

Exergy Analysis of CI Engine Using the Blends of Diesel and Biodiesel from the seed of *Pongamia pinnata* (L) Pierre

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ABSTRACT

The maximum theoretical useful work obtained as a system interacts with an equilibrium state is called Exergy. Energy analysis is not only enough to define the best efficiencies of any system, so exergy analysis uses to understand and improve the actual efficiencies of the whole system. The irreversible losses and location could not identify by the energy analysis but can determine the energy losses. These losses are clearly identified by using the exergy analysis. In this study both energy and exergy analyses were performed in a Single Cylinder, Naturally Aspirated, Direct Injection, Compression Ignition Engine using diesel, biodiesel and blending of diesel and biodiesel. The significance difference of efficiency of the engine using the different sample of blending of diesel and biodiesel from the *pongamia pinnata* (L) Pierre will be the objective of this analysis. The fuel exergy, exergy losses due to exhaust gases, cooling water, destruction and efficiencies of the engine are achieved at steady state condition using the data from experiment. The tested biodiesel and petrodiesel fuel displayed similar type of energetic performance as a result.

Keywords:- Energy, exergy, CI engine, diesel, biodiesel, exergy loss.

INTRODUCTION

An exergy-based performance analysis is the performance analysis of a system based on the second law of thermodynamics that overcomes the limit of an energy-based analysis. The maximum theoretical useful work obtained as a system interacts with an equilibrium state is called exergy. Exergy is not conserved as energy on the other hand it destroyed in the system.

The measure of irreversibility in the source of performance loss is term as exergy destruction. Thus, an exergy analysis assessing the magnitude of exergy destruction identifies the position, the magnitude and the source of thermodynamic inefficiencies in a thermal system. It gives the useful information to improve the cost effectiveness and overall efficiency and comparing the performance

of the two systems. IC engine simulation modelling is an effective tool for studying engine performance, contributing for evaluation and new development. In order to assay machine performance — that is, estimate the inefficiencies associated with the colorful processes — second- law analysis must be applied.

The availability or exergy is the main concept as per the second law analysis, so availability of a material represents its potential to do useful work. Unlike energy, exergy can be destroyed which is a result of such phenomena as combustion, friction, mixing and throttling. The destruction of vacuity — frequently nominated irreversibility — is the source for the imperfect exploitation of energy into useful mechanical work in a contraction or spark ignition machine. The

reduction of irreversibility can lead to better machine performance through a more effective exploitation of energy. To reduce the irreversibility, we need to quantify them. That is we need to evaluate the availability destructions-we need the second-law analysis.

REVIEW OF LITERATURE

A literature survey has been done to examine the work done on exergy analysis of a compression ignition engine of internal combustion engine. This has been carried out to get an idea on the different method and software used for the exergy analysis of the compression ignition engine. Few of the important works of researchers are discussed below.

The energy content of the universe is constant, just as its mass content is. What is not conserved is exergy, which is the useful work potential of the energy [1]. Once the exergy is wasted, it can never be recovered. Here the topics Exergy and dead state, Exergy forms, Exergy of kinetic energy, Exergy of potential energy, Useful work, Reversible work, Irreversibility, Second Law Efficiency, Exergy Change of a system, Exergy flow, Exergy Transfer by Heat, Work and Mass, the decrease of Exergy Principle and Exergy Destruction and Exergy Balance were discussed in detail.

The first law of thermodynamics does not differentiate between the quality and quantity of energy so the real useful energy loss cannot be justified by it. This study deals with the comparison of energy and exergy analysis of thermal power plants stimulated by coal and the gas [2]. By the exergy analysis they conclude that main energy loss in boiler, in coal based thermal power plant and combustion chamber in gas fired combined cycle thermal power plant. In every plant components such as boiler, combustion

chamber there is some intrinsic irreversibility which cannot, owing to the present state of technological development, be eliminated. Exergy methods are useful in assessing which improvements are worthwhile, and should be used along with other pertinent information to guide efficiency improvement efforts for steam power plant.

They analysed the system components separately, then identify and quantify the sites having largest energy and exergy losses at different loads of Shobra El-Khima power plant in Cairo, Egypt [3]. The maximum energy loss found in the condenser at the load of 50%, 75% and 100% are 56.4%, 55.2%, 54.4% respectively of input energy was lost to the environment. The exergy analysis of the plant showed that lost exergy in the condenser is thermodynamically insignificant due to its low quality.

In terms of exergy destruction, the major loss is found in the turbine were 46.1%, 59.6%, 42% of the fuel exergy input to the cycle was destroyed at 50%, 75%, full load respectively. Similarly percent exergy destruction in condenser was 23.8%, 20.3%, 28%, in all heaters and pumps 30.2%, 32.4%, 30% at 50%, 75%, full load respectively. The calculated second law efficiency of the power cycle was found to be 48.8%, 45.5%, 44.8% at 50%, 75%, full load respectively which is comparable to modern power plant.

In their study, energy and exergy analyses of Shobra EI-Khima power plant in Cairo, Egypt is presented. The different loads they considered were maximum load (100%), 75% load and 50% load. The energy losses mainly occurred in the condenser, turbine and feed water heater. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the turbine system followed by condenser and feed

water heater respectively. In addition, the calculated thermal efficiency based on the specific heat input to the steam was $\approx 43\%$ while the exergy efficiency of the power cycle was (44% - 48%).

The performance of an internal combustion engine is evaluated at the steady-state condition by application of energy and exergy analysis using the experimental test results [4].

