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Improved Efficiency Performance of a Gas Turbine with a Thermoelectric Generator

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Abstract— This research studied how to Improved Efficiency Performance of a Gas Turbine with a Thermoelectric Generator. The systems consist of the thermoelectric generator, its power conditioning unit and the interfaces to the gas turbine engine cooling and exhaust systems. The gas turbine whose operating condition was used for the design of the thermoelectric generator is based at Ughelli Thermal Power Station, Ughelli, Delta state, Nigeria. From the work carried out, the efficiency of the gas turbine increased from 0.342 to 0.44 with the introduction of a thermoelectric generator.

Index Terms— Efficiency, Gas Turbine, Thermoelectric Generator, Power Conditioning unit, Seebeck effect, Thermoelectric module, grid tie inverter.

1 Introduction

MOST of the operating cost of a gas turbine plant is the cost of the fuel used to power the turbine, and much of the energy of the flue (exhaust) gas is lost to the atmosphere after expansion, thus much of the money incurred in purchasing the fuel for power supply is being wasted.

Up to 40% of the energy rejected leaves in the exhaust. Furthermore, the exhaust temperature is much greater than that of the other heat rejection streams; therefore, the potential conversion efficiency of a bottoming cycle connected to this stream is expected to be the largest.

Semi-conductor technology has helped to overcome the challenges related to the enhanced energy efficiency by supplying means to produce energy from waste heat [1]. It has been estimated that the majority of the world's power is generated by systems that typically operate at efficiencies of about 40% or less i.e. there is an enormous need for thermoelectric systems that can "salvage" the energy currently lost as heat to the environment.

One way to improve the sustainability of electricity base is through the scavenging of waste heat with thermoelectric generators i.e. thermoelectric materials. Gas turbine exhaust, automotive exhaust, steam turbine and industrial processes all generate waste heat that could be converted to electricity using thermoelectric generator.

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2 The Seebeck Effect

The Seebeck effect represents a class of experimental observations that under conditions of zero electric current, a finite electromotive force is produced when the temperature gradient is finite [2], a temperature difference between two different metals or semiconductors produces a voltage of several microvolts per Kelvin difference. One such combination, copper constantan, has a Seebeck coefficient of 41μv/K at room temperature [1].

If the temperature difference ΔT between the two ends of a material is small, then the Seebeck coefficient α is defined as [3].

$$\alpha = \frac{\Delta V}{\Delta T} \quad (1)$$

Where ΔV is the thermoelectric voltage gradient between the terminals and ΔT is the temperature gradient.

The Seebeck coefficient of a material is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material.

The Seebeck coefficient is an important material parameter that determines the efficiency of a thermoelectric material. A larger induced thermoelectric voltage for a given temperature gradient will lead to a larger efficiency. Ideally one would want very large Seebeck coefficient values since only a small amount of heat is necessary to create a large voltage.

3 Thermoelectric Materials

According to Bulusu et al [4], the first thermoelectric materials were metals, but in the middle of the 20th century semi-conductors were noticed by Loffe [5] due to their high Seebeck coefficient and because heat conduction is dominated by photon transport. Positive feature in metals is relatively high ratio of electrical to thermal conductivities. However, modern thermoelectric materials are essentially semi conductors.

Semi-conductors are classified by their electrical resistivities at room temperature. The values are in the range 10-2 …… 109 Ωcm [4] and they are strongly dependent on temperature.

It was later in 1909 [6] and 1911 [7] that Altenkirch showed that good thermoelectric materials should possess large Seebeck coefficients, high electrical conductivity and low thermal conductivity. A high electrical conductivity is necessary to minimize Joule heating, while a low thermal conductivity helps to retain heat at the junctions and maintain a large temperature gradient.

These three properties were later embodied in the so called figure of merit, Z, defined as [3]

$$Z = \frac{\alpha^2 \sigma}{k} \qquad (2)$$

Where σ = electrical conductivity, α = Seebeck coefficient, k = thermal conductivity.

