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A Study on the Use of a Stirling Engine Generator to Reduce Fuel Oil Consumption Onboard a Tanker Ship

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Abstract: This study investigated the possibility of using a stirling engine generator to reduce the fuel consumption onboard a tanker ship. It is intended to function as a waste heat recovery unit fitted in the exhaust gas line of the main propulsion diesel engine and is to operate by means of recovering waste heat energy from the exhaust gas and converting it to mechanical work to drive an electric generator. The electric power generated will be supplied to the ship's main switchboard to help supplement the electric power requirement onboard. Since the energy input to the Stirling engine will be from waste heat, it is expected to cause a reduction in fuel consumption for electric power generation without the adverse effects of an increased carbon footprint and greenhouse gas emissions. Using data from a 157209 gross tonnage tanker ship, an estimation of power which could be produced by the Stirling engine generator from the exhaust gas of the 25090 kW two-stroke main propulsion diesel engine at full speed condition has been calculated. Expected reduction of the ship's fuel consumption has also been presented.

Key words: Fuel oil, stirling engine, tanker ship, stroke, Malaysia

INTRODUCTION

Energy efficiency is a research area that is seen to help address environmental concerns related to global warming and sustainability, including issues posed by the depletion of fossil fuel reserves. For example, in the shipping industry, ship designers and operators have come up with various designs, concepts and means to help reduce the fuel consumption of international ships. Among the many innovations are slow steaming, cold ironing, voyage optimization, no ballast system, exhaust gas recirculation, use of low carbon fuels, use of LNG fuel, improved ship hull design, advanced rudder and propeller systems, sail and kite propulsion systems, fuel and solar cell propulsion systems and a whole lot more.

In this study, the the possibility of using a stirling engine generator to help reduce the fuel consumption onboard a tanker ship has been investigated. It is intended to function as a waste heat recovery unit fitted in the exhaust gas line of the main propulsion Diesel engine and operates by means of recovering waste heat energy from the exhaust gas and converting it to mechanical work to drive an electric generator. The electric power generated will then be directed to the ship's main switchboard to help supplement the electric power requirements onboard.

Since, the energy input to the Stirling engine will be from waste heat, it is expected to help reduce fuel consumption for electric power generation without adversely increasing the ship's overall carbon footprint and greenhouse gas emissions. As much, using data from a 157209 gross tonnage tanker ship, an estimation of the power produced by the Stirling engine generator from the exhaust gas of the 25090 kW two-stroke main propulsion Diesel engine at full speed condition has been calculated. The expected reduction of the ship's fuel consumption has also been calculated.

Furthermore, due to the potential appeal of the Sterling engine as the "engine of the future", a number of studies have already been conducted on its application. For example, in shipping, a notable study conducted by Hirata and Kawada (2005) suggests the Stirling engine capable of generating 700 kW of power from the exhaust of a 20000 kW diesel engine. The study also included the use of a Stirling engine as the prime mover for a large freight ship and a Stirling engine hybrid system for a smaller passenger vessel.

MATERIALS AND METHODS

The stirling engine: The stirling engine (Fig. 1) was invented and patented by Robert Stirling in 1816. It was initially designed as a prime mover to drive pumps, but due to many other applications that can be exploited from the engine's rotating output shaft, it has been primarily utilized throughout the years to drive electric generators.

