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FUEL EFFICIENCY IMPROVEMENT OF SHIP POWER PLANTS IN A CHEMICAL TANKER VESSEL

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Abstract: This paper presents a study of fuel efficiency improvement of a tanker vessel aimed at optimizing the rate of fuel consumption on board a vessel. A chemical tanker is considered as a case study in this work and the three major sources of energy losses encountered onboard the vessel (machinery losses, propeller losses, and hull losses) are properly analyzed in terms of percentage. Propeller losses and hull losses are observed to constitute 16% and 32% of energy losses onboard the vessel respectively. Machinery losses make up the highest source of energy losses in the form of heat, exhaust and transmission losses that takes place in the main engine of the power plant of the studied vessel. This work particularly concentrates on ways of reducing the high amount of energy losses in the vessel's machinery system as a panacea to improve and boost the fuel efficiency of the vessel. This is achieved through the use of Waste Heat Recovery System to recuperate energy from the exhaust gases and heat produced in the engine compartment. Furthermore, installation of an exhaust gas turbine and exhaust gas boiler are incorporated on the vessel's power plant. This shows an increase in performance of the plant by 15%, as compared to when the main engine is running alone. Other efficiency improving configurations like heat-exchanger and jacket water cooler installed to the auxiliary generator exhausts set shows a 4% fuel consumption rate improvement. Turbochargers and air coolers are also considered. The mathematical models adequately analyses the plant efficiencies at different operating loads which are graphically presented. The benefits and cost evaluation in terms of energy savings are also presented. This research becomes necessary due to high cost of fuel in running diesel engines on a chemical tanker-vessel in terms of fuel consumption.

Keywords: efficiency, energy losses, fuel consumption, tanker vessel, waste heat recovery system

INTRODUCTION

The shipping industry is facing various challenges today. In a period of low freight rates, fuel prices have increased to levels only seen during the oil crisis in the 70's. Stricter environmental regulations are putting additional stress on the sector (1). Meanwhile, the latest IPCC Intergovernmental Panel on Climate Change (IPCC) report highlighted the increased confidence in the existence of an anthropic contribution to global warming. Shipping, though only contributing by an estimated 3% to global Carbon (IV) oxide emissions, is expected to increases its share in the future (2).

In such a context, it is not out of place to take up research findings towards improving the energy efficiency of vessels (3);(4). The critical role of shipping in global economy implies that increasing the efficiency of power plants of vessels, is one of the ways to reduce its fuel consumption without decreasing its output (5). There is the need of addressing energy efficiency in shipping from a number of different angles (6). This research approaches this challenge from a technical perspective, which has to do with improvements in fuel efficiency of ships, crew training and operational efficiency. Crew training and awareness can answer such questions as – do the vessel's systems operate in the most efficient mode? A lack of maintenance and overhaul increases the vessel's energy consumption (7). Other possibilities include slow steaming and taking advantage of the currents and avoiding bad weather and monitoring of hull and propeller fouling; working systemically with onboard best operational practice, such as avoiding idle machinery and monitoring engine performance.

1.1 Energy losses in propulsion system:

The table 1.0 summarizes the three top most important losses in propulsion system and possible means of reduction.

Table 1.0

Energy Losses:	Reduction of Energy losses:
- Heat - Exhaust **Machinery losses 52%** - Transmission loss	- WHR Systems, Improve engine thermal efficiency.
- Frictional Loss - Rotational loss - Axial loss **Propeller losses 16%**	- Propeller, energy-saving devices PBCF; Mewis duct; contra- rotating propellers; etc.
- Weather & waves - Residual resistance - Hull resistance **Hull losses 32%** - Air resistance - Wave-making	- Hull form optimization, reduce skin friction resistance: LSE coating; air lubrication Refine bow and stern Bulbous bow: reduce wave making resistance.

Source: Matsuzak, 2008

1.1 The case Study - Chemical Tanker

The case study represents is a vessel owned by Maersk line. It provided extensive operational measurements and technical information. The ship is equipped with an energy monitoring system which logs onboard measurements on a dedicated server with a frequency of acquisition ranging between 1 and 15 seconds. Data are automatically processed by the systems in order to produce minute's averages, to check data reliability, and to filter output values. The list of the measurements available on the energy monitoring system is presented in Table 2.0. Information and measurements manually collected related to onboard fuel consumption and machinery parameters are made use of in this work. Although the accuracy and reliability of these data is often questioned (Aldous et al., 2013), they constitute a broad source of knowledge and are used in this work when none of the previously mentioned sources could provide the required information.

Table 2.0 Parameters measured by energy monitoring system

Measured variable	Unit
Ambient Air:	
Dew Point temperature	^oC
Relative humidity	%
Auxiliary Engines:	
Fuel Consumption	Ton/15mins
Power Output	kW
Shaft Generator power output	Kw
Propeller:	
Power	kW
Speed	rpm
Torque	kNm
Main engines fuel consumption	ton/15mins
Fuel Temperature	^oC
Seawater Temperature	^oC

2. MATERIALS AND METHODS

For proper and adequate presentation of fuel efficiency improvement analysis for a tanker vessel, the marine diesel engine power plant (Sulzer RLB76 propulsion) is used in this work. The efficiency of an engine is the ratio of the engine's output to the energy in the fuel fed into the engine (work input). It therefore implies that increase in the work output will bring about a corresponding increase in efficiency (8);(9). Hence, the efficient and most economic methods applied to improving fuel efficiency for tanker vessel is waste heat recovery (like installing a turbo-generator to the main engine and installing a boiler at the exhaust of the main engine). This will form the focus of this work.