Bismuth telluride (Bi_2Te_3) and its alloys are good thermoelectric materials below room temperature. Above room temperature the relatively narrow band gap causes mixed conduction due to both electrons and holes, this leads to reduced Seebeck coefficient [1].

Bismuth telluride can be alloyed with Antimony Telluride (Sb_2Te_3) or Bismuth Selenium (Bi_2Se_3) which reduces thermal conductivity considerably. Lead telluride (PbTe) was found to have good thermoelectric properties at temperatures in the range of 300 – 700k. Similar materials are such as Lead Sulphide (PbS) and lead Selenium (PbSe) which belong to chalcogenides system.

PbTe has high mean atomic weight and a multi-valley band structure, the band gap at 300k is 0.32eV [1] which produces higher Seebeck effect than that of Bismuth telluride. Its thermoelectric figure of merit (ZT) is also higher when the temperature is raised although it has better lattice thermal conductivity than Bismuth Telluride [4]. PbTe – SuTe system has been studied since 1961. Lead Telluride forms isomorphous solid solution with Lead Selenide and Tin Telluride, which leads to lower thermal conductivity and improved ZT values [1].

Silicon-Germanium (SiGe) alloys are good materials for thermoelectric generation [4]. Silicon has a large bandgap and therefore Silicon rich alloys such as $Si_{0.7}\ Ge_{0.3}$, are suitable for high temperature applications because problems with minority carrier dominance do not arise. The large phonon scattering ensures low thermal conductivity without affecting the electron mobility [4].

Skutterudites ($ReTm_4M_{12}$) are complex materials containing rare earth elements (Re), transition metals (Tm) and metalloids (M). Binary Skutterudites have chemical formula of TmM_3 and relatively high thermal conductivity, but the Seebeck coefficient is also relatively large.

The crystal structure of binary skutterudites has two large empty spaces in each unit cell.

When the empty space is occupied by relatively heavy rare earth element, the result will be reduced thermal conductivity due to rattling of the heavy element within loosely bound lattice, the figure of merit (ZT) has been found to be higher than unity at 700K [1],

New class of thermoelectric materials was introduced by Ohta [8] based on a metal oxide: a two dimensional electron gas (2DEG) in $SrTiO_3$. The 2DEG demonstrates a Seebeck coefficient that is enhanced by a factor of ≈ 5 compared with the bulk and an optimized ZT that reaches 2.4 twice that of conventional thermoelectric materials. Other new oxide materials developed in Japan are such as Na_2CoO_4, $CaMnO_3$, $(ZnO)(In_2O_3)$, ZnO and $CuAlO_2$ [8].

4 METHODOLOGY

This research focus on a gas turbine bottomed with a thermoelectric converter that will effectively tap some of the energy of the flue gas and thus convert it into useful power which can be fed into the national grid. The gas turbine plant whose operating conditions was used for the design is Ughelli-Thermal Station (Delta IV) in Delta State Nigeria.

The technical steps taken involves firstly the collection of data at the plant site, notably the exhaust gas temperature exiting the gas turbine which acts as the source temperature to the thermoelectric generator and the coolant temperature of the gas turbine which acts as the sink temperature to the thermoelectric generator

Secondly, based on the magnitude of the exhaust temperature of the gas turbine, a suitable thermoelectric material was selected from a catalog of materials; the exit exhaust temperature favours Lead Telluride (PbTe) [1].

Thirdly, the thermoelectric generator was then design from the operating conditions of the gas turbine, the major components being sized.

Finally, the thermoelectric generator performance was simulated to depict how the efficiency of the thermoelectric generator varies with different sink temperature.

The thermoelectric generator (TEG) comprises of the following basic components:

4.1 The Thermoelectric Module

The module consists of pairs of p-type and n-type semiconductor thermoelements forming thermocouples which are connected electrically in series and thermally in parallel. In generating mode, a temperature gradient is maintained across the module. The heat flux passing through the module is converted into electrical power. In cooling mode, an electrical current is supplied to the module, heat is pumped from one side to the other, and the result is that one side of the module becomes cold. Fig 1 shows a thermoelectric module.