The results of this study have revealed that the most important source of the system inefficiency is the destruction of exergy by irreversible processes, mostly by the combustion. It may be concluded that the use of a combined exergy and energy analysis provides better criteria for the performance assessment of a thermal system.

The energy and exergy analyses were done in a four cylinder, direct injection diesel engine using petroleum diesel and biodiesel [5]. To do these analyses they collect the data like accurate measurements of air, fuel and cooling water flow rates, engine load and all the relevant temperatures using steady state tests.

According to the study, using exergy as a measure of quality, the petroleum diesel fuel is greater quality fuel than biodiesel because of the net calorific value of diesel is greater than that of the biodiesel.

It means that to cover the same distance, greater amount of diesel is needed. In addition to this, using biodiesel fuel shows the similar energetic performance values with that of diesel fuel.

Kinematic viscosity is one of the most important properties as it measures the resistance to flow due to internal friction [6]. High values of kinematic viscosity

give rise to poor fuel atomisation, incomplete combustion and carbon decomposition on the injectors. Therefore, the biodiesel viscosity must be low.

Cold Filter Plugging Point (CFPP) of a fuel reflects its cold weather performance. At low operating temperature, fuel may thicken and might not flow properly affecting the performance of fuel lines, fuel pump and injectors. CFPP defines the fuel limit of filterability, having a better correlation than cloud point for biodiesel as well as petrodiesel [7].

Lebedevas S et al carried out research in to the change of parameters concerning the fuel economy thrust and harmful components of exhaust gases, namely hydrocarbon (HC), carbon monoxide (CO) and nitric oxide (NO_x) was carried out to evaluate the efficiency of fuel replacement; and that is, mineral diesel fuel, which is normally used by diesel engine fleets of agricultural machinery in Lithuania, was replaced with biofuel (biodiesel), which is rapeseed oil methyl ester (RME) and the research was done on a model diesel engine F2L511 and a single section of diesel engine A41 [8].

Ozkan M did comparative study of the effect of biodiesel and diesel fuel on a four cylinder, four strokes, turbocharged IDI CI engine [9]. The engine was operated with the same settings for both fuel types during the experiments and no alternation has been made in the fuel system elements.

In this, Kannan TK et al study an oxygenated additive diethyl ether (DEE) was blended with biodiesel in the ratio of 5%, 10%, 15% and 20% and tested their performance in a computerized Kirloskar diesel engine of AVI model, four stroke, direct injection, naturally aspirated, water cooled engine [10].

Non-edible filtered viscous (72cst at 40°C) and high acid value (44mg KOH/gm)

polanga (*Calophyllum inophyllum* L.) oil based monoesters (biodiesel) produced by triple stage transesterification process and blended with high speed diesel (HSD) (20%, 40%, 60%, 80% and 100%) were tested for their use at varying loads (0%, 20%, 40%, 60%, 80% and 100%) as a substitute fuel of diesel in a single cylinder diesel engine [11].

EXERGY OF A SYSTEM

The exergy or availability of a system in a given state can be defined as the maximum

$$\chi^{tm} = (E - U_o) + p_o(V - V_o) - T_o(S - S_o) \quad (1)$$

where $E = E_{kin} + E_{pot} + U$ with E_{kin} the kinetic energy and E_{pot} the potential energy, p_o and T_o are the fixed pressure and temperature of the environment; and

useful work that can be produced through interaction of the system with its surroundings, as it reaches thermal, mechanical and chemical equilibrium. Usually, the terms with thermo mechanical and chemical equilibration are differentiated and calculated separately.

For a closed system experiencing heat and work interactions with the environment, the following equation holds, for the thermo mechanical exergy.

U_o , V_o and S_o are the internal energy, volume and entropy of the contents were they brought to p_o and T_o .

General energy balance equation

The total energy on time basis for an open system:

$$\frac{dE_{cv}}{dt} = \sum_j \dot{Q}_j - \dot{W}_{cv} + \dot{m}_i \cdot e_i - \dot{m}_e \cdot e_e \quad (2)$$

Where

- $\dot{Q}_j$ Represents the time rate of heat transfer at the boundary of the control volume.
- $\dot{W}_{cv}$ Mechanical work transfer from control volume.
- $\dot{m}_i \cdot e_i - \dot{m}_e \cdot e_e$ are the energy terms associated with inflow and outflow of masses, respectively.

In particular, the terms and refer to the flow or energy of the incoming and the outgoing cylinder mass flow rates, respectively, given by $e = c_p \cdot T$ (neglecting kinetic and potential energy contribution).

General exergy balance equation

The total exergy on time basis for an open system:

$$\frac{dX_{cv}}{dt} = \int_j^o \left(1 - \frac{T_o}{T_j}\right) \cdot \dot{Q}_j - \left(\dot{W}_{cv} - p_o \cdot \frac{dV_{cv}}{dt}\right) + \sum_i \dot{m}_i b_i - \sum_e \dot{m}_e b_e - \dot{x}_d \quad (3)$$

Where

- $\frac{dX_{cv}}{dt}$ is the time rate of change in the exergy of the control volume content (i.e. engine cylinder, or exhaust manifold, etc.).

- $\int_j^o \left(1 - \frac{T_o}{T_j}\right) \cdot \dot{Q}_j$ is the exergy term for heat transfer, with the temperature at

the boundary of the system, which in general, is different from the temperature level of a process (although these two temperatures are the same when applying the most usual simulation approach of internal combustion engines operation, i.e. single-zone coronate).

