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Thermal Energy Conversion Model: A Case Study of Gas Turbine Power Plant Olorunsogo Phase I, Ogun State, Nigeria

Bitrus, I[1], Olayiwola, J.O.[2], Adamu, D.[3], Babarinde, F.[4]
[1]*Department of Electrical/Electronics Engineering*
[2&3]*Department of Computer Engineering*
[4]*Department of Mechanical Engineering the Federal Polytechnic Ilaro, Ogun State, Nigeria.*
Corresponding Author: Bitrus, I

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ABSTRACT: Over the years, Gas Turbine Power Plant (GTPP) has been the major source of electricity in Nigeria. GTPP contributes about 87.5% of the total 12,500MW installed capacity of power plants in Nigeria. However, shortage of natural gas has been the major challenge militating against its optimal performance. A survey carried out revealed that, Olorunsogo GTPP has a total installed capacity of 335MW. The plant has eight units of gas turbine with 41.875MW each. The temperature dissipated by the system through the exhaust of each unit is 500^0C. This paper, present a model which could be used to generate a significant amount of electric power by harnessing the huge amount of temperature dissipated by the turbine through the exhaust and converts it to electric power. This will tremendously improve the electricity generation in Nigeria, and also curb the global warming associated with the excessive heat dissipated to the atmosphere by the Gas Turbine Power Plants.

Keywords: Energy conversion, Energy model, Electric power, Global Warming, Steam turbine.

I. INTRODUCTION

Thermal energy refers to the energy obtained by harnessing temperature and pressure and transformed it into useful work. The process is based on the law of energy conservation which states that 'energy can neither be created nor destroyed, but it can be transformed from one form to another'. Thermal energy can be obtained primarily from: fossil fuel (gas, coal, diesel etc.), geothermal, solar etc. [1]

Nigeria has about 12,500MW installed generating capacity with about 87.5% contribution by thermal plants (Gas Turbine Power Plants). [2]

Fig.1.0: Pictorial view of Olorunsogo gas turbine power plant

Source: [3].

Olorunsogo phase I Gas Turbine Power Plant (OGTPP) is located in Papalanto, Oguns state the south-western part of Nigeria. It was commissioned in February 20, 2015. It is a simple cycle power plant. Okoye et al (2017). The OGTPP comprises of eight (8) gas turbine units with a total installed capacity of 335MW. Each unit has about 41.875MW. Following the privatization of generationa distribution subsector of power system by the government in 2013, OGTPP is manage by Pacific Energy Company Ltd.[4]

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Fig. 2.0: A Snapshot of the Supervisory Control And Data Acquisition (SCADA) system being used in Olorunsogo Gas Turbine Power Plant.

The OGTPP is one of the twenty-two thermal power plants in Nigeria. The electric power generated by it, is controlled by the National Control Centre (NCC) Osogbo, Osun State. The plant has two outgoing 330KV lines: Ikeja west and Aiyede in Lagos State Nigeria. NCC, (2019). [5].

Fig. 3.0: A Snapshot of bus-bar and lines connectivity on Supervisory Control And Data Acquisition (SCADA) system in Olorunsogo phase I Gas Turbine Power Plant.

Thermal power plants dissipates a lot of heat and greenhouse gases (CO, CO_2, NO, etc.) which contribute to global warming. [6]. This large amount of heat being dissipated to the atmosphere could be harnessed with the array/module of a mirror as a heat collector and hence convert it to electricity. This could be achieved by heating the mixture of sodium nitrate and potassium nitrate (conducting fluid) in a tube to produce steam by the help of heat exchanger. [7]. The steam produced is then used to drive the steam turbine thereby producing electricity through the synchronous generator. By so doing, it will go a long way to curb environmental pollution by the greenhouse gases produced by the action of Gas Turbine Power Plant. Also, the power produced could be a plus on the overall power generating capacity in Nigeria. The availability of electricity in Nigeria has the potential to empower the youths and improve industrialisation in Nigeria.

II. METHODOLOGY

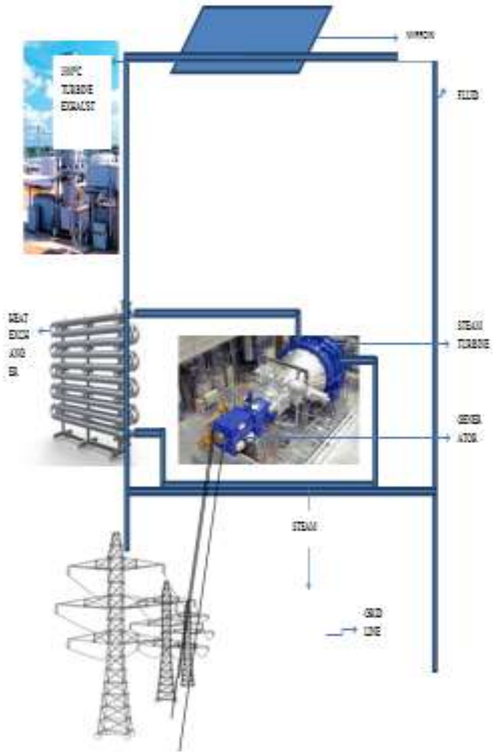

Fig. 3.0: A visual design of temperature to electrical energy conversion system

Models for Energy Conversion

1. Temperature Conversion to Heat Energy

The conversion of the temperature dissipated by the gas at the exhaust of the gas turbine is based on the first law of thermodynamics, also known as the law of energy conservation which states that: "energy can neither be created nor destroyed, but can transformed form one state to another".