2.1 Waste Heat Recovery

Main industrial, commercial, and institutional uses of energy result in excessive rates of waste heat rejection. Recovering and reusing rejected heat is known as waste heat recovery. Waste heat is usually recovered in the forms of steam, hot water, or hot air. The recovery medium is dependent on the quality of the waste stream, the potential use for the waste heat at the host, and the cleanliness of the waste stream. In this entry, the energy engineer is introduced to issues that should be considered in the economic and technical evaluation of waste heat recovery potential.

These issues include:

(1) The quality of the waste heat stream

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(2) The calculation of the availability and applications of waste heat

(3) The types of heat recovery equipment available.

In many industrial and commercial energy applications, only a portion of the energy input is used in the process. The remainder of the useful energy is rejected to the environment. This rejected energy may potentially be recaptured as useful energy through waste heat recovery (10);(11). Not all rejected energy can be recovered due to quality, usefulness in a host's, and/or economic reasons that may make its recovery infeasible. For the purposes of this entry, there are three classifications of waste heat. These are:

(1) High-grade waste heat, generally 1000^{O}F and above;

(2) Medium-grade waste heat, generally in the range of 400^{o}F-1000^{O}F; and

(3) Low-grade waste heat, generally below 400^{O}F.

Typically, the higher the grade of waste heat, the better the application for a successful and economical waste heat recovery project. It is better to have a marginal amount of high quality waste heat than large quantities of lower-grade waste heat.

2.2 Engineering Consideration

There are several engineering factors that must be evaluated when considering and designing a waste heat recovery system and these are:

(1) Quantifying the waste heat stream;

(2) Determining the value of the waste heat stream;

(3) Evaluating the best form of heat recovery for the host of facility;

(4) Determining the host site heat load profile;

(5) Determining the grade of waste heat;

(6) Determining the cleanliness and quality of the waste stream; and

(7) Selecting the proper waste heat recovery equipment by considering size, location, and maintainability.

The first step that should be executed is to quantify the waste heat stream by determining how many Joules/h are in the waste stream. The equation to calculate this is as follows:

$$Q = Mass\ flow\ rate\ \times Specific\ heat\ \times temperature$$

$$Q = M \times C_p \times \Delta T \qquad (1)$$

Where:

Q = Total heat flow rate of waste stream in Joule/h;

$M = mass\ flow\ rate\ in \frac{kg}{h} \times \Delta$

$C_p = Specific\ heat\ for\ air, 1.005\ (kJ/kg/\ K);$

$\Delta T = Temperature\ change\ (T_{upper} - T_{lower})\ in\ K.$

The mass flow rate (M) is calculated as follows:

$$M = \rho \times V \qquad (2)$$

$where\ \rho = density\ of\ the\ waste\ stream\ in\ kg/m^3;$

$V = Volumetric\ flow\ rate\ in\ m^3/h.$

Note that the value of Q is not the total amount of waste heat that will be recovered, but, rather, the total amount of waste heat that is ideally available for recovery. Not all of this waste heat will be recovered, or even can be recovered. The total amount that will be recovered will be determined by numerous other factors such as: the cleanliness of the waste stream and the form of recovery (i.e., high pressure, superheated steam, saturated steam, or hot water). This step is necessary in determining if there are sufficient volumes available for waste heat recovery.

The monetary value of the waste heat stream can be determined by Eqns. 3 and 4 below:

$$Value = Q \times unit\ cost \qquad (3)$$

$$Unit\ Cost = \frac{fuel\ cost}{Efficiency} \qquad (4)$$

Where:

Value = monetary value of the waste heat stream, per hour

Unit cost = unit cost of the waste stream in Naira/Joule

Fuel cost = cost for fuel displaced in Naira/Joules;

Efficiency = Efficiency of unused equipment; for example, a steam boiler at 75%.

To calculate the amount of waste heat that is available for recovery, the actual volumetric flow must first be converted to standard cubic feet per minute (SCFM) at 60^{O}F, using the following equation:

$$SCFM = ACFM\ \times \frac{(T_{absolute} + 60)}{(T_{absolute} + T_{actual})} \qquad (5)$$

Where:

SCFM = Standard Cubic Feet per Minute;

ACFM = Actual Cubic Feet Per minute;

$T_{absolute} = 460\ ^{o}F\ (also\ 273K);$

$T_{actual} = actual\ gas\ temperature.$

To obtain steam mass flow, we use Eq. 6 below:

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$$M_s = \frac{Q}{(h_g - T_f)} \quad (6)$$

Where;
$h_l = enthalpy\ for\ saturated\ liquid\ (Joules/kg).$
$h_g = saturated\ vapor\ (Joules/kg).$

2.3 Installing Turbo-Generator to the Main Engine

Like the turbo-charger, the exhaust gas could also be made to pass through sets of turbine blades in which on the overall could be geared for power generation in driving compressors, pumps(12); (13) or for possible electric power generation which is more convenient through am alternating current (AC) generator, see Fig. 1.