(c) $(\dot{W}_{CV} - p_o \cdot \frac{dV_{CV}}{dt})$ is the exergy term associated with (mechanical or electrical) work transfer $p_o \cdot \frac{dV_{CV}}{dt}$ denotes the dead state work.

(d) $\sum_i \dot{m}_i b_i - \sum_e \dot{m}_e b_e$ are the exergy terms associated with inflow and outflow

(e) $b = h - h_o - T_o(s - s_o)$

with s_o the entropy of (cylinder) flow rate were it brought to p_o and T_o . Flow exergy is defined as the maximum work output that can be obtained as the fluid passes reversibly from the given state to a dead state, while exchanging heat solely with the environment.

(f) $\dot{x}_d$ is the rate of exergy destroyed due to irreversibility production inside the

of masses, respectively. In particular, the terms b_i and b_e in refer to the flow or stream exergy (or exergy) of the incoming and the outgoing cylinder mass flow rates, respectively, given by (neglecting kinetic and potential energy contribution):

(4)

control volume due to combustion, throttling, mixing, heat transfer under finite temperature difference to cooler medium, etc. $\dot{x}_{gen} = T \cdot \dot{S}_{gen}$ based on an entropy balance, with $\dot{S}_{gen}$ denoting the rate of entropy creation due to irreversibilities.

Fuel exergy

The chemical exergy of fuel of type C_zH_y is approximated by:

$$\psi_{fch} = LCV(1.04224 + 0.011925 \frac{y}{z} - \frac{0.042}{z}) \quad (5)$$

LCV is the Lower Calorific Value.

Engine cylinder exergy balance

For the engine cylinder on crank angle basis, we have:

$$\frac{d\chi_{cyl}}{d\varphi} = \frac{\dot{m}_i b_i - \dot{m}_e b_e}{6N} - \frac{d\chi_w}{d\varphi} - \frac{d\chi_L}{d\varphi} + \frac{d\chi_f}{d\varphi} - \frac{d\chi_d}{d\varphi}$$

The right hand side terms are:

a) $\dot{m}_i$ is the incoming flow rate form the inlet manifold and $\dot{m}_e$ outgoing flow rate to the exhaust manifold.

b) $\frac{d\chi_w}{d\varphi}$ is the exergy rate of work transfer, given by

$$\frac{d\chi_w}{d\varphi} = (p_{cyl} - p_o) \frac{dV}{d\varphi} \text{ where } p_{cyl} \text{ is the instantaneous cylinder pressure.}$$

c) $\frac{d\chi_L}{d\varphi}$ is the exergy rate of the heat transfer to the cylinder walls, given by

$$\frac{d\chi_L}{d\varphi} = \frac{dE_L}{d\varphi} \left(1 - \frac{T_o}{T_{cyl}}\right) \text{ where } T_{cyl} \text{ is the in cylinder temperature.}$$

d) $\frac{d\chi_f}{d\varphi}$ is the fuel exergy rate, given by $\frac{d\chi_f}{d\varphi} = \psi_{fch} \cdot \frac{dm_f}{d\varphi}$

where $\psi_{fch} = 1.0599$ LHV for diesel fuel.

e) $\frac{d\chi_d}{d\varphi}$ is the rate exergy generation due to irreversibility production within the cylinder, which consists of combustion (dominant contribution), viscous dissipation, turbulence, inlet valve throttling and mixing of the incoming air or air– fuel mixture with the cylinder residuals.

And,

$$\frac{d\chi_{cyl}}{d\varphi} = \frac{dU}{d\varphi} + p_o \frac{dV}{d\varphi} - T_o \cdot \frac{dS}{d\varphi}$$

represents the rate of change in the total exergy of the cylinder contents.

As regards cumulative terms, these are defined after integration of the respective

rate terms over an engine cycle. Especially, for steady-state operation, the cumulative value for the cylinder exergy is $\int_0^{720} \frac{d\chi_{cyl}}{d\varphi} \cdot d\varphi = 0$

Second-law or exergy or exergetic efficiencies

For the cylinder alone, the following second-law efficiency is used:

$$\varepsilon = \frac{W_{br}}{m_f(1.06LHV)}$$

with W_{br} the brake work production and M_f the total mass of fuel entering the cylinder per cycle.

Efficiency can be then compared to a first-law one, such as:

$$\eta = \frac{W_{br}}{m_f.LCV}$$

Energy Analysis of the engine at different loads

Energy content of fuel:

$$\dot{E}_f = LCV \cdot \dot{m}_f$$

CV = calorific value of fuel

Effective power of engine:

$$\dot{E}_w = \frac{\pi \cdot N \cdot \tau}{30}$$

N = rpm of engine ; τ = Torque applied by dynamometer

Energy loss in exhaust gases:

$$\dot{E}_e = \dot{m}_{eg} \cdot c_{pg}(T_3 - T_4) = \dot{m}_{ccw} \cdot c_{pw} \cdot (T_6 - T_5)$$