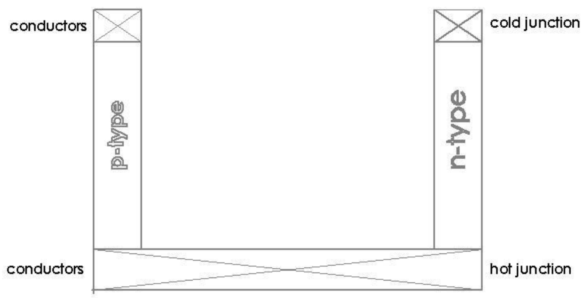

Fig. 1. A thermoelectric module

4.2 Exhaust Gas Heat Exchanger

Is the device through which the heat is transferred to the thermoelectric modules. The exhaust gas temperature that the TEG receives is determined by the location of TEG within the exhaust system.

4.3 The Coolant Heat Exchanger

Is the device through which heat is removed from the thermoelectric modules.

4.4 The Gas Turbine

The gas turbine unit supplies the waste heat in the form of exhaust gas to the TEG. It thus acts as a high temperature heat source to the thermoelectric generators. It also supplies the cooling fluid i.e. compressed oil to the TEG and thus acts as the low temperature heat sink.

The gas turbine consists essentially of a compressor which increases the pressure of the atmospheric air, followed by combustion of compressed air/fuel mixture which further raises the temperature of the working fluid.

Expansion of the hot working fluid then produces a power output from the turbine that is able to provide a net useful output in addition to the power necessary to drive the compressor.

Fig. 2 shows the schematic diagram of the gas turbine unit.

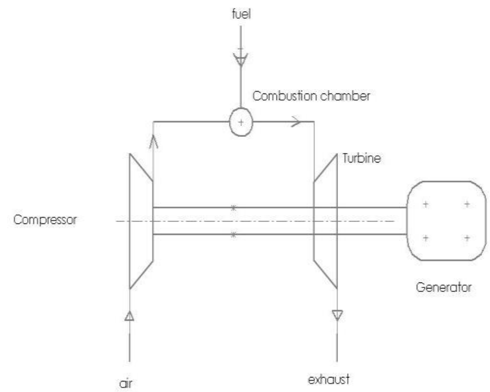

Fig. 2. Schematic diagram of gas turbine unit [9]

In practice, losses occur in both the compressor and turbine which increase the power absorbed by the compressor and decrease the power output of the turbine.

The T – S diagram of the simple gas turbine unit is as shown in fig. 3.

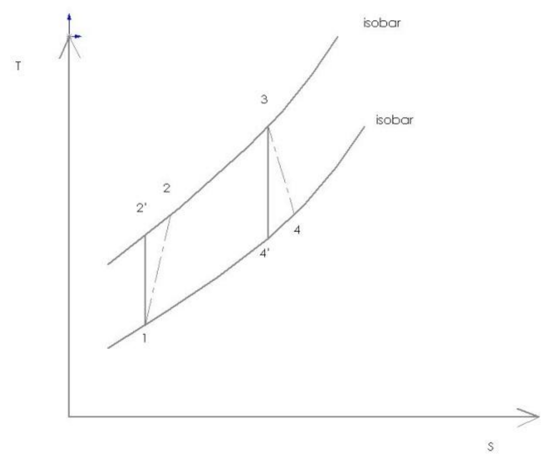

Fig. 3. T-S diagram of gas turbine unit [9]

1 – 2′ = isentropic compression
1 – 2 = actual compression
2 – 3 = heat addition at constant pressure
3 – 4′ = isentropic expansion
3 – 4 = actual expansion