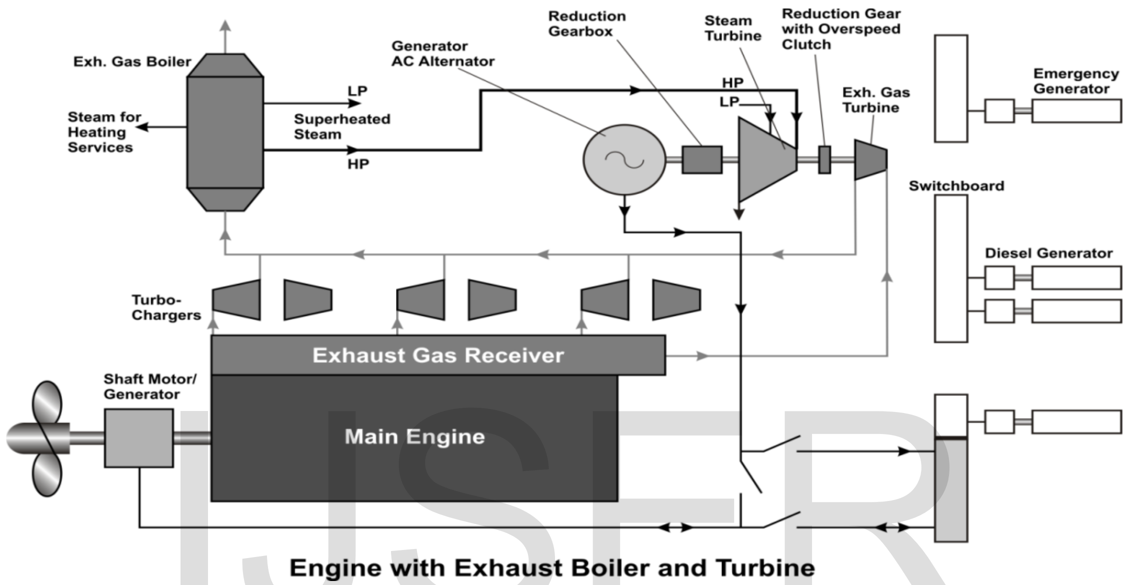

Fig. 1 Installing Turbo-Generator to the Main Engine

2.4 Installing a boiler at the Exhaust of the Main Engine

The exhaust gas boiler (EGB) in its simplest form consist of a steam generating section only, which is used to produce steam that is saturated for heating purpose. In this system, water is circulated from the systems space. In cases where steam requirement is high in relation with the generated steam, the economizer section is then introduced to effect the extraction of more steam from the available heat (13);(14). Where it is needed to take advantage of the waste heat available from auxiliary diesel sets, a steam raising unit can be incorporated into the existing main engine waste heat steam system.

On board ships, air-conditioning system requires some amount of steam. The amount of steam consume by an air-condition system may be assumed from the formulae:

$$Q = 0.001 \times N \times C \quad (7)$$

Where:
$Q = Steam\ consumption\ (kg/h).$
$N = Total\ complement\ of\ ship$
$C = 150\ or\ 120\ for\ bulk\ carriers\ and\ dry\ cargo\ ship\ respectively.$

Usually, when hotel heating service is supplied by steam, the allowance for heating of domestic water, gallery, laundry, etc. are always observed. Generally, the total steam consumption for hotel heating service should not be less than 50 kg/h. if 'N' is the total complement for domestic water heating, then steam consumed will be given by:

$$Q = 0.4 \times N \quad (8)$$

$$For\ gallery, Q = 0.25N$$

$$For\ laundry, Q = 0.05N$$

Where
$Q = steam\ consumption\ (kg/h)$

Usually on board ships, certain amount of steam is needed for dehumidification of cargo in cargo holds. The steam consumption for dehumidification is given as:

$$Q = 0.2V_H \quad (9)$$

Where

$Q = steam\ consumption\ (kg/\square)$

$V_H = total\ cargo\ base\ cubic\ capacity(m^3)$

2.5 Other Methods

Other methods that can be applied to improve the fuel efficiency of a chemical tanker vessel include:

2.5.1 Production of fresh water

With respect to ship diesel power plant with an extremely high consumption of fresh water, the heat in the exhaust gas can be utilized to provide the amount of the fresh water required. The exhaust heat used for the steam production is normally recovered in the exhaust gas boiler at 8MN/m^2. The necessary consumption of saturated steam for heating purpose in the ship or power plant is normally smaller than he obtainable steam production. The remaining amount of available steam can be used to supply heat to the heat exchanger of the fresh water generator (14);(15). The heat transfer can for instance be established by means of steam injector for circulation and heating a closed heating water system heated to about 120^{O}C or by steam/water heat exchanger. Due to the temperature level, it is possible for us to install a highly efficient six-stage fresh water generator. When using a steam/water heat exchanger, only the vaporizing heat of the steam may be used and as well, a heating water circulating pump is also required.

2.5.2 Addition of boiler to the auxiliary generator exhaust gas

In addition to the waste heat recovered from the main propulsion engine, more waste heat recovery is being achieved by the installation of exhaust gas boiler on the auxiliary diesel sets. This can be done in a similar manner to the main engine exhaust gas boilers. The steam produced from the waste heat recovery of these auxiliary diesel sets can be supplemented to the steam produced from the main engine exhaust gas boiler for heating services or top steam for turbo-generator duties. Also, when the vessel is in port, the steam can be utilize for heating duties reducing the load and in some cases eliminating the start-up of oil fired boiler.

2.5.3 Jacket water cooling system

The fresh water cooling system is used for removal of heat from cylinder jackets, cylinder and exhaust valves as well as turbochargers. All the fresh water heat is normally removed sea water cooled fresh water cooler. The fresh water outlet of the coolers fitted with a thermodynamically controlled regulating valve, which maintains a temperature of 75% at the cooling water outlet of the main engine. If necessary, the temperature may be increased to 80^{O}C without any alteration of the diesel engine. Simply locating heat exchanger(s) in the jacket cooling water system, part of the heat, does this or all of the heat can be utilized for heating of accommodation, tanks, fresh water generator etc. a low grade heat is available from the main engine cooling water at temperature up to 70^{O}C. due to the extra cost of heat exchangers, utilizing this source becomes extremely unattractive economically at the moment. This fresh water generator located in jacket cooling systems is commonly used on ships.

