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Improving The Efficiency Of Marine Power Plant Using Stirling Engine In Waste Heat Recovery Systems

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Abstract:
Energy seems to be the subject at the heart of many of the greatest issues and debates facing the world today. Global warming is a huge issue that promises to change the face of the planet in unimaginable and irreversible ways. This alone is considered as a major driving factor in development of energy efficient technologies for various purposes including marine transportation for sustainable development. The predominant source of power in a ship is the Diesel engine which has evolved as a highly efficient means of generating necessary power for propulsion and auxiliary uses However it is widely recognized that about 30% of the total energy converted in a Diesel engine is rejected in the exhaust gas.. On large ships some of this heat is recovered partly using exhaust gas boilers. However on a majority of small ships or on large ships on short voyage durations, there is no or limited mechanism to recover this energy. The recently mandated energy efficiency design index (EEDI) has the provision to deduct the power produced from any energy saving device thereby giving credit to the design. While some of the energy saving devices being contemplated, use wind and solar power, it is being recognized that some of the energy from the engine exhaust gases and cooling water can still be tapped to generate power resulting in improved energy efficiency of the plant.

One of the ways of utilizing waste heat without conversion to steam is to use a Stirling engine. A Stirling engine requires only an external heat source (such as external combustion chamber or waste heat) for its operation. For marine use this engine could be utilized to generate some amount of power from the exhaust gas. This paper advocates the use of heat balance studies for improving the efficiency of the marine power plant. An estimation of the power which could be generated from a Stirling engine is presented based on estimation of the power which could be produced from the exhaust gas of a high speed (560 KW) propulsion engine and expected savings in fuel.

1.Introduction

Most of the ships today use Diesel engines for propulsion and for producing electrical power. The points of heat rejection form diesel engines which are normally considered to have practical potential for waste heat recovery are the exhaust and the jacket coolant. Heat is usually recovered from the exhaust gas of a main propulsion engine of large ocean liners in the form of steam as it is the most preferred medium for fuel and cargo heating including heating required for domestic services. Heat from jacket cooling water is usually recovered in the form of fresh water generation. Waste heat recovery from auxiliary engines was not considered economical and practical except in case of large passenger ships or ships operating with a Diesel electric propulsion system.

The debate at the IMO and other international forums on the green house effect of emissions from shipping has changed the outlook of many with respect to looking at various options for enhanced waste heat recovery as a means of improving the overall efficiency of the ship. The Energy Efficiency Design Index (EEDI) have mandated that new constructions with conventional Diesel Engine power plant as applicable to few ship types and sizes will need to demonstrate improved energy efficiency from an established baseline at the time of delivery of the vessel. This has led all the shipping industry to think on various options available for meeting the targets.

2. EEDI Formula

The calculation of EEDI is based on the following

$$EEDI = \frac{CO_2\ Emissions}{Benifit\ to\ Society}$$

$$EEDI = \frac{CO_2\ Emissions}{Transport\ Work} \qquad (1)$$

With respect to power plants using hydrocarbon fuels for combustion as a means of generating power this can be redefined as

$$Efficiency\ Index = \frac{E_1 - (f_2E_2 + f_3E_3)}{Transport\ Work} \qquad (2)$$

Where E_1 is the Energy generated using fossil fuels, E_2 is the energy recovered from losses in the generation process and E_3 is the energy generated using renewable energy sources, f_2 and f_3 are the availability factors. It is widely recognized that the availability factor for extracting power from renewable energy sources such as wind and solar power is less than unity and for waste heat recovery systems it is unity. Therefore this becomes an important area in improving energy efficiency.

3.Waste Heat Recovery (WHR) Systems In Large Ships

Traditionally the primary objective of WHR systems was generation of steam for fuel heating purposes. However some of the ships have incorporated additional Steam turbine generators for meeting the sailing load. Recently renewed interest in WHR systems coupled with the advancement in Turbochargers and advances in material ethnology have led to the development of advanced WHR systems involving a combination of exhaust gas turbo alternators and steam turbo alternators. These have resulted in various configurations such as Thermo efficiency System (TES MAN) [1] or High Efficiency WHR system [2] (Wartsila). The amount of power generated from such WHR systems is around 5% of the energy input from the fuel. Both the systems referred to above have claimed an overall plant efficiency of around 54% from around 49% .

