)\ m2\} = 0.392\ m^2$$

According to the dimension of the radiator/ cooling water jacket, the number of the pallets may increase or decrease as well as the dimension. The whole TEM is of height 1mm, hence it was ignored during the dimension calculation. [1]

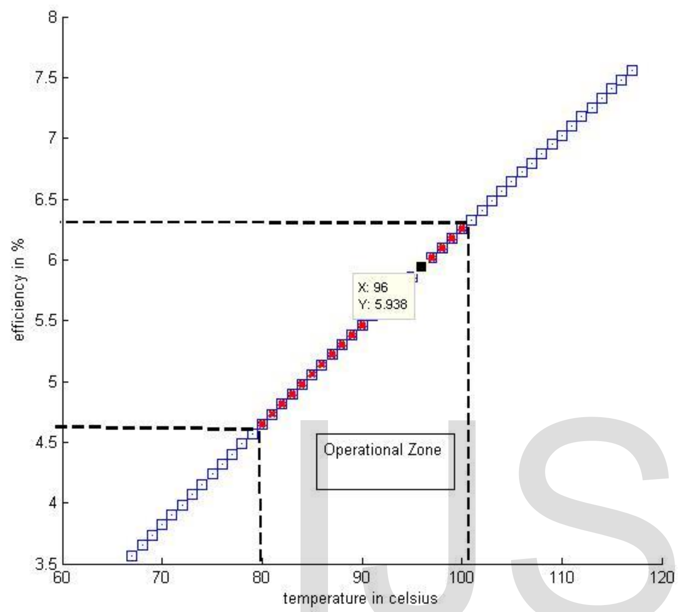

Figure 3: Bi_2Te_3 efficiency curve

At the Exhaust side, due to higher temperature gradient, $Si_{0.7}Ge_{0.3}$ TEG was used because of its higher melting point [12]. The Exhaust gas temperature after the turbocharger of the generator at 100% load is 379°C (652K), is considered as the high temperature side and room temperature 27°C (300K) is considered as low temperature side.

$Si_{0.7}Ge_{0.3}$ is used at the exhaust side for its better performance at higher temperature. Low side temperature is considered as the room temperature, 27°C (300K) and high side temperature is 379°C (652K). [15]

7.2 Matlab code for efficiency calculation of $Si_{0.7}Ge_{0.3}$

A similar type of Matlab code for efficiency calculation of $Si_{0.7}Ge_{0.3}$, illustrates the temperature versus efficiency curve and indicates the optimum operational zone in figure 4.

The calculation shows the 7.906% efficiency at 379°C (652K), and power produced from each pallet is 41.48Watt.

Heat rejection at the exhaust is calculated from the percentage of heat distribution of the engine. The engine is of 45% thermal efficiency (excluding auxiliary losses) [13], which provides 9000KW power. Hence, 45% = 9000 KW, that concludes 100% = 20000KW thermal power. Heat balance at the water cooler, charged air, friction and radiation comprises of (1512+ 1440 + 1193+ 1091 + 206) KW = 5442 KW [15], that is 27.21% of the total thermal energy.