3.0 Efficiency Calculations at 100%, 80% and 50% Loading.

From the improved power plant of the case study vessel, we will calculate the efficiency of the main engine, the efficiency of the gas turbine and the overall efficiency of the power plant.

$$Efficiency\ (\eta) = \frac{E_{out}}{E_{in}}$$

$E_{out} = Energy\ out$

$E_{in} = Energy\ in = Q_{in} = M_f \times LCV$

$E_{out1} = MCR$

$Q_{in} = Rate\ of\ energy\ supplied\ by\ combustion\ of\ fuel.$

$LCV = Net\ calorific\ value$

$M_f = Mass\ flow\ rate\ of\ fuel = \frac{SFC \times W_b}{3600}$

From diesel engine data,

$SFC = Specific\ fuel\ consumption$

$W_b = Brake\ power$

$= Maximum\ continuous\ rating\ (MCR)$

From the diesel engine,

$$\eta_{ME} = \frac{E_{out1}}{E_{in}}$$

Efficiency of the plant when an exhaust gas turbine is installed from the energy block diagram is shown in fig. 2a & 2b.

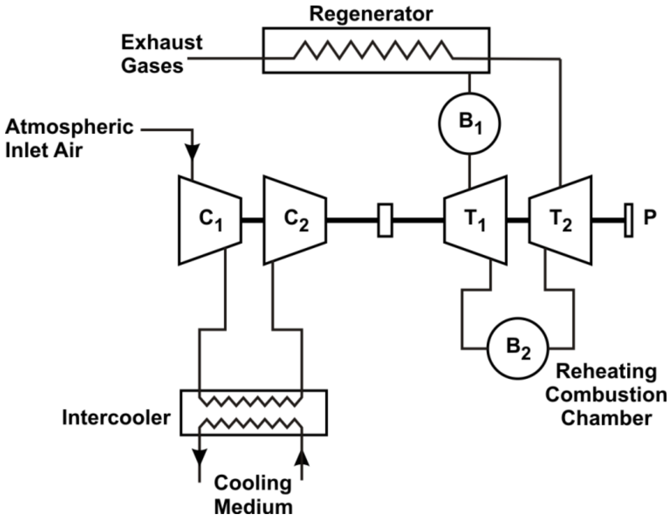

Fig. 2a Plant Configuration with Exhaust Gas Turbine Installed

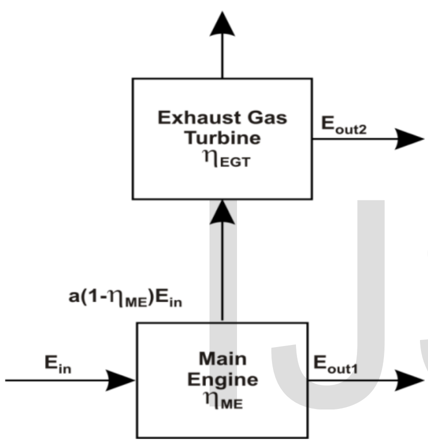

Fig. 2b The Overall Plant Efficiency when an exhaust gas turbine is installed

Heat transfer to exhaust gas is express below:

$$E_{exh} = Q_{exh} = M_{exh} \times Cp_{exh} \times (T_2 - T_1)$$

$$Q_{exh} = heat\ transfer\ rate\ to\ exhaust\ gas$$

$$Cp_{exh} = Specific\ heat\ capacity\ of\ exhaust\ gas$$

From the block diagram the efficiency of the improved power plant is given by the equations:

$$E_{out1} = \eta_{ME} \times E_{in} \qquad (10)$$

$$E_{out2} = a\,(1 - \eta_{ME}) \times E_{in} \times \eta_{EGT} \qquad (11)$$

The overall efficiency for one of the improved diesel engine is given by the following expression:

$$E_{out1} = \eta_{ME} \times E_{in}$$

$$E_{out2} = a\,(1 - \eta_{ME}) \times E_{in} \times \eta_{EGT}$$

The value of ‘a’ = fraction of lost energy from energy input contained in the exhaust gases.

$$a = \frac{Q_{exh}}{E_{in} - W_b} \qquad (12)$$

$$\eta_{ME\ EGT} = \frac{E_{out1} + E_{out2}}{E_{in}}$$

Calculation using the above formulas will show an overall increase in the system’s efficiency as a result of adding the exhaust gas turbine. Considering the efficiency of the plant when an exhaust gas boiler is installed as shown in fig. 3,

$$E_{out2} = a\,(1 - \eta_{ME}) \times E_{in} \times 0.7\eta_{st} \quad - \qquad (13)$$

$$E_{out3} = a\,(1 - \eta_{ME}) \times E_{in} \times 0.3\eta_{Hs} \quad - \qquad (14)$$

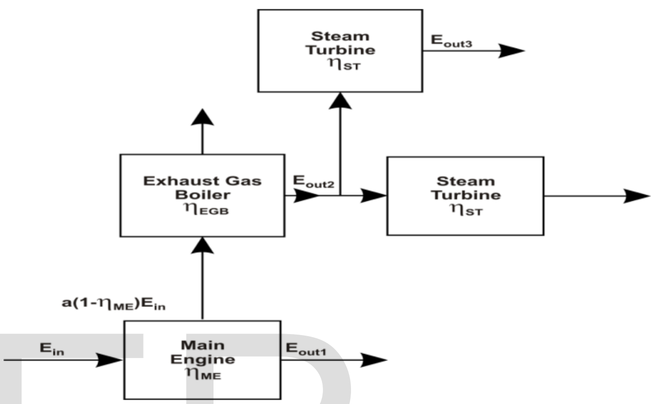

Fig. 3 The Overall plant efficiency when an exhaust gas boiler is installed.

$$\eta_{ME.EGB} = \frac{E_{out1} + E_{out2} + E_{out3}}{E_{in}} \qquad (15)$$

Considering, the efficiency of the plant when both exhaust turbine and exhaust gas boiler is installed.