Energy loss to cooling water:

$$\dot{E}_L = \dot{m}_{ecw} \cdot c_{pw} \cdot (T_2 - T_1)$$

Energy Balance

$$\dot{E}_f = \dot{E}_w + \dot{E}_e + \dot{E}_L + \dot{E}_r$$

Energy Efficiency:

$$\eta_{energy} = \frac{\dot{E}_w}{\dot{E}_f}$$

Exergy Analysis of the system

Exergy of fuel:

$$X_f = 1.06 \times LCV \times \dot{m}_f$$

Work exergy:

$$X_w = \dot{E}_w$$

Exergy of heat lost to exhaust gases:

$$X_e = \dot{E}_e \left(1 - \frac{T_o}{T_3}\right)$$

Exergy of heat lost to cooling water:

$$X_L = \dot{E}_L \left(1 - \frac{T_o}{T_2}\right)$$

Exergy of heat lost to radiation:

$$X_r = \dot{E}_r \left(1 - \frac{T_o}{T_w}\right)$$

Exergy Balance:

$$X_f = X_w + X_e + X_L + X_r + X_{des}$$

Exergy Efficiency:

$$\eta_{exergy} = \frac{X_w}{X_f}$$

Engine Setup

Experiments were conducted on an existing test unit. The test unit was a

Single Cylinder, Naturally Aspirated, Direct Injection, Compression Engine using standard diesel fuel

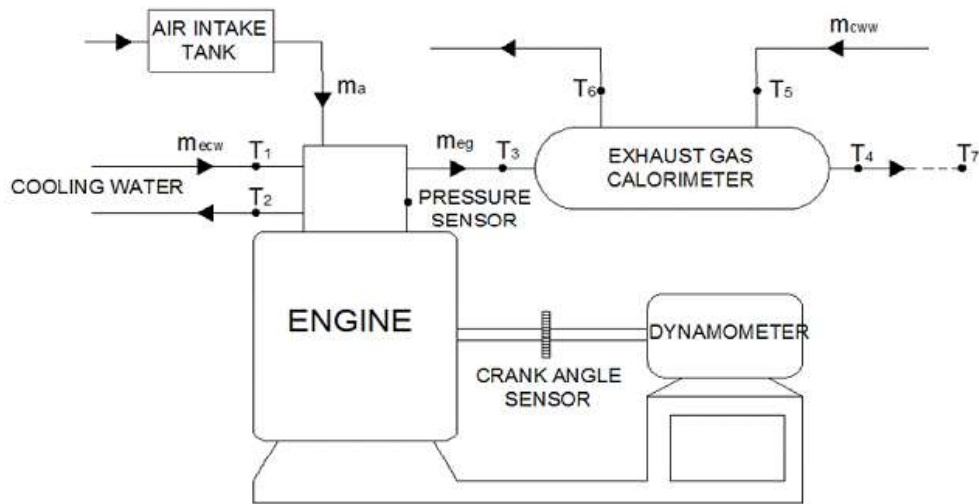


Fig.1:-Schematic diagram of engine test unit.
(Source: www.elsevier.com/locate/peccs)

PROCEDURE

This engine setup shows that it enabled the measurement of in-cylinder pressure and volume as a function of crank angle; fuel rate, air flow rate, cooling water flow rates to engine and gas calorimeter, engine load; and inlet and outlet temperatures for each stream.

m_{ecw} = engine cooling water flow rate (kg/s)

m_{cww} = calorimeter water flow rate (kg/s)

m_a = air flow rate (kg/s)

m_{eg} = exhaust gas flow rate (kg/s)

m_f = fuel flow rate (kg/s)

T_1 = Inlet engine cooling water temperature ($^{\circ}\text{C}$)

T_2 = Outlet engine cooling water temperature ($^{\circ}\text{C}$)

T_3 = Exhaust gas temperature at inlet of calorimeter ($^{\circ}\text{C}$)

T_4 = Exhaust gas temperature at outlet of calorimeter ($^{\circ}\text{C}$)

T_5 = Inlet calorimeter cooling water temperature ($^{\circ}\text{C}$)

T_6 = Outlet calorimeter cooling water temperature ($^{\circ}\text{C}$)

T_7 = Ambient temperature ($^{\circ}\text{C}$)

Results Energy and Exergy balances at different loads:

The data for different samples from the biodiesel and its blends are applied to the mentioned relations for different loads and the results of the energy and the exergy are depicted in Fig. 1 to 19.

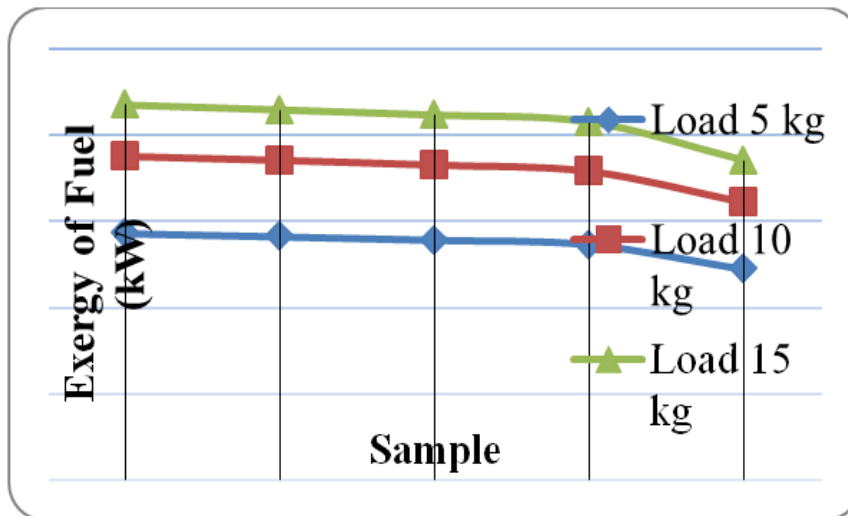


Fig.1:-Fuel exergy for different samples at different loads.