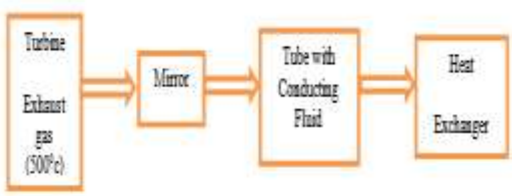

Fig. 4.0: Visual Model of Temperature Conversion To Heat Energy

The mathematical expression of the first law of thermodynamics is given as under:
$\Delta U = Q - W$ ……………………….. (1.1)
Where ΔU is the change in internal energy of the system.
Q is the quantity of heat generated
W is the work done on the system by the surrounding.
The metallic tube which contains the steam in this case is a constant volume system. This means that it will undergo an Isochonic process. It is a constant volume process where the volume of the system does not change; hence, no work is done on the surroundings. i.e. from equation (1.1);
W = 0, ΔU = 0. This means that heat transfer equation could be applied.
∴ $Q = mC_x\Delta T$ …………………. (1.2)
Where Q is the amount of heat required to raise a mass of gas (steam) by a certain amount of temperature.
C_x is a constant called the specific heat of the substance x. It is expressed in J/kg-K.
For a constant volume, equation (1.2) could be expressed as:
$Q = nC_V\Delta T$ ………...………………… (1.3)
Where C_V is the heat capacity at a constant volume. It is given by:
$C_V = \frac{3}{2}R$ …………………..………..(1.4)
R is the universal gas constant. Its value is equals to 8.314J/mol-K.
n is the number of gas molecules

2. Conversion of Heat Energy to Kinetic Energy

Conversion of heat energy in this model obeys the Joseph Gay-Lussac's law of thermodynamics which states that the 'pressure of a given mass of gas varies directly with the absolute temperature of the gas, when the volume is kept constant. The mathematical model is as under:
$\frac{P_1}{T_1} = \frac{P_2}{T_2}$……………………………………..........(2.1)
this means that P α T
The temperature of the gas will set the molecule of the gas into motion at a particular pressure P. The steam will then begin to move at a certain velocity, V.
The kinetic energy $K.E. = \frac{1}{2}mV^2 = \frac{3}{2}kT$ ………(2.2)
Where $k = \frac{R}{N_A}$ …………………………………(2.3)
∴ equation (2.2) becomes:
$K.E. = \frac{1}{2}mV^2 = \frac{3}{2}\frac{R}{N_A}T$……………..…………….…(2.4)
Where m is the mass of the substance (steam), V is the velocity of the gas; and R is the gas constant (8.314J/mol.K)
N_A is the Avogadro's number ($6.002x10^{23}$atoms/mol) and T temperature measured in kelvin (K)
https://study.com/acdemy/lesson/avearage-kinetic-enrgy-temperature-of-a-system.html
the system under consideration has a temperature of 500^0C
i.e. T = 500 +273 = 773K.
by substituting the above value in equation (2.5) above, we obtained:
$K.E. = \frac{3}{2}x\frac{8.314}{6.022x10^{23}}$ x 773 = $\mathbf{1.6x10^{-20}}$J

3. Conversion of Kinetic Energy of the Steam to Rotational Energy of the Turbine

The process of conversion of kinetic energy of the steam to produce rotational energy required to set the turbine into motion, is based on the principle of centripetal force acting on the turbine blade. [8]

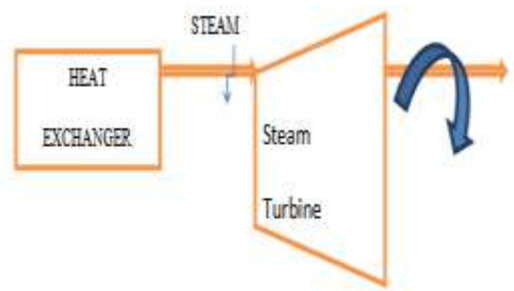

Fig. 3.1: Visual model of Conversion of Kinetic Energy to Rotational Energy

The mathematical model of the process is as illustrated under:
The centripetal force acting on the turbine blade is given by $F = mr\omega^2$ ……………….…………. (3.1)
Where m is the mass of the turbine, r is the radius of the turbine shaft and ω is the angular speed of the turbine.
The quantity, mr in equation (3.1) can be expressed in terms of torque, **τ** which is the moment of a force that tends to set turbine into rotational motion. Thus; (3.1) can be rewritten as:
$F = \boldsymbol{\tau}\omega^2$ ……………………………………… (3.2)
Recalled that kinetic energy is represented as $K.E. = \frac{1}{2}mV^2$ ………………..………...……………..(3.3)