From the energy block diagram shown in fig. 4

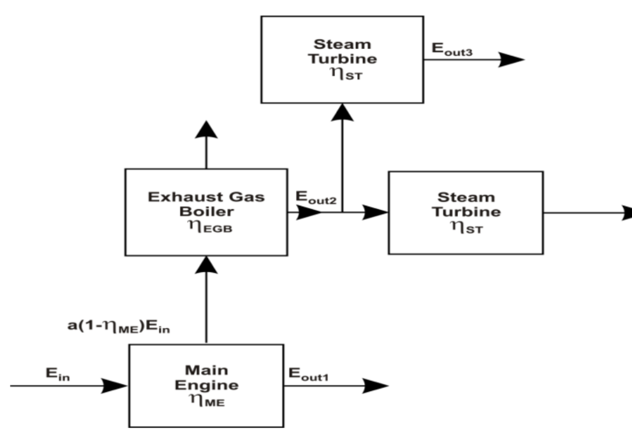

Fig. 4 The Overall plant efficiency when an exhaust gas boiler is installed.

$$E_{out1} = \eta_{ME} \times E_{in}$$

$$E_{out2} = a\,(1 - \eta_{ME}) \times E_{in} \times \eta_{EGT}$$

$$E_{out3} = (1 - \eta_{EGT})a\,(1 - \eta_{ME})E_{in} \times \eta_{EGB} \times 0.7$$

$$E_{out4} = (1 - \eta_{EGT}) a\ (1 - \eta_{ME}) E_{in} \times \eta_{EGB} \times 0.3\eta_{Hs}$$

$$\eta_{overall} = \frac{E_{out1} + E_{out2} + E_{out3} + E_{out4}}{E_{in}} \quad (16)$$

3.6 Cost analysis

When running the diesel engine with the installed exhaust gas turbine at 100% load the efficiency gain (η_{gain}) is given by the equation.

$$\eta_{gain} = \eta_{EGT} - \eta_{ME} \quad (17)$$

$$Savings = \eta_{gain} \times E_{in} \quad (18)$$

From the calculation above it shows that when the power plant is improved by the installation of exhaust gas turbine the efficiency of the power plant will increase.

As a result, there is increase in efficiency gain. The savings in total energy input also increases, resulting in the increase in the overall economy of the ship.

Amount of fuel savings per day:

$$V_f = \frac{M_F}{P_f} \quad (19)$$

$$M_F = \frac{SFC \times W_b}{3600} \quad (20)$$

For running the plant with diesel + exhaust gas boiler the efficiency gain (η_{gain}) is given by the equation:

$$\eta_{gain} = \eta_{ME.EGB} - \eta_{ME}$$

$$Savings = \eta_{gain} \times E_{in}$$

It is seen from the calculation above that when the power plant is improved by the installation of exhaust boiler the efficiency of the power plant will increase.

As a result, there is an increase in efficiency gain. Therefore, the savings in the total energy input also increases, resulting in the increase in the overall economy of the ship.

Amount of fuel savings per day:

For running the plant with diesel + exhaust gas turbine gas boiler the efficiency gain (η_{gain}) is given by the equation.

$$\eta_{gain} = \eta_{OV} - \eta_{ME}$$

$$Savings = \eta_{gain} \times E_{in}$$

It can be seen from the calculation above that when the power plant improved by the installation of exhaust boiler the efficiency of the power plant will increase.

As a result, there is increase in efficiency gain. Therefore, the savings in the total energy input also increases, resulting in the increase in the overall economy of the ship.

3.6 Economic Benefits Derived

For ships, the economic speed is that speed at which fuel cost represents half of the total operational cost. A rise in the fuel cost reduces the economic speed and there is a subsequent reduction in installed power.

Power consumed on these auxiliary machines at sea can be reduced by installation of a turbo-generator which is capable of using the energy recovered from the exhaust gas to produce steam for electricity generation which in turn reduces the load on the auxiliary generator.

The provision of large waste heat recovery boiler economizer to extract sufficient heat from the main engine exhaust gases to generate steam for heating purposes and supply a turbo-generator, offer positive fuel savings. The turbo-generator is a reliable low maintenance unit and replaces one of the diesel sets which would have otherwise been fitted. It can be used in ports. However, the combined plant will initially be more expensive but the extra cost is recovered by the fuel savings when in operation.

Experience has proved that at engine power as low as 6000kW, the sea loadings can be sustained from waste heat recovery plant and at large powers the potential exists up to 10-11% of power recovery (10);(16). The use of a simple system to provide auxiliary power and heating services for large powered ships is in practice but where the main engine power is marginal for this or where additional power or heat can be gainfully absorbed on board, dual pressure system will prove greater efficiency of small increase in cost.

Dual pressure system in spite of its operational high temperature and pressure offers fuel cost savings even where a ship may have to be operated at a reduced speed since steam output may be supplemented by burning heavy fuel oil. The installation of fresh water generators on board ships reduces the total running and operational cost of the vessel. It also solves the problem of fresh water shortage at sea, which could arise due to emergency situation resulting to unusual longer voyages. Hence, the heat recovery fresh water generation is therefore economically based since part of the energy used for the plant operation is gotten from the heat recovery systems.