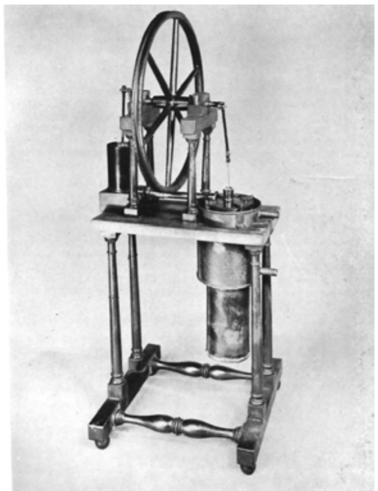

Fig. 1: Early design of a stirling engine

The engine is a closed-cycle regenerative heat engine which operates by cyclic compression and expansion of the working fluid at different temperatures, such that there is a net conversion of heat energy to mechanical work. The heat energy source for the engine is externally generated rather than by internal combustion as with the Otto cycle or Diesel cycle engines. In addition, some other positive attributes of the Stirling engine include quiet operation, high thermal efficiency, safe operation, ease of operation and the ability to function on any form of thermal energy; this would include both traditional combustion and nonpolluting sources, such as biomass, solar energy and geothermal energy (Pulkrabek, 2003; Karabulut *et al*., 1998; Minassians and Sanders, 2009).

The stirling cycle: The stirling cycle is a reversible thermodynamic cycle consisting of four phases (Fig. 2):

- Compression (isothermal compression)
- Heat addition (isovolumetric heating)
- Expansion (isothermal expansion)
- Heat rejection (isovolumetric cooling)

The stirling cycle has four phases which constitute one complete cycle and is completed in a single 360° revolution (Biwa *et al*., 2008).

The engine itself operates by moving the working fluid back and forth between hot and cold heat exchangers within a closed looped system, often with a regenerator between the heater and cooler as shown in Fig. 3. The hot heat exchanger is in thermal contact with an external heat source, e.g., a fuel burner; the cold heat exchanger is in thermal contact with an external heat sink,

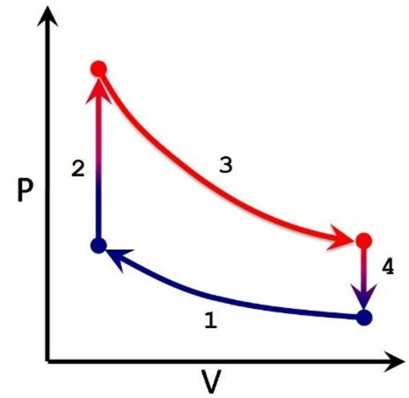

Fig. 2: Ideal air-standard stirling cycle

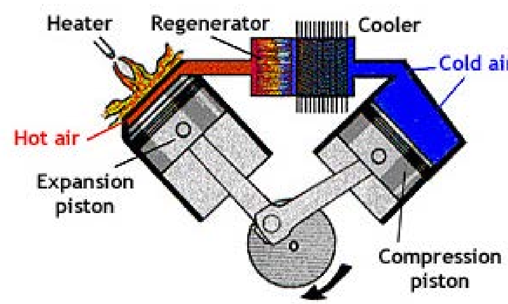

Fig. 3: An alpha configuration stirling engine

e.g., air fins. A change in input gas temperature causes a corresponding change in gas pressure while the motion of the piston causes the gas to be alternately expanded and compressed.

The gas follows the behaviour prescribed by the gas laws that describes how gas pressure, temperature and volume are related. Accordingly, when the gas is heated and, because it is in a sealed chamber, the pressure rises and this then acts on the expansion piston to produce a power stroke. Furthermore, when the gas is cooled on the heat rejection phase the pressure drops facilitating less work needing to be done by the piston to compress the gas on the return stroke, thus yielding a net power output.

The three basic types of stirling engines that are distinguished by the way they move the air between the hot and cold areas are shown in Fig. 4 (Kongtragool and Wongwises, 2003):

- The alpha configuration has two power pistons, one in a hot cylinder, one in a cold cylinder and the gas is driven between the two by the pistons; it is typically in a V-formation with the pistons joined at the same point on a crankshaft