Neglecting, the mass of the fuel
The cycle efficiency is given as [9]

$$\eta_{th} = \frac{Cp_g(T_3 - T_4) - Cp_a(T_2 - T_1)}{Cp_g(T_3 - T_2)} \qquad (3)$$

5 GRID TIED INVERTER

As the output of the thermoelectric generator is direct in nature, a grid-tie inverter (GTI) help to converts direct current electricity into alternating current electricity and feeds it into an existing electrical grid. GTIs are often used to convert direct current produced by many renewable energy sources, such as thermoelectric generators, solar panels or small wind turbines, into the alternating current used to power homes and businesses. The technical name for a grid-tie inverter is "grid-interactive inverter". They may also be called synchronous inverters. Grid-interactive inverters typically cannot be used in standalone applications where utility power is not available. Inverters take DC power and invert it to AC power so it can be fed into the electric utility company grid. The grid tie inverter must synchronize its frequency with that of the grid (e.g. 50 or 60 Hz) using a local oscillator and limit the voltage to no higher than the grid voltage. A high-quality modern GTI has a fixed unity power factor, which means its output voltage and current are perfectly lined up, and its phase angle is within 1 degree of the AC power grid. The inverter has an on-board computer which will sense the current AC grid waveform, and output a voltage to correspond with the grid [10].

Fig. 4 shows the schematic diagram of the conceptual thermoelectric generator.

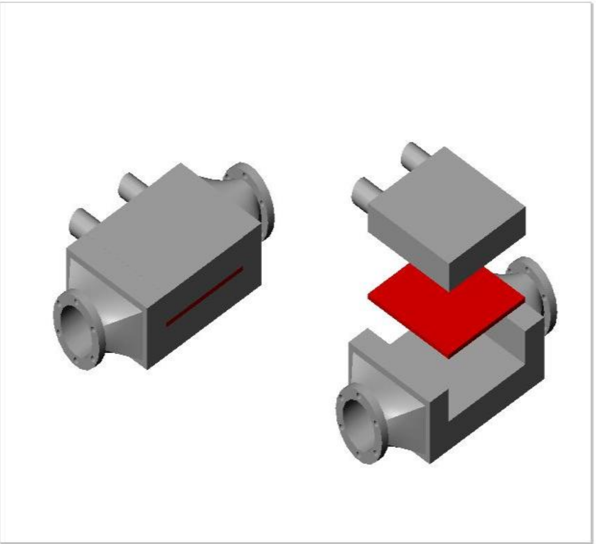

Fig. 4. Conceptual thermoelectric generator

While fig. 5 shows the schematic thermoelectric generator combined plant.

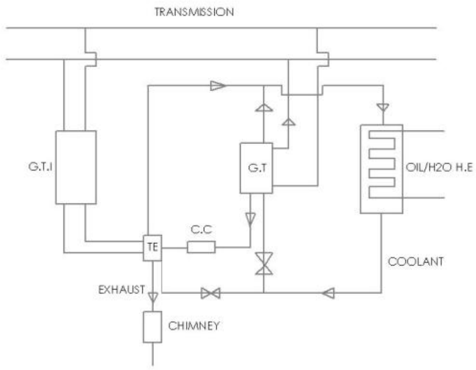

Fig. 5. schematic diagram of the thermoelectric generator combined plant

6 DESIGN

The design of the thermoelectric generator is based on the operating conditions of Ughelli power plant (Delta IV), Delta state Nigeria [11].