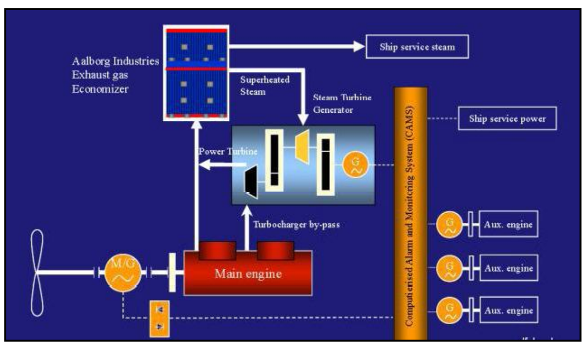

Figure 1:Typical enhanced WHR system : Alfa Laval

As shown in Figure 1, at over 50% load, part of the exhaust gas is diverted to a power turbine while the rest is sent to the turbocharger. The exhaust outlet form the turbochargers as well as the power turbine then pass through a high efficiency exhaust gas boiler producing steam to power a steam turbo alternator. These methods are finding increased acceptance as the ships machinery spaces have the space and the additional equipment weight does not impose a serious restriction on the Dwt or safety of the sh ip.

4.Waste Heat Recovery In Small Vessels And Vessels Operating In Coastal Trade

In small ships the luxury of either having space for such mechanisms is generally not available. Other ships generally operating in coastal trade do not generally use fuels which require heating due to their trading pattern hence do not recover energy from exhaust systems. As shown in Figure 2, the second IMO GHG study conducted in 2009 [3] has estimated nearly 80 million tons per year as the worldwide fuel consumption on these vessels. Taking an average of 200g/Kwh as the Specific fuel consumption for the engines in this category and an average operating days of 200 /year, works out to nearly 1 ton of fuel per KW of energy recovered /year. Considering CO_2/Fuel ratio of 3.1, this works out to a saving of 3.1 tons of CO_2/KW of energy produced. This itself may be considered as an incentive to develop WHR systems in small vessels.

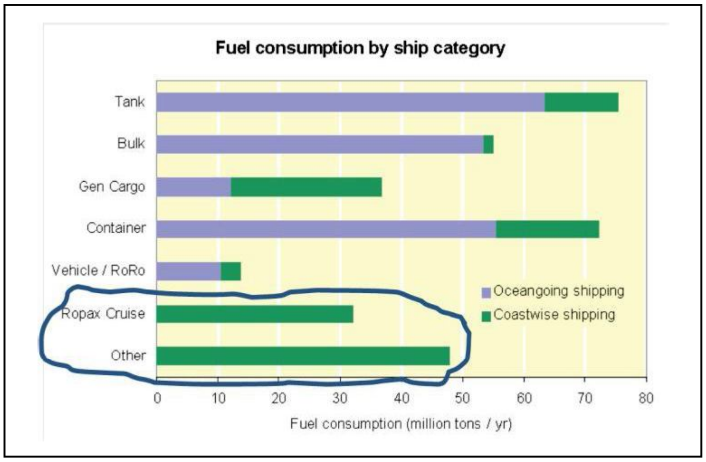

Figure 2: Annual Fuel Consumption according to 2nd IMO GHG Study

While EEDI as a regulatory mechanism for improving energy efficiency is currently not extended to all types of ships the quantum of fuel consumption as a whole itself justifies mechanisms to be developed to extract as much as possible from waste heat of these vessels. If technologies could be developed / adapted to this category of vessels, the number of installations required may eventually lower the production costs and hence the prices. While considering waste heat recovery options on small vessels, the constraints of space and weight will determine the adaptability of the technology along with the price and hence the traditional methods of WHR using steam as a conversion medium may not be an acceptable mechanism. Additionally the amount of energy which can be recovered, will depend on the power of the main and auxiliary engines which effectively determines the amount of heat energy available in the exhaust gas. Therefore it is imperative that a heat balance study is carried out to determine the amount of heat content in the exhaust gas. This can be estimated from the data sheet of the engine manufacturer.

The quest for energy conservation along with energy generation using renewable energy sources from land based requirements have led to developments in distributed generation, cogeneration and combined heat and power (CHP) technologies, some of which utilize the waste heat or heat from solar collectors to generate power without conversion to steam. Two of the most promising technologies are

- Thermoelectric power generation
- Stirling engine
-

5. Thermoelectric Power Generation (TEG)

Thermoelectric power generators are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). Their typical efficiencies are around 5-10%. Older Seebeck-based devices used bimetallic junctions and were bulky while more recent devices use bismuth telluride (Bi_2Te_3) or lead telluride (PbTe) semiconductor p-n junctions and can have thicknesses in the millimeter range. These are solid state devices and unlike dynamos have no moving parts, with the occasional exception of a fan. With the advent of nanotechnology there has been renewed interest in this area to develop new thin film structures which resist high temperatures and generate power. Figure 3, shows the basic principle in thermoelectric power generation.