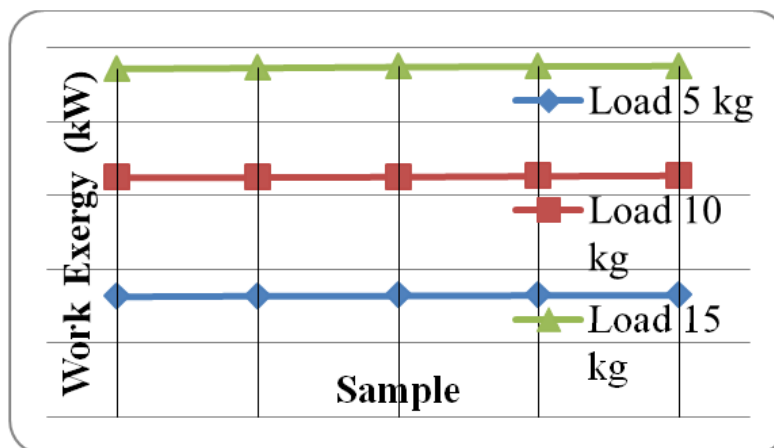


Fig.2:-Work exergy for different samples at different loads.

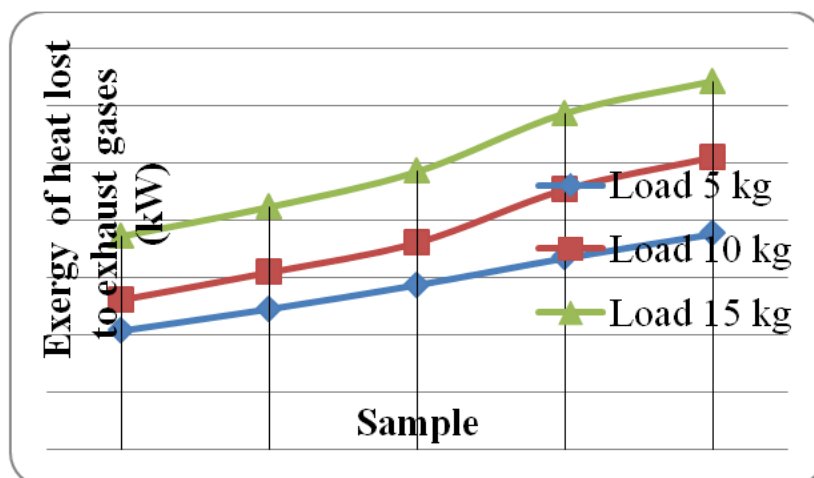


Fig.3:-Exhaust exergy for different samples at different loads.

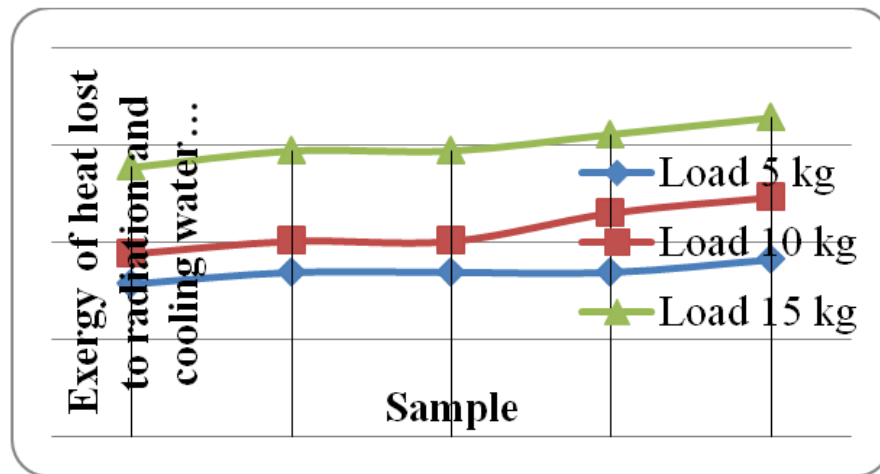


Fig.4:-Exergy of heat loss to radiation and cooling water for different samples at different loads.

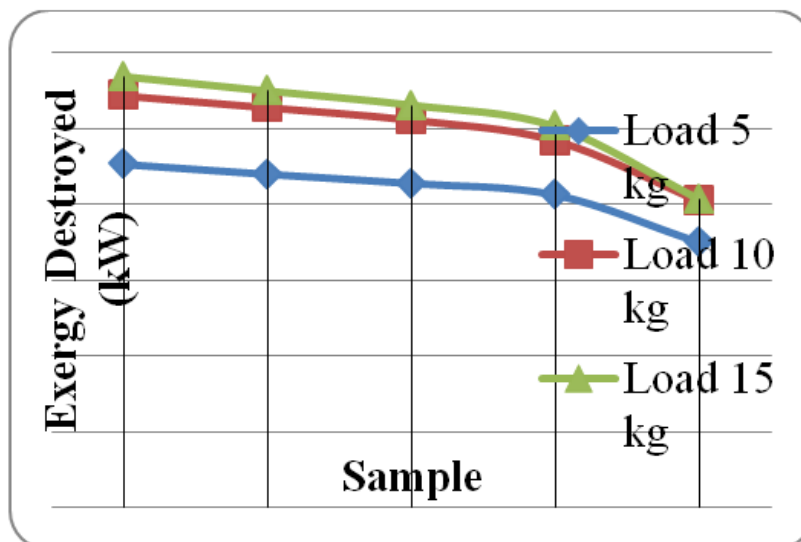


Fig.5:-Exergy destroyed for different samples at different loads.