Hence the thermal energy dissipated at the exhaust is

[100 – (45+27.21)] % = 27.79% of the total thermal energy = 5558KW

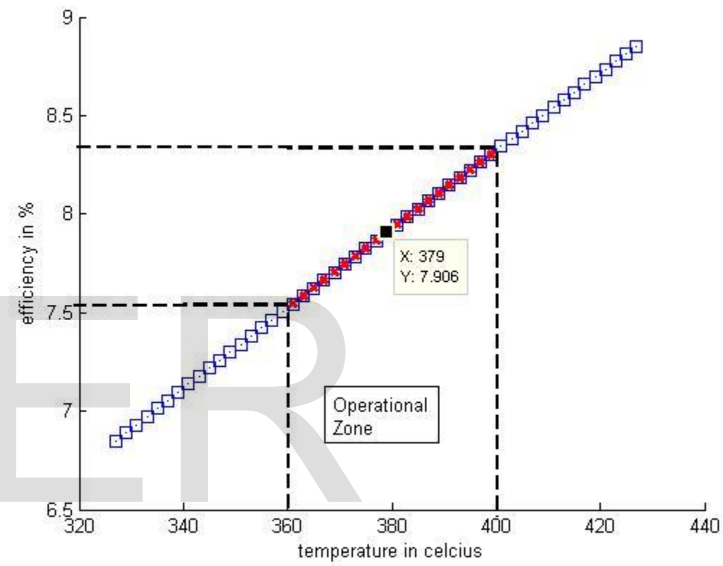

Figure 4: $Si_{0.7}Ge_{0.3}$ efficiency curve

With 7.906% efficiency, (5558 x 7.906%) KW = 439.41 KW electricity can be produced. And since each pallet can produce 41.48watt of electricity,

$$439410/41.48 = 10593.29 \approx 10594 \text{ pallets required.}$$

Dimension of each pallet is 10mm diameter, 0.3 mm thick (height), and those will be mounted on the exhaust system at in an octagonal form, at the 8 sides of the wall of the octagonal structure, as shown in figure 5. [16]

The dimension of the thermos-electric module will be,

$$[10594 \times 3.14 \times (.01/2)^2]\ m^2 = 0.831629\ m^2$$

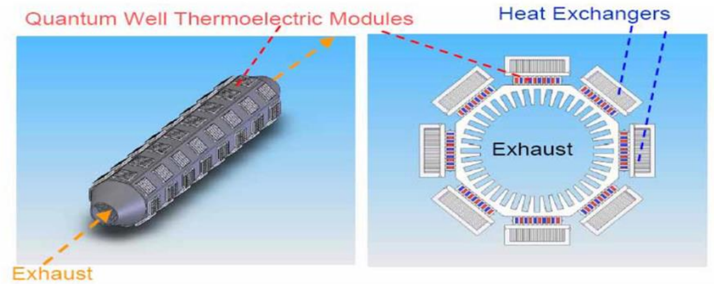

Figure 5: TEG pellets design at exhaust system [16]**[4]**

Although the TEG pellets are of circle shape, each pallet will require a square area 10mm side. Considering that, the required area for TEM appears,

$$[10594 \times (0.01)^2] = 1.0594 \text{ m}^2$$

Each wall of the octagonal structure will be of (1.0594/8) m^2= 0.1324 m^2 and contain (10594/8) ≈ 1325 pallets

Hence, the total electrical energy harvested from the coolant and exhaust system is:

$$(246.04 + 439.41) \text{ KW} = 685.45 \text{ KW}$$

This is ***7.62***% of the engine output (9000 KW) and **3.43**% of the total thermal energy. Considering this harvested electricity, the total efficiency of the generator becomes (45+ 3.42) % = ***48.42%.***

8 Comparison of Diesel and Gas Engine Generators

Diesel engines have relatively higher efficiency (about 38%) [16] than gas engines (32%) [17]. Due to the lower efficiency of the gas engine, its coolant and exhaust contains higher waste heat.

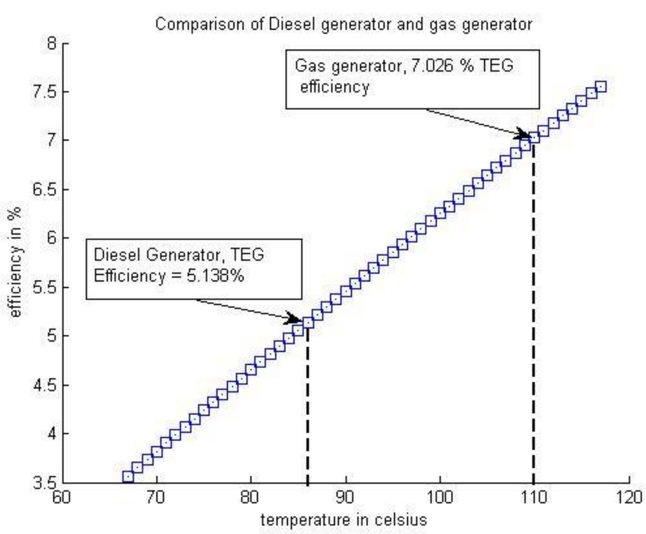

Figure 6: Comparison of Diesel generator and Gas generator ''coolant temperature vs TEG (Bi_2Te_3) efficiency''