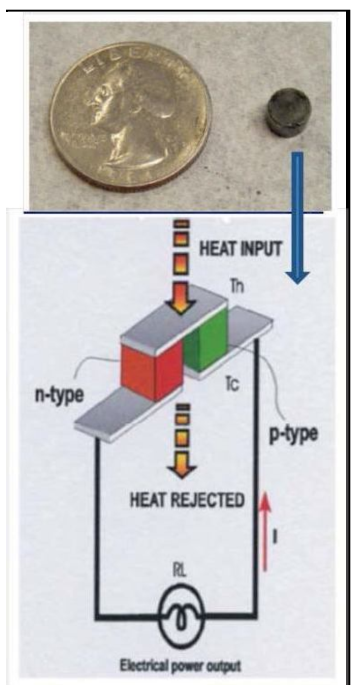

Figure 3: A Thermo Electric Device.

In application of this technology for WHR in marine application, University of Maine and Maine Marine Academy have tested in the laboratory and conducted field tests on a fishing boat. They have also simulated and demonstrated a small scale diesel electric propulsion system while utilizing a 180 Watt TEG in parallel with a 27KW Diesel Generator [4] in a converted lifeboat. More research is being carried out by University of Maine and University of Hokkaido [5] to improve the power output and efficiency. It has been reported that thermoelectric generators can generate a power output of 160 KW when working on a exhaust gas temperature of 180-300 deg C with a mass flow rate of 60000Nm3/hr [6].

6. Stirling Engine

The basic principle of any engine is to convert heat to mechanical work. The engines follow any of the ideal thermodynamic cycles. The Stirling cycle dates even prior to the Carnot cycle. The Stirling engine was first invented in 1816 and the Carnot cycle was proposed in 1824. In the Stirling cycle, heat from an outside source is transferred to an enclosed quantity of working fluid, generally an inert gas (Helium) or even Air; and drives it through a repeating sequence of thermodynamic changes. By expanding the gas against a piston and then drawing it into a separate cooling chamber for subsequent compression, the heat from external combustion can be converted to mechanical work and then, in turn, to electricity. The unutilized heat is rejected to a heat sink thereby completing the thermodynamic process. The Cycle consists of two constant volume and two isothermal processes as indicated in figure 4

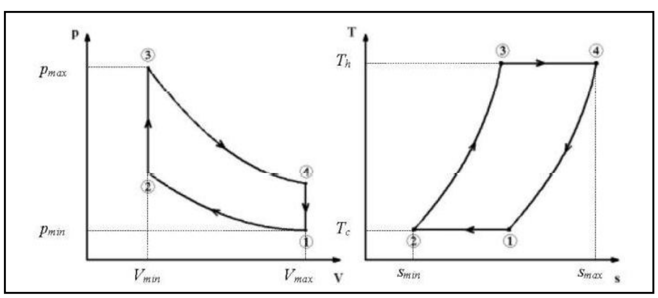

Figure 4: The Stirling Cycle

It can be proved that the efficiency of an ideal Stirling cycle is equal to that of Carnot cycle between operating between the same source and sink temperatures.

The Stirling engines were simple and safe to operate, ran almost silently on any combustible fuel. In 1853, john Ericsson built a large Marine Stirling Engine having four 4.2 m, diameter Pistons with a stroke of 1.5 m producing a brake power of 220 KW at 9 RPM. The first era of Stirling engines was terminated due to rapid advances in Internal combustion engines, steam turbines and electric motors. In 1930's Phillips company took up interest in the development of these engines to power their radio sets in remote areas where electrical power was not available.

Renewed interest in using renewable energy low temperature differential (LTD) sources such as Solar, biomass and landfill gas and as means of supplying power to rural and remote areas led to increased advances in Stirling engine technology aided by development of advanced materials and theoretical analysis models. Extensive literature review has been documented on solar powered and LTD Stirling engines [7]. In India a 1 & 1.9 KW solar powered Stirling engine has been developed with an efficiency between 5.5 to 5.7% [8]. A compact power generating Stirling engine working on a wide variety of solid fuels including biomass as local power source has been reported to be designed and analysed [9].