The specifications of the Ughelli power plant are:

Turbine alternator output power	=25MW
Alternator current	= 1100A
Alternator output voltage	= 11KV
Alternator frequency	= 50HZ
Efficiency of the gas turbine	= 0.342
Alternator speed	= 7280rpm
Gas turbine inlet temperature	= 1200^{o}C
Exhaust gas temperature	= 520^{o}C
Gas turbine inlet pressure	= 1.4MPa
Turbine type	= Axial
Turbine stages	= 3
Compressor stages	= 17
Cooling oil inlet temperature	= 59^{o}C

6.1 Specification of the Thermoelectric Generator

The inlet temperature of the exhaust gas to the thermoelectric generator is limited to the exhaust gas temperature of the gas turbine:

Inlet temperature of exhaust gas = 424^{o}C

The cooling oil temperature entering the thermoelectric generator is fixed by the temperature of the coolant used to cool the gas turbine

Cooling oil temperature = 59^{o}C

To ensure synchronization of the output of the thermoelectric generator to the gas turbine alternator output, the output voltage and frequency are fixed by the gas turbine alternator as:

Output voltage = 11kV

Frequency = 50 Hz

The choice of thermoelectric material/module is dictated by the source temperature; lead telluride (PbTe) is therefore used due to its high figure of merit and high temperature range.

The power output is limited to 20% of 10 MW of the gas turbine operating output i.e 2MW, this enable the determination of the current flowing through the modules and cross sections of the thermoelectric modules.

6.2 Parameters Used for Analysis

Seebeck coefficient (α)	= 628μV/K
Figure of merit (ZT)	= 1.5 at 700K
Temperature range for operation	= 300 – 700K
Thermal conductivity (k)	= 1.11W/cmK
Current density (Id)	= 6A/cm2
Resistivity	= 0.011Ωcm

Fig. 5 shows the schematics of thermoelectric generator and gas turbine plant. Here the exhaust from the gas turbine flows through the catalytic converter (C.C) into the thermoelectric generator; the exhaust exits through the chimney after the supply of the quantity of heat required to maintain the thermolegs at maximum temperature. The cooling oil after exchanging heat with water in the oil/H20 heat exchanger is also passed through the thermoelectric generator maintaining the themolegs at the minimum temperature. The coolant from the gas turbine and thermoelectric generator is then recycled by cooling with the oil/H2O heat exchanger.
The output voltage of the thermoelectric generator being D.C is feed into the grid tie inverter (GTI), the GTI converts the DC voltage to A.C voltage to ensure synchronization with the gas turbine alternator output, before being fed into step-up transformer and subsequent transmission.

6.3 Voltage per Module

The voltage per module is determined by the equation [3]

$$VL = \alpha p,n\,(T1 - To)\left(\frac{\sqrt{1+ZT}}{1+\sqrt{1+ZT}}\right) \qquad (4)$$

A figure of 0.1404 was obtained for the Lead Telluride module.

6.4 Heat supplied by the Exhaust Heat Exchanger

The heat supplied to the thermoelectric generator by the exhaust gas is determined by [3]

$$Q_1 = \alpha_{p,n} I T_1 - \frac{1}{2}\left(\rho_{p,n}\frac{L}{A}I^2\right) + k_{p,n}\frac{A}{L}(T_1 - T_O) \qquad (5)$$

The heat exchanger capacity is 9162.89 W

6.5 Heat rejected by the Coolant Heat Exchanger

The heat rejected by the thermoelectric generator to the coolant is determined by [3]

$$Q_2 = \alpha_{p,n} I T_O + \frac{1}{2}\left(\rho_{p,n}\frac{L}{A}\right)I^2 + \left(Kp,n\frac{A}{L}\right)(T_1 - T_O) \qquad (6)$$

The coolant heat exchanger capacity is 9139.4 W

7 Result

The efficiency of the thermoelectric generator is determined by [3]

$$\eta_{TEG} = \frac{T_1 - T_O}{T_1}\left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_O}{T_1}}\right) \qquad (7)$$

A figure of 0.148 is obtained.
The overall combined efficiency of the plant with thermoelectric generator installed is determined by [3]:

$$\eta_{comb} = \eta_{GT} + (1 - \eta_{GT})\eta_{TEG} \qquad (8)$$

A figure of 0.44 is obtained. This is a substantial improvement in the efficiency of the gas turbine plant.