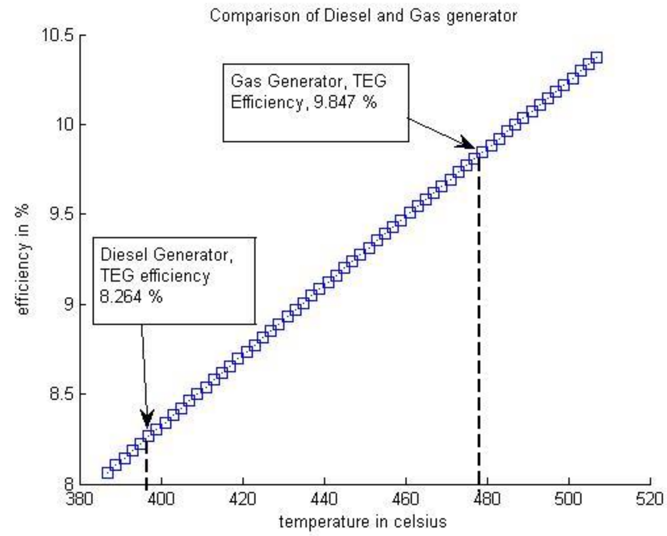

Figure 7: Comparison of Diesel generator and Gas generator ''exhaust temperature vs TEG ($Si_{0.7}Ge_{0.3}$) efficiency''

Comparing a Caterpillar diesel generator of rating 1088 eKW with a Caterpillar gas engine generator of 1030 eKW the result is observed in figure 6 and 7.

8.1 Comparing the Generators According to Their Technical Data

For comparison we have chosen two Caterpillar generators (1 diesel generator, 1 gas generator). From their data sheet, the heat wasted has been calculated at the coolant and the exhaust and afterwards compared the overall efficiency of the TEG modeled previously.

Table 2.1 Overall efficiency calculation of equivalent diesel and gas generators [17] [18]

	Diesel Generator	**Gas generator**
Generator model	CAT 3512B-1500	CAT® G3516 LEAN BURN GAS ENGINE
Rated electrical output (ekw)	1088	1030
Electrical Efficiency	38%	32%
Temperature at coolant/ radiator (℃)	86 (359 K)	110 (383 K)
TEG Efficiency (Bi_2Te_3)	5.138 %	7.026 %
Heat rejection to coolant	472 KW	817 KW

Recoverable electricity from coolant wasted heat	**24.25 KW**	**57.40 KW**
Exhaust temperature (℃)	397.4	479
TEG Efficiency ($Si_{0.7}Ge_{0.3}$)	8.246 %	9.847 %
Heat Rejection to exhaust	1057 Kw	929 KW
Recoverable electricity from exhaust waste heat	**87.16 KW**	**91.47 KW**
Total recovered electricity	**111.41 KW**	**148.87 KW**
Percentage of electrical output	**10.23 %** [note 1]	**14.45 %** [note 1]
Overall electrical output	**1199.06 KW** [note 2]	**1178.8 KW** [note 2]
Improved Efficiency	**41.88 %** [note 3]	**36.59 %** [note 3]

Notes

1. For Diesel generator, total electrical output is 1088 eKW and recovered electricity from waste heat is 111.41 KW, which is 10.23% of the electrical output 1088 eKW. Similarly, 148.8 KW electricity produced from the waste heat of the gas generator of rating 1030 eKW, which is 14.45% of its electrical output.
2. Overall electrical output for the diesel generator is (1088+111.41)KW = 1199.06 KW

For Gas generator, the total electrical output is

(1030 + 148.8) KW = 1178.8 KW

3. Improved efficiency can be calculated according to the derived data.

For diesel engine, **1088 eKW** refers to **38%** efficiency.