4.0 NUMERICAL ANALYSIS

The efficiency of the plant at various load-100%, 80% and 50% will be considered at this stage. This will involve the efficiency of the main engine, efficiency of the main engine with exhaust gas turbine installed, efficiency of the main engine with exhaust gas boiler installed, efficiency of the main engine with both exhaust gas turbine and exhaust gas boiler installed.

4.1 Technical Data of the power plant

Sulzer RLB76 power plant data for propulsion used in this work at 100% operating load are as follows:

Diesel Engine Data

MCR:	-	19,080kW
Bore:	-	900mm

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Speed:	-	102rpm
Mean effective pressure:	-	14.31bar
Engine Power (P):	-	2,940kW/cyl
Specific fuel consumption:	-	0.182kg/kWh
No. of Cylinder:	-	9
Suction air temperature:	-	$32^{O}C$
Cooling water inlet temperature:	-	$32^{O}C$
Suction air relative humidity:	-	60%
Stroke:	-	1600mm
Net calorific value:	-	42,707kJ/kg
Charge air flow rate	-	146,900kg/h
Exhaust gas mass flow rate	-	146,900kg/h
Exhaust gas temperature at turbine outlet	-	$315^{O}C$
Temperature of exhaust gas after boiler	-	$170^{O}C$
Specific heat capacity of sea water	-	3.925kJ/kgK

4.1.1 Efficiency calculation at 100% Load

From the improved power plant of the case study vessel, calculation of the efficiency of the main engine, the efficiency of the gas turbine and the overall efficiency of the power plant will be carried out.

$Efficiency\ (\eta) = \frac{E_{out}}{E_{in}}$

$E_{out} = Energy\ out$

$E_{in} = Energy\ in = \ Q_{in} = M_f \times LCV$

But:

$Q_{in} = Rate\ of\ energy\ supplied$
$\quad by\ combustion\ of\ fuel.$

$LCV = Net\ calorific\ value = 42{,}707kJ/kg$

$M_f = Mass\ flow\ rate\ of\ fuel = \frac{SFC \times W_b}{3600}$

From the diesel engine data we have that;

$SFC = Specific\ fuel\ consumption = 0.182kg/kW\square$

$W_b = Brake\ power$

$= Maximum\ continuous\ rating\ (MCR) = 19.080MW$

$= 19{,}080kW$

$$M_f = \frac{0.182 \times 19{,}080}{3600}$$

$M_f = 0.9646kg/s$

$Q_{in} = 0.9646\ \times 42{,}707 = 41{,}195.172kJ/s$

$E_{out1} = MCR = 19{,}080kW$

Similarly;

$\eta_{ME} = \frac{E_{out1}}{E_{in}}$

$\eta = \frac{19{,}080}{41195.172}$

$\eta = 0.46 = 46\%$

Efficiency of the plant when an exhaust gas turbine is installed from the energy block diagram as shown in fig. 2a & 2b is adopted in the calculation.

Heat transfer to exhaust gas can be calculated as shown:

$E_{ex\square} = Q_{ex\square} = \ M_{ex\square} \times Cp_{ex\square} \times (T_2 - T_1)$

$M_{ex\square} = \frac{146{,}900}{3600}$

$M_{ex\square} = 40.81kg/s$

$Q_{ex\square} = \square eat\ transfer\ rate\ to\ ex\square aust\ gas$

$Cp_{ex\square} = Specific\ \square eat\ capacity\ of\ ex\square aust\ gas$

$\quad = 1.0145kJ/kgK$

$T_1 = Suction\ air\ temperature = 45^oC$

$T_2 = Ex\square aust\ gas\ outlet\ temperature\ of\ t\square e\ turbine$

$= 315^oC$

Therefore, the energy in ($E_{ex\square}$) will be,

$E_{ex\square} = Q_{ex\square} = \ M_{ex\square} \times Cp_{ex\square} \times (T_2 - T_1)$

$E_{ex\square} = Q_{ex\square} = \ 40.81 \times 1.0145 \times (315 - 45)$

$E_{ex\square} = Q_{ex\square} = \ 111{,}78.47115kJ/s$

The value for ‘a’ = fraction of lost energy from energy input contained in the exhaust gases.

$a = \frac{Q_{ex\square}}{E_{in} - W_b}$

$a = \frac{111{,}78.47115}{411{,}95.172 - 19{,}080}$

$a = 0.50$

From the block diagram the efficiency of the improved power plant is given by the equations:

$E_{out1} = \eta_{ME} \times E_{in}$

$E_{out2} = a\ (1 - \ \eta_{ME})E_{in} \times \eta_{EGT}$

Use efficiency of the exhaust gas turbine to be

Efficiency of exhaust gas turbine (η_{EGT}) = 0.35

The overall efficiency for one of the improved diesel engine is given by the following expression:

$E_{out1} = \eta_{ME} \times E_{in}$

Where,

$E_{in} = 41{,}195.172kJ/s$

$E_{out} = 19{,}080kW$

Put, $E_{out} = 19{,}080\ and\ \eta_{ME} = 046$ in the following expression below

$E_{out2} = a\ (1 - \ \eta_{ME})E_{in} \times \eta_{EGT}$

$E_{out2} = 0.50\ (1 - \ 0.46), 195.172 \times 0.35$

$E_{out2} = 3{,}892.944kW$

$\eta_{ME\ EGT} = \dfrac{E_{out1} + E_{out2}}{E_{in}}$

$= \dfrac{19{,}080 + 3{,}892.944}{41{,}195.172} = 0.56 = 56\%$

From the calculation, it is observed that when the exhaust gas turbine was installed, the overall efficiency increased from 0.46 to 056.