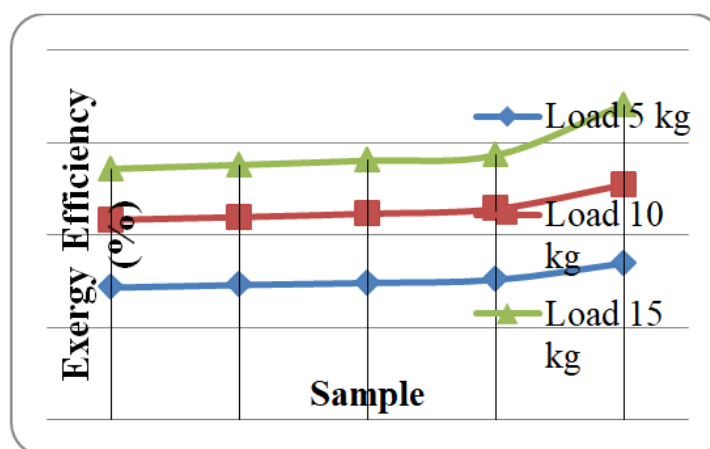


Fig.6:-Exergy efficiency for different samples at different loads.

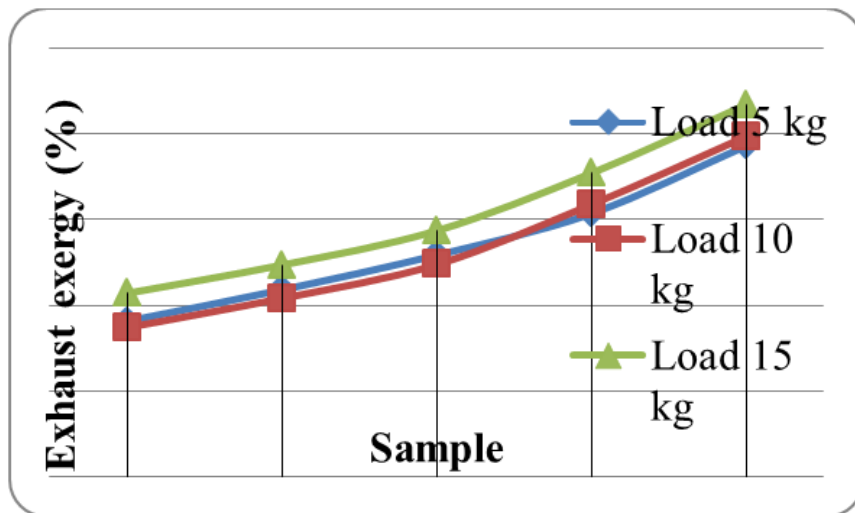


Fig.7:-Exhaust exergy for different samples at different loads.

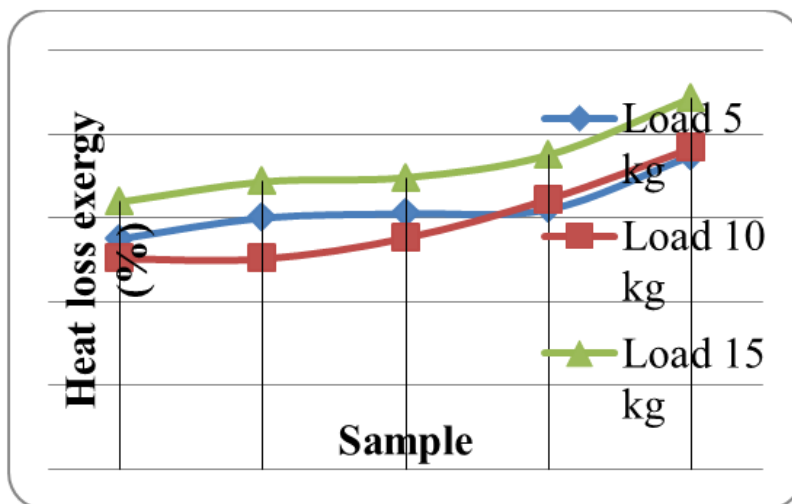


Fig.8:-Heat loss exergy for different samples at different loads.

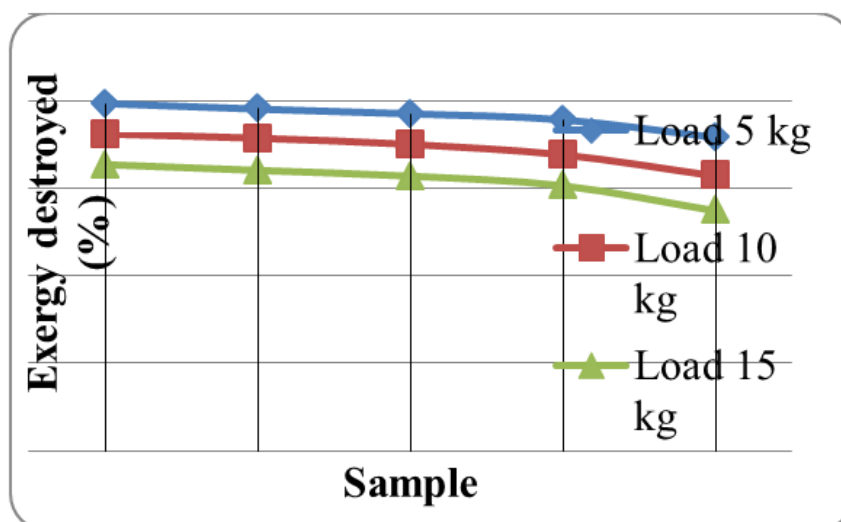


Fig.9:-Exergy destroyed for different samples at different loads.