Hence, **1199.06 eKW** refers to $[\frac{1199}{1088} \times 38\%] = \mathbf{41.88\%}$

Similarly, for gas engine generator, the current efficiency is 32% and the improved efficiency is **36.59**%.

Hence, the overall efficiency of both the diesel and the gas generator can be improved using Bi_2Te_3 and $Si_{0.7}Ge_{0.3}$ thermo-electric modules. However, the electricity produced from these TEM is DC current. This can be directly used to feed the auxiliaries or as AC output using high performance inverters.

9 Potential Waste Heat Recovery and Use

The Orion Power Meghnaghat power plant with a capacity of 100MW consists of 12 engines, each one of capacity 8.924 MW. Model of the Genset is W20V32, origin in Wartsila, Finland. [14]

With the TEM design shown, 7.62% of the total electric capacity can be recovered. Hence, from 100 MW power plant of Meghnaghat, 7.62 MW of electricity can be produced from the waste heat.

35.92 % of total electricity produced from reciprocating engines. Maximum demand served on **11387.00 MW as on 18/07/2018** [19]. Hence, 4090 MW produced from the reciprocating engines. If 7.62% of the waste heat from the reciprocating engines can be recovered, then (4090× 7.62%) MW = 311.67 MW electricity is expected to be produced from waste heat.

Since the electricity produced from TEG is DC and maximum auxiliary powers for the generators are DC powered, the recovered electricity can be effectively used for feeding the auxiliaries. The auxiliary power requirements is the 5-10% of the gross power generation. [20] For 100 MW power plant in Meghnaghat, 6-7% auxiliary power is required. Hence, the recovered waste heat electricity can cover up for the auxiliary power requirement for 100 MW or more capacity power plants.

10 TEM Pallet Optimization

As a versatile, compact and scalable device (mm to meter-scale footprint), TEMs can be of various use such electricity generation, heating, cooling (refrigeration) etc. For electricity generation which can be referred as ‘‘generation mode’’, optimal geometry of TEMs is both complex and necessary for desirable output.

According to Hodes [4], the optimal TEM pallet geometry depends on its electrical resistance. Hence, the height (H) , effective footprint/area (A_e) and number of thermocouples (N) in a TEM should be given germane parameters that ensures desirable geometry to maximize TEM's efficiency. Here, the term relative efficiency, η_r has been used.

Where, $\eta_r = \frac{optimum\ efficiency}{theoritical\ efficiency} = \frac{\eta_o}{\eta}$

Here, optimum efficiency is the practical efficiency that is obtained from experimental procedures. Hodes [4] showed that, the relative can be obtained close to unity such as 98.2% by sufficiently decreasing the height (H) and increasing the effective footprint (A_e) of the pellets.

Taking this relative efficiency (98.2%) into consideration, the practical efficiency of previous calculations can be rendered as (5.936×98.2%) = **5.83%** and (7.906× 98.2%) = **7.76 %.**

11 Conclusion

Thermoelectric generators have a huge potential for compensating the energy losses of the reciprocating engines. As long as the efficiency of the reciprocating engines reach higher and close to unity, the use of TEMs will be very effective for wasted heat recovery system. In near future, it is expected the thermoelectric efficiency of the TEMs to be improved significantly so that those can be used in low temperature gradient thermoelectric generations.

Renewable energy is highly desired and thermoelectric generators/modules have the major role in extracting electricity from thermal energy in a more convenient and eco-friendly manner. Further researches should be done to improve efficiency of the TEG/TEMs significantly in order to make the best out of it.

Acknowledgment

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