Considering fig. 3, the efficiency of the plant when an exhaust gas boiler is installed is analyzed as: 0

Take the efficiency of the exhaust gas boiler (η_{EGB}) to be 0.9 and that of the steam turbine (η_{ST})to be 0.32 and $a = 0.50$ ($from\ calculation$). From the energy block diagram of fig. 3:

$E_{in} = 41{,}195.172kJ/s$

$E_{out} = 19{,}080kW$

$E_{out2} = a(1 - \eta ME)E_{in}\eta EGBX0.7\eta_{ST}$

$E_{out2} = 0.50(1 - 0.46)41195.17X0.9X0.7X0.32$

$E_{out2} = 2242.336KW$

$E_{out3} = a(1 - \eta ME)E_{in}\eta EGBX0.3\eta_{HS}$

$E_{out3} = 0.50(1 - 0.46)41195.172X0.9X0.3X0.3$

$E_{out3} = 900.9384KW$

$\eta_{ME.EGB} = \frac{E_{out1}+E_{out2}+E_{out3}}{E_{in}}$

$= \frac{19080+2232.336+900.9384}{41195.172}$

$= 0.54$

$= 54\%$

From the calculation, we saw that when the exhaust gas turbine was installed the overall efficiency increased from 0.46 to 0.54

Considering, the efficiency of the plant when both exhaust turbine and exhaust gas boiler is installed.

From the energy block diagram fig. 3

$E_{in} = 41{,}195.172kJ/s$

$E_{out} = 19{,}080kW$

$E_{out2} = 3{,}892.944kW$

$E_{out3} = (1 - \eta_{EGT})a\ (1 - \eta_{ME})E_{in} \times \eta_{EGB} \times 0.7\eta_{ST}$

$E_{out3} = (1 - 0.35)0.50\ (1 - 0.46)41{,}195.172 \times 0.9 \times 0.7 \times 0.32$

$E_{out3} = 1{,}457.518kW$

$E_{out4} = (1 - \eta_{EGT})a\ (1 - \eta_{ME})E_{in} \times \eta_{EGB} \times 0.3\eta_{HS}$

$E_{out4} = (1 - 0.35)0.50\ (1 - 0.46)41{,}195.172 \times 0.9 \times 0.3 \times 0.3$

$E_{out4} = 585.61kW$

$\eta_{overall} = \frac{E_{out1} + E_{out2} + E_{out3} + E_{out4}}{E_{in}}$

$\eta_{overall} = \frac{19{,}080 + 3{,}892.944 + 1{,}457.518 + 585.61}{41{,}195.172}$

$= \frac{25{,}016.072}{41{,}195.172} = 0.6 = 60\%$

From our calculation we discover that when only the engine is running the efficiency was 0.46 and when exhaust gas turbine was added the efficiency increased from 0.46 to 0.56 and when another installation was made i.e. installation of the exhaust gas boiler to the gas turbine, the efficiency increased from 0.56 to 0.60. This shows that a further addition will still increase the efficiency of the power plant.

4.2.2 Efficiency calculations at 80% load

For diesel only

$\eta_{ME} = 0.46 = 46\%$

For diesel with exhaust gas turbine

$\eta_{ME.EGT} = 0.56 = 56\%$

For diesel with exhaust gas boiler

$\eta_{ME.EGB} = 0.54 = 54\%$

For diesel with both exhaust gas turbine and exhaust gas boiler (η_{OV})

$\eta_{OV} = 0.61 = 61\%$

4.2.3 Efficiency calculations at 80% load

For diesel only

$\eta_{ME} = 0.45 = 45\%$

For diesel with exhaust gas turbine

$\eta_{ME.EGT} = 0.55 = 55\%$

For diesel with exhaust gas boiler

$\eta_{ME.EGB} = 0.53 = 53\%$

For diesel with both exhaust gas turbine and exhaust gas boiler (η_{OV})

$\eta_{OV} = 0.60 = 60\%$

From the calculation it is observed that when only the engine is running the efficiency was 0.46 and when exhaust gas turbine was added the efficiency increased from 0.46 to 0.56 and when another installation was made i.e. installation of the exhaust gas boiler to the gas turbine, the efficiency increased from 0.56 to 0.60. This shows that a further addition will still increase the efficiency of the power plant.

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4.3 Presentation of Results

Table 4.0 Various Plants efficiencies at Different Operating Load.

Percentage Load(%)	Efficiency			
	A	B	C	D
100	0.46316	0.55766	0.53946	0.60726
80	0.46572	0.56074	0.54244	0.61061
50	0.45813	0.5516	0.5336	0.60066

From the table,
A= Main engine
B = Main engine with exhaust gas turbine
C = Main engine with exhaust gas boiler
D = Main engine with both exhaust gas turbine and exhaust gas boiler
Graphs were plotted using efficiency against different operating load (100%, 80% and 50%).