7.Principle Of Operation

The Stirling engine consists of two Pistons, One connected to the heat source and another to the sink. Both the pistons are connected externally by linkages and are known as Kinematic type of Stirling Engines. There are three configurations usually available, termed as Alpha, Beta and Gamma. The Principle of operation is described with an Alpha configuration as shown in Figures [10] 5-8.

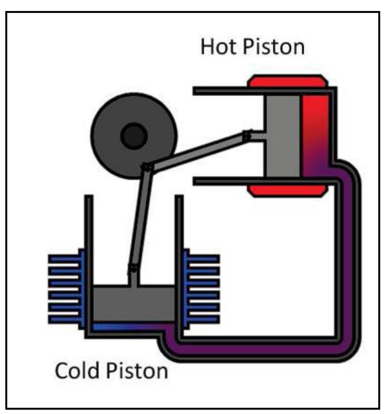

Figure 5

Almost all the gas is now in the hot cylinder and heat is added raising its pressure (2-3 in Figure 4). The volume of the gas being kept constant due to the position of the pistons. The gas reaches is at its minimum volume and maximum pressure (Position 3 in Figure 4), and starts expanding.

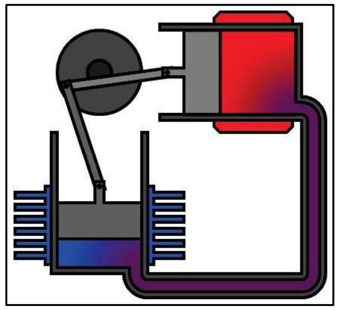

Figure 6

The Gas will now expand in the hot cylinder, driving the hot piston in its power stroke. As the cylinder is in constant contact with the heat source the expansion is isothermal and heat is continuously added in this stroke. The expansion continues in the cold cylinder, which is 90° behind the hot piston in its cycle, extracting more work from the hot gas. (3-4 in Figure 4).

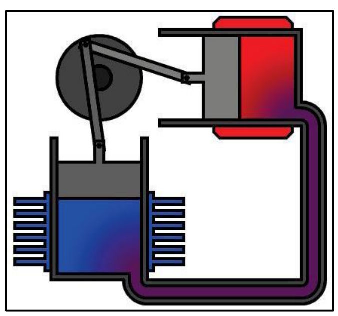

Figure 7

As the gas expands, its pressure drops and the hot piston on its return stroke pushes all the gas to the cold piston. Almost all the gas is now in the cold cylinder and cooling continues at constant volume resulting in further drop in pressure. (4-1 in Figure 4).

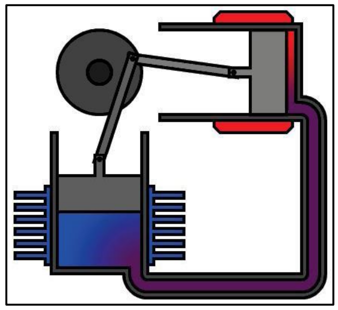

Figure 8

The cold piston, powered by flywheel momentum (or other piston pairs on the same shaft) starts compressing the gas which moves to the hot cylinder for heating (1-2 in Figure 4). As the heat is being continuously removed from the gas the process is isothermal starting the cycle again.

8.Effect Of Regenerator.

The Principle of the Stirling engine described above is essentially that of a hot air engine. Robert Stirling in his invention in 1816 added a crucial element known as the regenerator which improved the thermal efficiency of the engine and is now an essential element in all types of engines.

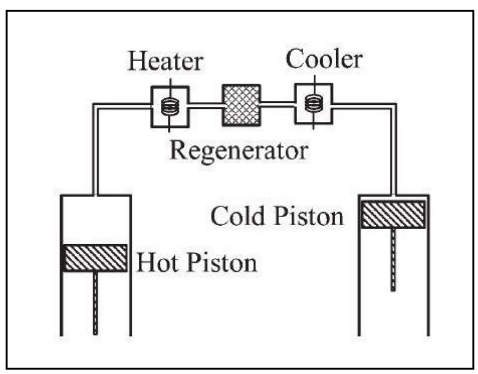

Figure 9: Positioning Of The Regenerator

As shown in Figure 9, the regenerator is an internal heat exchanger and temporary heat store placed between the hot and cold spaces such that the working fluid passes through it first in one direction then the other. Its function is to retain within the system that heat which would otherwise be exchanged with the environment at temperatures intermediate to the maximum and minimum cycle temperatures, thus enabling the thermal efficiency of the cycle to approach the limiting Carnot efficiency defined by those maximum and minimum cycle temperatures.