8 Simulation

As seen in the efficiency expression, the efficiency is a function of the sink temperature. The performance is thus simulated using Matlab to depicts the variability of efficiency with sink temperature.
Fig. 6 shows the efficiency curve against temperature difference, the curves reveal that the increase in efficiency of the curves occurs primarily because the effective Seebeck coefficient of Lead Telluride modules decreases with increasing temperature difference for a constant cold side temperature, and the efficiency of the module depends upon the square of the Seebeck coefficient.
The curves reveal that the efficiency increases as the sink temperature decreases. For a temperature difference of 300°C the efficiencies are 0.1360, 0.1307, 0.1282 and 0.1213 at T0 equal 40, 60, 70 and 100°C respectively.

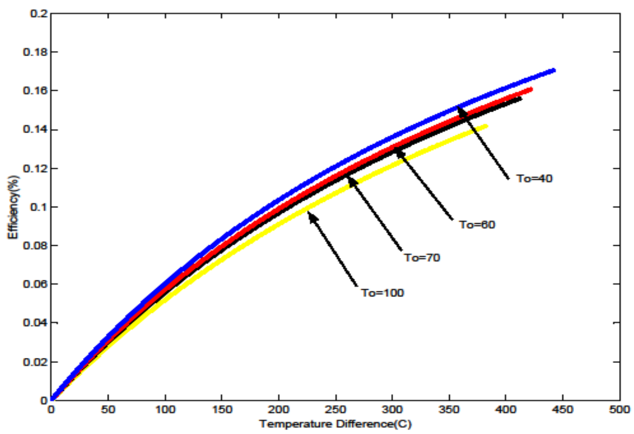

Fig. 6. Thermoelectric module efficiency curves

By dividing top and bottom by T1 in the efficiency expression, the efficiency of the thermoelectric generator can be expressed as:

$$\eta_{TEG} = 1 - \frac{T_0}{T_1}\left(\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_O}{T_1}}\right) \quad (9)$$

Fig 7 shows a plot of efficiency against sink – source temperature ratio obtained from fig 6. As expected the curves collapsed into one curve.
Also plotted on fig. 7 is the Carnot cycle efficiency, for the purpose of comparison. The Carnot cycle efficiency is defined by:

$$\eta_{carnot} = 1 - \frac{T_0}{T_1} \quad (10)$$

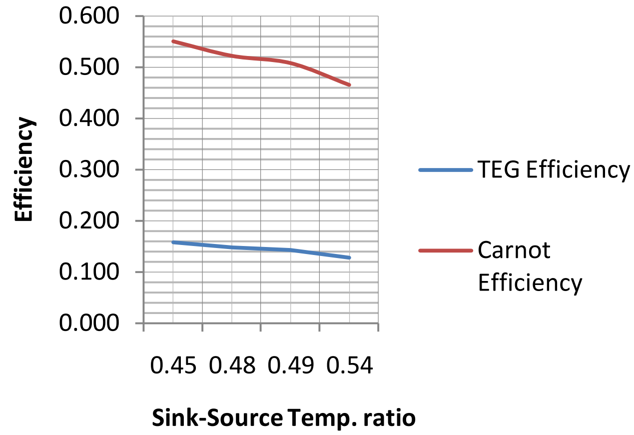

Fig. 7. Efficiency against Sink – Source temperature ratio

The maximum efficiencies for the Carnot cycle and thermoelectric generator are 0.55 and 0.16 respectively representing an efficiency difference of 70.9%, the corresponding minimum efficiencies for the Carnot cycle and thermoelectric generator are 0.47 and 0.13 representing an efficiency difference of 72.3%.
However, both efficiencies decrease with an increase in the sink temperature ratio. For any given value of sink – source temperature ratio, the Carnot cycle efficiency is always higher validating the second law of thermodynamics due to the reversible nature of the Carnot cycle and irreversibility associated with the heat transfer processes in the thermoelectric generator.

Fig. 8 shows the relationship between η and To obtained from fig. 5.2a for a fixed value of T1.