4.4 Graphical Representation of Results:

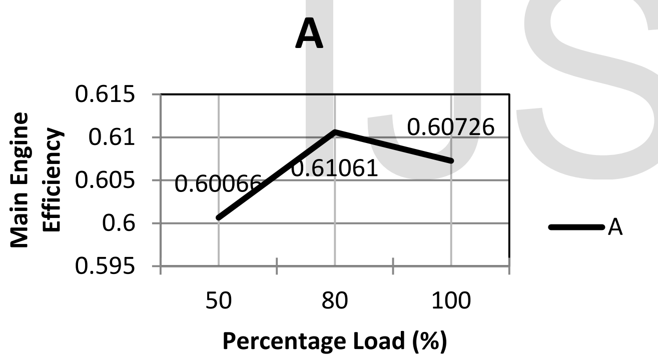

Fig. 4.1 Main Engine Efficiency against Percentage load for A

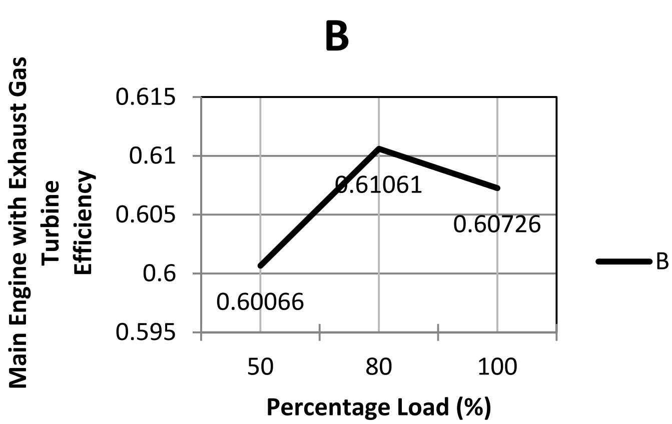

Fig. 4.2 Main Engine Efficiency against Percentage load for B

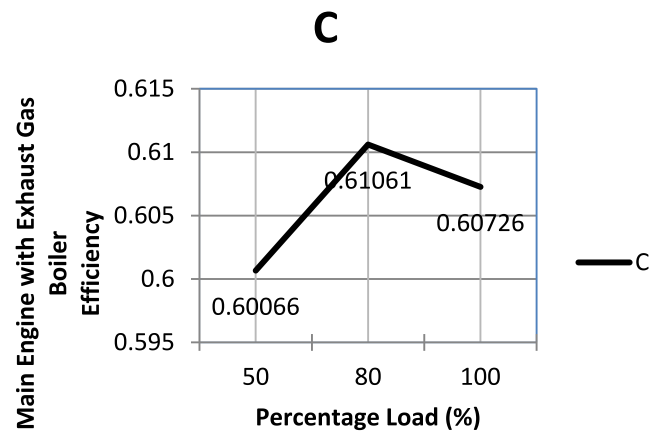

Fig. 4.3 Main Engine Efficiency with Exhaust Gas Boiler against Percentage load for C

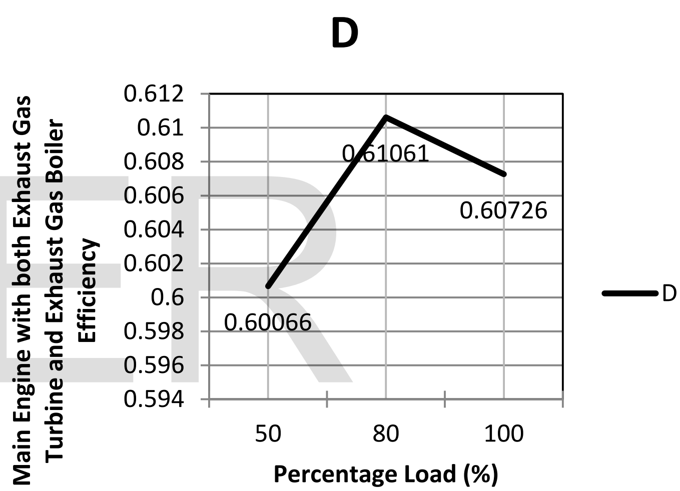

Fig. 4.4 Main Engine Efficiency with both Exhaust Gas Turbine and Exhaust Gas Boiler against Percentage load for D

From the graphical representations above, the greatest efficiencies of the various configurations of the plant as shown by the shape of the curve are attained at the 80% operating load condition. With the combined graph also, it can be deduced that when both the exhaust gas turbine and exhaust gas boiler are installed the efficiency becomes higher at 80% operating load condition.

Hence, the prospect of improvement of fuel efficiency for a chemical tanker vessel is viable via the installation of an exhaust gas turbine and an exhaust gas boiler to the main engine power plant of the vessel operating at 80% load condition.

CONCLUSION

In this research work, various ways of utilizing energy available in the exhaust gas which would have been wasted have been adequately discussed. Comprehensive configurations depicting the arrangement of various components to achieve a sustainable improvement of power plant efficiency have been described. This is imperative because exhaust gas constitute a latent source of energy which can be converted into useful energy for further utilization.

The results obtained based on this research work showed that: at an operating load condition of 100%, when the main engine only is running, the efficiency of the plant was gotten as 46%. With the installation of an exhaust gas turbine to the main engine, the plant efficiency increase by 10%. Improvement was made on the configuration of the power plant at 100%, with the installation of an exhaust gas boiler, the overall efficiency of the set-up increased to 60%.

At 80% operating load, the efficiency of the plant with only the main engine running is 46%. With the improvement in configuration by reason of addition of an exhaust gas turbine to the main engine, under this same load condition, the efficiency of the plant increased to 56%. Again, an exhaust gas boiler was further added to the plant configuration under the same operating load, and the overall efficiency increased to 61%.

At 50% loading condition, when only the main engine was running, the efficiency of the plant was determined as 45%. But when an exhaust gas turbine was added to the main engine at that same operating load, the efficiency increased to 55%. Upon a further improvement on the configuration of the power plant by reason of the installation of an exhaust gas boiler the overall plant efficiency increased to 60%. From the above, it can be inferred that the operating load condition that best optimized the performance of the power plant is the 80%; at which condition the overall efficiency of the plant is 61%. The higher the efficiency of any system within a limited margin the better the performance. This enhances a further attestation of the economic reality; since the overall efficiency of a system has an inverse relationship with the specific fuel oil consumption.

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