Also recalled that linear velocity is given by
V = ωr……………………………………….. (3.4)
By substituting equation (3.3) in (3.2), we obtained:
K.E. = $\frac{1}{2}m(\omega r)^2$ …………………………….. (3.5)
Equation (3.5) is called the 'Classical Newtonian Expression' for the kinetic energy of the rigid body.
Thus; K.E. = $\frac{1}{2}m\omega^2 r^2 = \frac{1}{2}(mr^2)\,\omega^2$ ……….. (3.6)
The quantity mr^2 can be represented with **J**.
That is, **J** = mr^2 ……………………………….. (3.7)
Thus; K.E. = $\frac{1}{2}J\omega^2$ ……………………………. (3.8)
Where **J** is the moment of inertia of the steam turbine, and ω is the angular speed of the turbine shaft.
The moment of inertia can also be expressed in terms of inertia constant, H of the steam turbine, which given by:
H = $\frac{1}{2}\frac{J\omega_0^2}{S_b}$ ……………………………………… (3.9)
From equation (3.8), moment of inertia **J** could be obtained as;
J = $\frac{2HS_b}{\omega_0^2}$ ……………………………………… (3.10)
Where H is the inertia constant, S_b is the rated power of the turbine in (VA) and ω_0 is the nominal angular frequency of rotation of the turbine.
$\omega_0 = 2\pi\frac{n}{60}$ …………………………………… (3.11)
Where n is the nominal rotational speed of the turbine in rpm.

The Mathematical Model of Faraday's laws of Electromagnetic Induction is as under:

e = $N\frac{d\emptyset}{dt}$ ………………………………………….(4.1)
Where N is the number of turns of the armature winding, $\frac{d\emptyset}{dt}$ is the rate of change of magnetic flux.
Also, according to the emf equation of the synchronous generator, emf,
e = $\frac{P\emptyset NZ}{60}$ ………………………………………. (4.2)
where P is the number of rotor poles, Z is the number of conductors, Ø is the flux per pole and N is the rotor speed in (rpm).
If $\frac{PZ}{60}$ is kept constant, then equation (4.2) can be rewritten as:

https://wiki.openelectrical.org/index.php?title=inertia
Equation (3.7) implied that, the kinetic energy of the steam is converted to the rotational motion of the turbine.

4. Conversion of Rotational Energy to Electrical Energy

To convert rotational energy of the turbine shaft to electrical energy, the turbine shaft is normally connected to the synchronous generator. The conversion of rotational energy to electrical energy is based on Faraday's laws of electromagnetic induction which states that 'whenever there is interaction between a conductor and the magnetic field, an e.m.f. is induced in the conductor. And the magnitude of the induced emf, is proportional to the rate of change of magnetic flux linkages'.

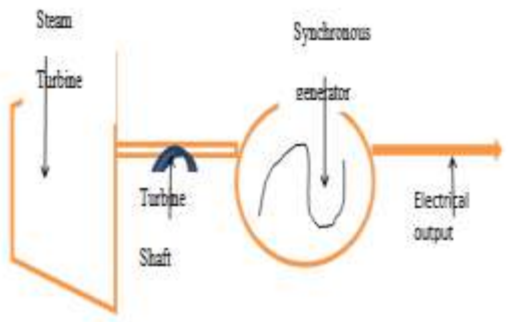

Fig.4.1: Visual model of Conversion of Rotational Energy to Electrical Energy

e α ØN ………………………………………… (4.3)
Equation (4.3) implied that the emf generated by the synchronous generator (alternator) is directly proportional to the speed of the rotor. i.e. the higher the speed of the rotation of the rotor, the higher the emf generated by the alternator. [9].
Equation (4.3) implied that rotational energy of the rotor is converted to the electrical energy at the output of the generator.
That is, $\frac{1}{2}\mathbf{J}\omega^2$ = eit ……………………………. (4.4)
Where **J** is the moment of inertia of the turbine in (kg.m^2), ω is the angular speed in (rpm), e is the generated emf in (V), i is the induced current in (A) and t is the time rate in (seconds).

III. CONCLUSION

Visual and mathematical models for conversion of temperature to useful electrical energy have been extensively discussed. It was clearly pointed out that the 500^0C temperature dissipated by each (i.e. total of 4000^0C) of the eight units of Gas Turbine Power Plant could be harnessed and converted into useful electrical energy by using a Steam Turbine Power Plant arrangement. This will result in improving the capacity of the generation subsector of electrical power system in Nigeria.

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