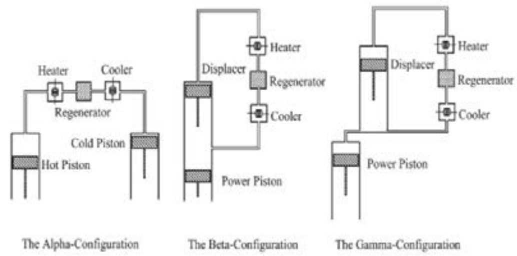

Fig. 4: Basic stirling engine configurations

- The beta configuration has a single cylinder with a hot end and a cold end, containing a power piston and a 'displacer' that drives the gas between the hot and cold ends. It is typically used with a rhombic drive to achieve the phase difference between the displacer and power pistons but they can be joined 90° out of phase on a crankshaft
- The gamma configuration has two cylinders: one containing a displacer with a hot and a cold end and one for the power piston; they are joined to form a single space with the same pressure in both cylinders; the pistons are typically in parallel and joined 90° out of phase on a crankshaft

Stirling cycle efficiency For an air-standard stirling cycle, the amounts of heat added and rejected per unit mass of working fluid are as follows (Howell and Bannerot, 1977):

$$Q_{Added} = x \times C_v \times (T_H - T_C) + R \times T_H \times \ln V_1/V_2 \quad (1)$$

$$Q_{Rejected} = x \times C_v \times (T_C - T_H) + R \times T_C \times \ln V_2/V_1 \quad (2)$$

Where x is the fractional deviation from ideal heat regeneration (i.e., x = 1 for no heat regeneration and x = 0 for ideal heat regeneration) , C_v the specific heat capacity at constant volume in Jkg^{-1}°K, T_H the source temperature in the Stirling cycle in °K, T_C the sink temperature in °K, R being the gas constant in Jkg^{-1}°K, V_1 and V_2 are specific volumes of the constant-volume regeneration processes of the cycle in m^3 kg^{-1} and V_2/V_1 is the volume compression ratio. The Stirling cycle efficiency can be determined by Howell and Bannerot (1977):

$$E_S = \Sigma Q/Q_{Added} \quad (3)$$

which can also be expressed as:

$$E_S = [(T_H - T_C) \times R \times \ln V_1/V_2] / [x \times C_v \times (T_H - T_C) + R \times T_H \times \ln V_1/V_2] \quad (4)$$

simplified in the form:

$$E_S = (1 - T_C/T_H) / [1 + (x \times C_v/R \times \ln V_1/V_2) \times (1 - T_C/T_H)] \quad (5)$$

It can be seen from the above equations that the Stirling cycle efficiency is greatly influenced by the source, sink temperatures and regenerator effectiveness.

RESULTS AND DISCUSSION

A 157209 gross tonnage tanker ship under the Bunga Kasturi class of Malaysian International Shipping Corporation Berhad (MISC) was selected for this study. The ship's principal particulars are shown in Table 1.

The tanker ship is fitted with one unit of Hitachi B&W (7S80MC) two-stroke main propulsion Diesel engine with a maximum continuous output of 25090 kW. Data taken when the ship is running at full speed is shown in Table 2.

The intention for the stirling engine in this study is to function as a waste heat recovery unit and at the same time serve as a prime mover to drive an electric generator, hence, it is termed 'Stirling engine generator'. It is to be situated in the exhaust gas line of the main propulsion Diesel engine. An illustration of the tanker ship's main propulsion Diesel engine exhaust gas system with the Stirling engine generator integrated into it is shown in Fig. 5.

When the tanker ship runs at full speed, the heat energy in the the exhaust gas produced by the main propulsion Diesel engine is maximum. Some amount of this waste heat energy will be recovered and serve as the heat input energy to the Sterling engine generator. The electric power generated from the recovered waste heat is then supplied to the ship's main switchboard as shown in Fig. 6 to help supplement the electric power requirements onboard.

Ship's electrical power supply: The tanker ship employed in this study was equipped with three diesel engine generators to generate electrical power supply. When the ship runs at full speed, a 1020 kW diesel generator engine, with the specifications shown in Table 3, supplies all the necessary electrical power requirements.