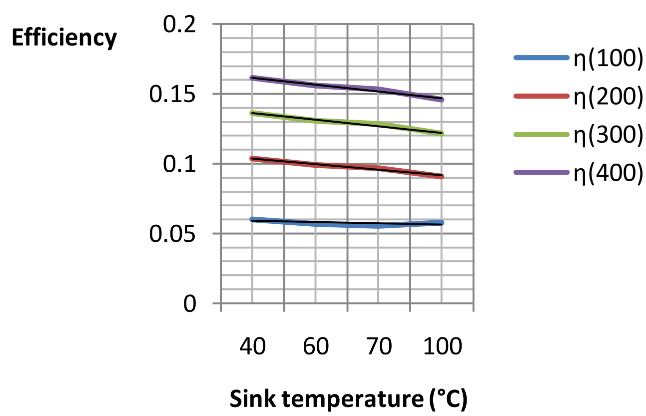

Fig. 8. Graph of efficiency against sink temperature

Fig. 8 clearly shows that efficiency increases as the temperature difference increases as seen in fig. 8. Also, the efficiency decreases as sink temperature increases.

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Therefore to obtain a high efficiency the sink temperature should be as low as possible.

9 Conclusion

A high powered thermoelectric generator to provide additional electric power for a gas turbine and thus improve efficiency is feasible, thus a thermoelectric generator system was designed from the operating conditions of a gas turbine. The choice is made of lead telluride as the thermoelectric module because of the temperature involved and its high dimensionless figure of merit (ZT).

It was found that to get improved fuel efficiency using this system, thermal management is very important: insulating the exhaust and lowering the coolant temperature had dramatic effects on the efficiency improvement. The efficiency generated is a function of the temperature difference and the dimensionless figure of merit, thus one can assume that better performance can be achieved by finding appropriate materials using nano-science with higher ZT values; current research work on thermoelectric is geared towards achieving this.

The sensitivity to the coolant temperature is especially high because the thermoelectric efficiency increases with decreasing cold side temperature.

Emphasis has to be laid on exploring different feasible options for the source of heat sink because of additional pumping power required for the coolant flow through the plant.

The efficiency of the gas turbine was considerably increased to 0.44 from 0.342.

10 Recommendation

Experimental testing will be an important phase of the research. It will show the effect of the thermoelectric generator on different systems of the gas turbine plant and will validate the simulation studies. Considering the energy crisis in the word and the large number of existing gas turbines, more research still has to be done, a physical hardware built for experimental purposes before commercialization.

11 SYMBOLS AND MEANING

Symbols	Meaning	Unit
ZT	Dimensionless figure of merit	-
□comb	Overall efficiency of plant	%
□TEG	Efficiency of thermoelectric generator	%
QO	Heat rejected from the module	W
Q1	Heat supplied to the module	W
□	Resistivity	Ωcm
T1	Source temperature	^oC
T0	Sink temperature	^oC
Lp,n	Length of module	Cm
Ap,n	Cross sectional area of module	Cm2
Kp,n	Thermal conductivity of module	W/cmK
αp,n	Seebeck coefficient of module	MV/K
□GT	Gas turbine efficiency	%

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13 APPENDIX

13.1 Data for Efficiency

S/N	ΔT	η40OC	η60OC	η70OC	η100OC
1	0	0.0000	0.0000	0.0000	0.0000
2	50	0.03276	0.0310	0.0301	0.0279

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3	100	0.0602	0.0571	0.0557	0.0578
4	150	0.0834	0.0795	0.0777	0.0726
5	200	0.1034	0.0989	0.0967	0.0909
6	250	0.1207	0.1158	0.1134	0.1070
7	300	0.1360	0.1307	0.1282	0.1213
8	350	0.1494	0.1440	0.1414	0.1341
9	400	0.1614	0.1558	0.1531	0.1457
10	450	0.1721	0.1665	0.1638	0.1562
11	500	0.1818	0.1761	0.1734	0.1657