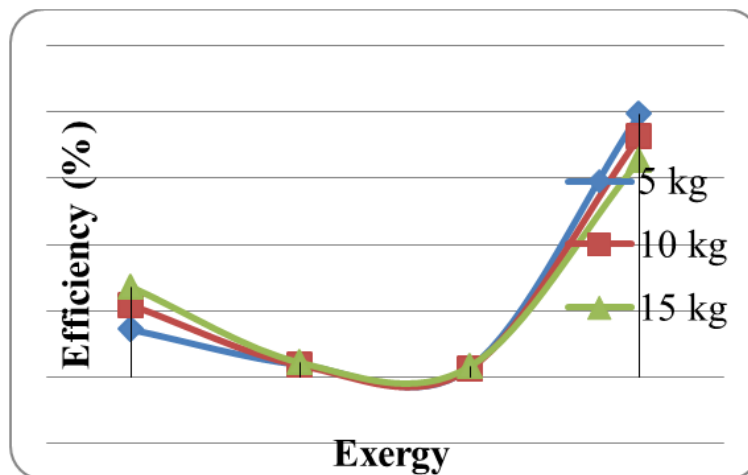


Fig.10:-Efficiency of different exergy of sample B00 at different loads.

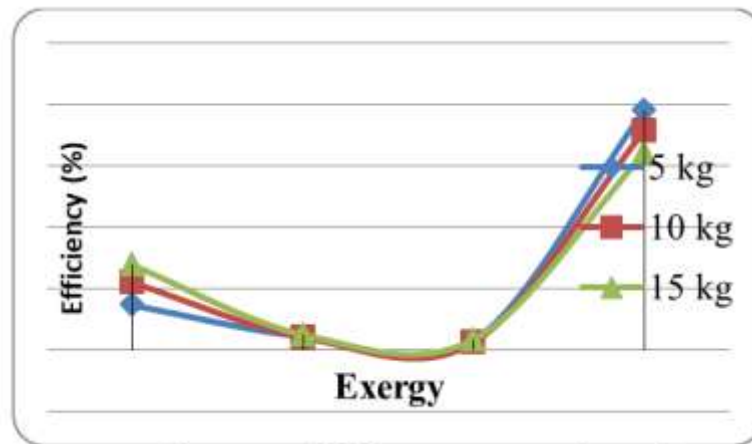


Fig.11:-Efficiency of different exergy of sample B10 at different loads.

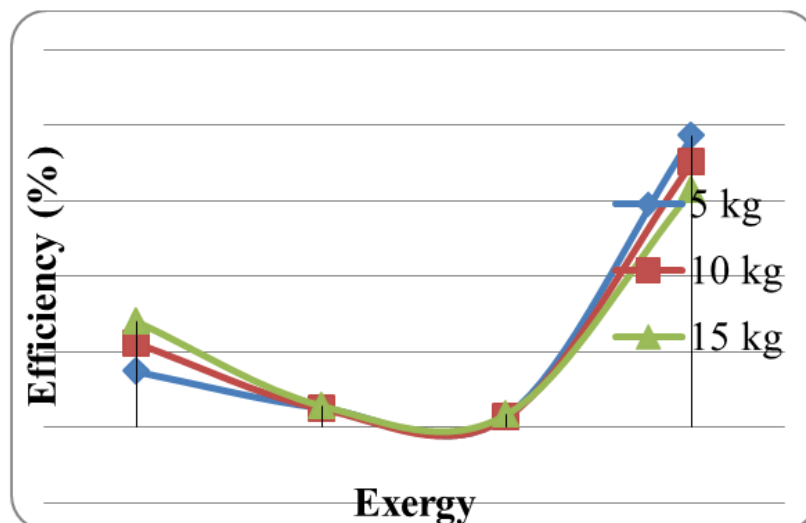


Fig.12:-Efficiency of different exergy of sample B20 at different loads.

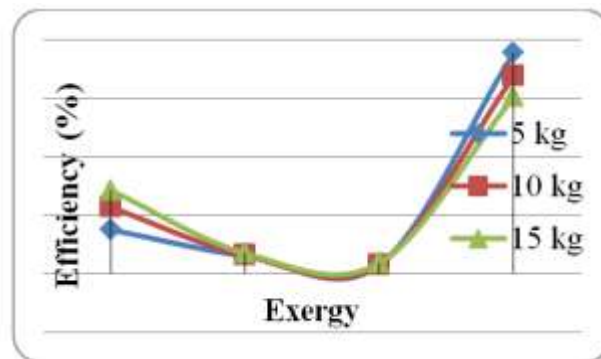


Fig.13:-Efficiency of different exergy of sample B30 at different loads.