Heat energy input to the sterling engine: As a waste heat recovery unit, the heat input to the stirling engine mainly depends on the main propulsion diesel engine exhaust gas heat which is determined by the heat energy input of the fuel. A typical heat energy balance of the tanker ship's two-stroke main propulsion diesel engine is shown in Fig. 7 (Hirata and Kawada, 2005; Woodyard, 1984; Kuiken, 2012). The heat energy input to the main

Table 1: Ship's principal particulars

Particulars	Values
Length overall	329.99 m
Length between perpendiculars	316.00 m
Breadth moulded	60.00 m
Depth moulded	29.70 m
Draft loaded moulded	19.20 m
Deadweight	257 803 ton
Gross tonnage	157 209 ton
Net tonnage	99 808 ton
Speed	15.5 knot

Table 2: Main propulsion diesel engine data

Variables	Values
Main shaft revolution (min^{-1})	79.6
Brake power (kW)	22750.0
Specific fuel consumption g $kW \times h^{-1}$	173.8
Daily Consumption (t day^{-1})	94.9
Fuel oil calorific value (MJ kg^{-1})	42.7
Exhaust gas cylinder outlet (°C)	322.9
Turbocharger outlet (°C)	265.0

Table 3: Diesel engine generator data

Parameters	Values
Specific fuel consumption (g $kW \times h^{-1}$)	195.000
Rated output (kW)	1020.000
Revolution (rpm)	900.000
No. of cylinder	6.000
Cylinder bore (mm)	210.000
Cylinder stroke (mm)	290.000
Mean effective pressure (MPa)	2.257

Diesel engine generator: Yanmar 6N21AL-GV, Vertical, single action, 4- cycle, direct-injection water-cooled Diesel engine with turbocharger and air cooler

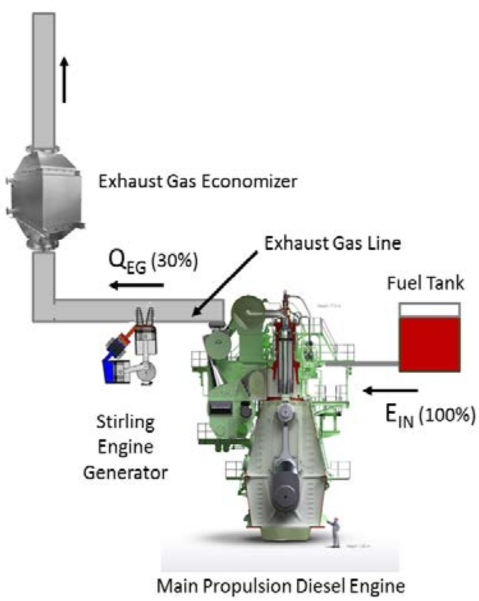

Fig. 5: Main propulsion diesel engine exhaust gas system with stirling engine generator

propulsion diesel engine can be calculated using the equation:

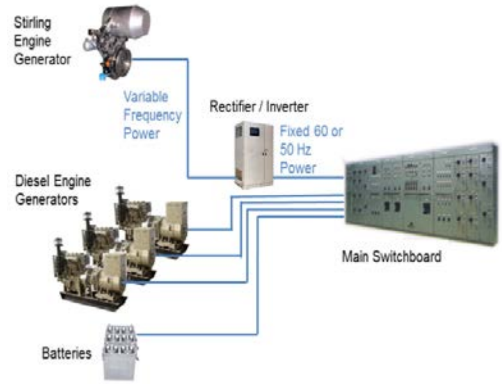

Fig. 6: Ship's electric power plant layout

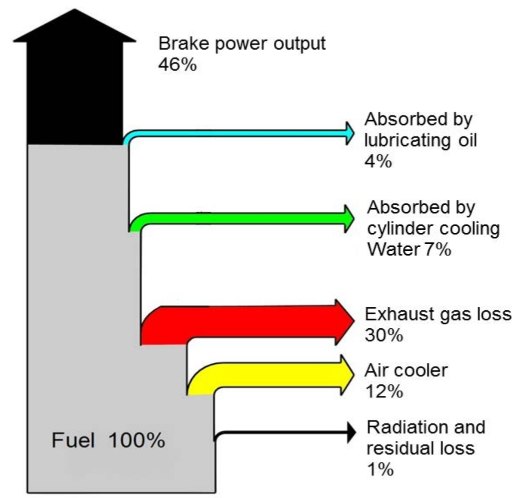

Fig. 7: Two-stroke diesel engine heat balance

$$E_{IN} = SFC \times BP \times CV \quad (6)$$

where E_{IN} is in kilowatts or kJ/s, SFC is the specific fuel consumption in g/kW•h, BP is the brake power in kilowatts and CV is the fuel oil calorific value in $kJkg^{-1}$. As this heat energy input is further converted to mechanical work, around 30% of it will be converted and transferred to exhaust gas heat (Hirata and Kawada, 2005). In simple mathematical form, the exhaust gas heat Q_{EG} may be found as follows:

$$Q_{EG} = 30\% \ E_{IN} \quad (7)$$

A more accurate way to determine Q_{EG} is by the equation:

$$Q_{EG} = m \times C_p \times \Delta T \quad (8)$$

Where:

m = The mass flow rate of the exhaust gas in kg/s

C_p = The specific heat of exhaust gas which is 1.04 kJ kg^{-1} °K (Ramesh and Kalyani, 2012)

Table 4: Values of empirical factors in Malmo formula (and Hooper, 1983)

Factors	Range of values
E_H	0.85-0.95
E_M	0.75-0.90
K_C	0.55-0.88

ΔT = The temperature difference between the stack temperature and a value which is higher than the dew point temperature (Reader and Hooper, 1983)

In a more rigorous approach, corrections must be taken into account for the actual exhaust gas composition (increased H_2O and CO_2, decreased O_2).

The heat input to the Stirling engine, Q_{SE} is estimated as 21% of the exhaust gas heat (Hirata and Kawada, 2005) and may be written in the form:

$$Q_{SE} = 21\%\ Q_{EG} \quad (9)$$

Stirling engine power output calculation: A simple formula using the concept of brake engine efficiency to determine the Stirling engine power output is expressed by the equation:

$$P_S = E_{BT}\Delta Q_{SE} \quad (10)$$

where P_S is the shaft power output in watts and E_{BT} is the brake thermal efficiency. Another is the Malmo formula (Reader and Hooper, 1983) by the equation:

$$P_S = E_H \times E_M \times K_C \times E_S \times Q_{SE} \quad (11)$$

Where:

E_H = The heat source efficiency
E_M = The mechanical efficiency
K_C = The stirling coefficient
E_S = The stirling cycle efficiency

The values of these empirical factors are shown in Table 4. Other means to calculate the stirling engine power output is by using the Schmidt formula, West formula or the Beale number concept. However, their use would not be possible in this investigation due to the specific Stirling engine informations they require which were not presented nor covered in this study.

Using the data of the tanker ship when running at full speed (Table 2), the heat energies necessary to estimate the stirling engine power output are calculated and are shown as calculated heat energies of the tanker ship:

- Heat energy input to main engine (Eq. 6)
- E_{IN} = 46 898.2 kW
- Exhaust gas heat (Eq. 7)
- Q_{EG} = 14 069.5 kW
- Heat input to sterling engine (Eq. 9)
- Q_{SE} = 2954.6 kW

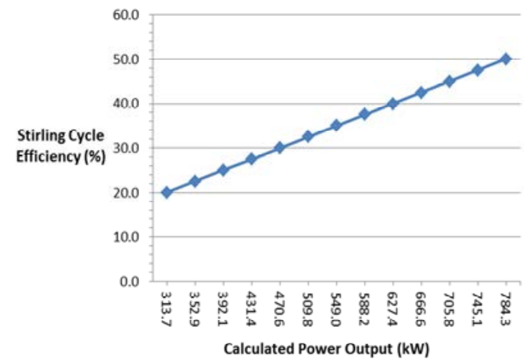

Fig. 8: Calculated stirling engine power output

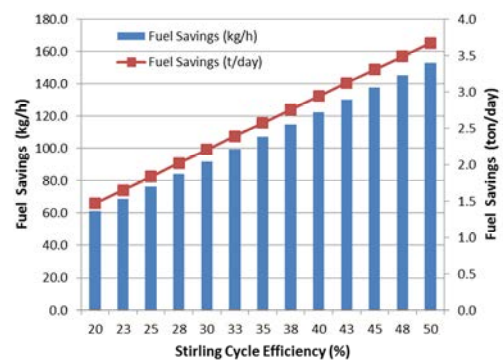

Fig. 9: Calculated fuel savings

Since, no specific model of the Sterling engine has been identified nor selected in this study and some of the engine details and specifications are necessary to determine the stirling cycle efficiency as presented in (Eq. 5), a typical cycle efficiency range of 20-50% (Thombare and Verma, 2006) was considered to calculate the engine power output using Eq .11. With the heat input Q_{SE} from Table 5 and taking the mid-range values of E_H, E_M and K_C in Table 4, the sterling engine power output is plotted and shown in Fig. 8.

As the stirling engine generator supplements electrical power to the main switchboard which feeds all the electrical machinery consumers onboard, the electrical load of the diesel engine generator is expected to be reduced since it is shared by the Stirling engine generator, being connected in the same power grid. Therefore result in reduction of the amount of fuel required for electrical power generation. Assuming the same electric generator efficiency for both the Stirling and Diesel engines and using the diesel engine generator specific fuel consumption in Table 3, reduction of fuel consumption or fuel savings is calculated and plotted in Fig. 9.

CONCLUSION

The benefits of fitting a Stirling engine generator on the tanker ship employed in this study may be realized in terms of power generation and fuel savings from waste heat energy. Even with the lowest projected cycle efficiency of 20%, a considerable amount of fuel savings of 1.5 ton/day may be achieved. Considering the quantity of fuel that could be saved by a tanker ship which usually spends most of its time at sea, the gains are substantial. Other benefits it bring includes operating a more environmental friendly and energy efficient ship, in line with the requirements of the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. Actual fuel savings may even be greater since modern Stirling engine generator designs have greatly improved through the years. Improved exhaust line insulation may also further increase the cycle efficiency due to increased heat energy input to the Stirling engine generator.

However, since the Stirling engine generator is to be fitted in the exhaust line between the main propulsion Diesel engine and Exhaust Gas Economizer (EGE) one drawback is the reduction of waste heat energy input to EGE. This will require increased heat energy input to the auxiliary boiler from the fuel burners to generate steam causing increased boiler fuel consumption. Another is the possible backflow pressure created in the exhaust line which may affect the main propulsion Diesel engine performance. These are areas which may be considered for further study in the future including the integration of the Stirling engine generator into the system of other types of ship.

NOMENCLATURE

x = The fractional deviation from ideal heat regeneration
Cv = The specific heat capacity at constant volume in J/kg·°K
TH = The source temperature in the Stirling cycle in °K
TC = The sink temperature in °K
R = The gas constant in J/kg°K
V1 and V2 = Specific volumes of the constant-volume regeneration processes of the cycle in m3/kg
V2/V1 = The volume compression ratio
EIN = Kilowatts or kJ/s
SFC = The specific fuel consumption in g/kWh
BP = The brake power in kilowatts
CV = The fuel oil calorific value in kJ/kg
EH = The heat source efficiency
EM = The mechanical efficiency
KC = The stirling coefficient
ES = The stirling cycle efficiency

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