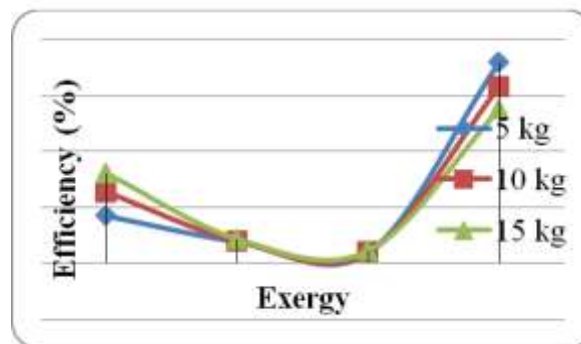


Fig.14:-Efficiency of different exergy of sample B100 at different loads.

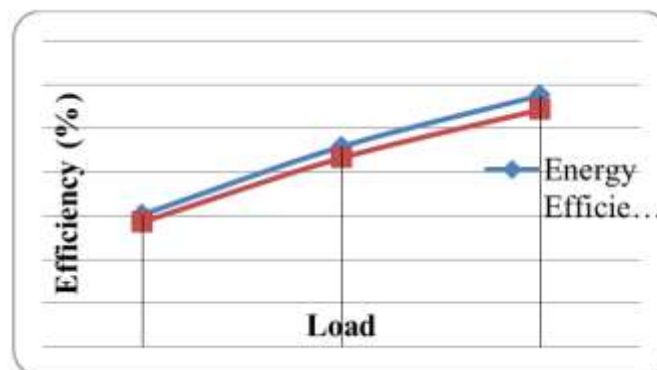


Fig.15:-Efficiency for B00 at different load.

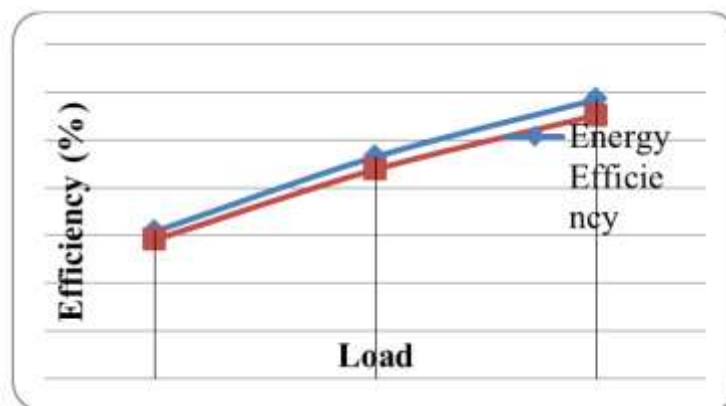


Fig.16:-Efficiency for B10 at different load.

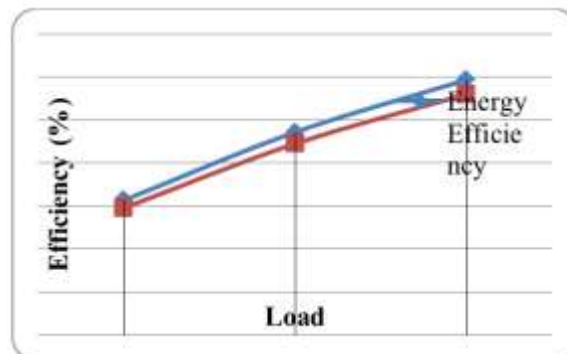


Fig.17:-Efficiency for B20 at different load.

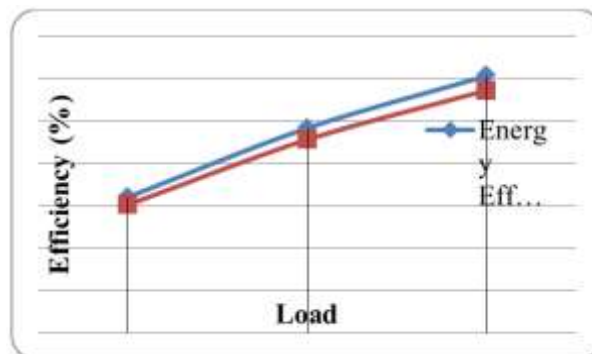


Fig.18:-Efficiency for B30 at different load.

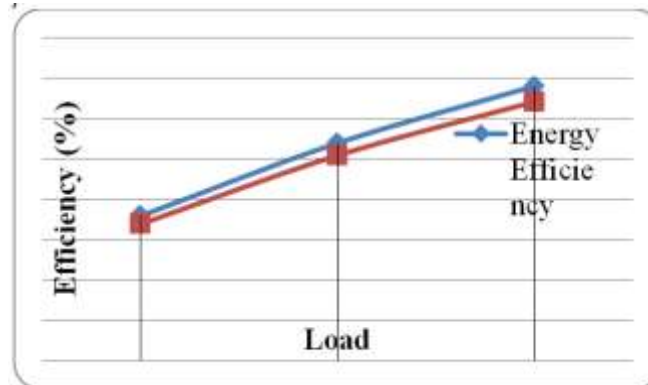


Fig.19:-Efficiency for B100 at different load.

RESULTS AND DISCUSSION

Figures 10-14 show that the efficiency of different exergy of samples at different loads. From these figures it shows that the exergy destruction decreases, because combustion irreversibility decreases with increasing load.

Greater load results in less degradation of the fuel chemical exergy when transferred to the exhaust gases and also less mixing of exhaust gases with air.

Figure 15-19 shows the efficiency of the samples at different loads. In these figures both energy efficiency and the exergy efficiency increases with increasing load.

The exergy efficiency is lower than the energy efficiency for the five samples for the same power output. This is due to the fact that the input fuel exergy of the fuel is slightly higher than its input fuel energy.

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