The primary effect of regeneration in a Stirling engine is to increase the thermal efficiency by 'recycling' internal heat which would otherwise pass through the engine irreversibly. As a secondary effect, increased thermal efficiency yields a higher power output from a given set of hot and cold end heat exchangers. It is these which usually limit the engine's heat throughput. In practice this additional power may not be fully realized as the additional "dead space" (un swept volume) and pumping loss inherent in practical regenerators reduces the potential efficiency gains from regeneration.

9.Kinematic & Free Piston Stirling Engines

In Kinematic engines the pistons are connected externally to act out of phase to the crank for is working. In order to achieve higher power the mean cycle pressure would need to be increased which imposes difficulty in sealing the working fluid through these connections. This has led to the development of free Piston Stirling engines which have revolutionized the development of engines using low temperature differentials. The Free piston engine eliminated the need for external linkages. The Oscillating piston can be connected to a linear alternator in the same sealed space through which power can be generated. The whole unit is hermitically sealed giving a scope for increased mean pressure. This also facilitates the use of lighter than air gases (such as Helium) as the working fluid to improve the performance. The lighter gases have lower viscosity, resulting in less flow losses, as well as a greater specific heat capacity, *cp*, and a higher gas constant value, *R* which increases the heat carrying capacity and better thermal efficiency.

10.Application of Stirling Engines in Ships

The quest for increased submerged endurance in small submarines led to the development of Stirling engines in Marine use. The Stirling-cycle engine forms the basis of the first Air Independent Propulsion system to enter naval service in recent times. The Swedish builders, Kockums Naval Systems, tested a prototype plant at sea in 1989, and today, three Swedish Gotland-class boats are each fitted with two adjunct, 75 kilowatt Stirling-cycle propulsion units that burn liquid oxygen and diesel fuel to generate electricity for either propulsion or charging batteries within a conventional diesel-electric plant. The resulting underwater endurance of the 1,500-ton boats is reported to be up to

14 days at five knots. Large power Stirling engines are difficult to develop as the sizes required for effective heat transfer from heat source to the working fluid become very large. Hirata Et.al have shown that a 20,000 Kw equivalent Stirling engine for propulsion needs of a large cargo ships needs to be at least twice the length of a comparative Diesel Engine which makes its application prohibitive for propulsion applications at present [11]. However in the range of 2-5 KW its compactness and ease of operation makes it attractive for use as a WHR unit to charge batteries in small ships, which can later be used to supply power during harbour thereby eliminating the release of exhaust emissions in harbour areas..

11.Estimation Of Energy From Exhaust Gases

The energy produced due to combustion of fuel in an engine is partly converted into work and the rest is lost. Energy supplied to the engine is the heat value of the fuel consumed.

Two main parts of heat not available for work from the internal combustion engine are

- The heat carried away by Exhaust gases
- The Cooling Medium

The generalized form of heat balance for external combustion engine is shown in Figure 10

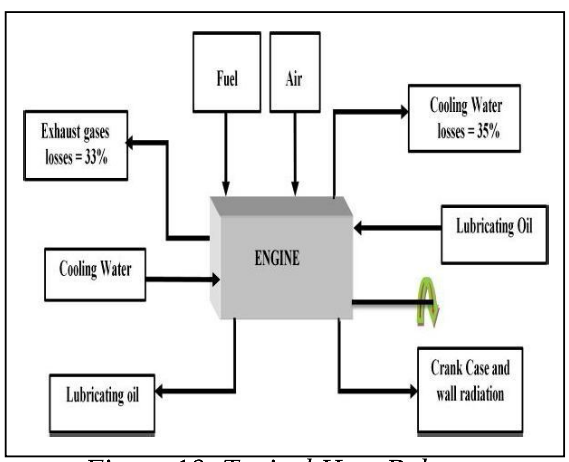

Figure 10: Typical Heat Balance

An estimate to determine the heat losses by the exhaust gases can be determined as follows:.

The Input energy or heat supplied by the fuel can be calculated from the equation

$I_E = SFC * P * CV$ (3)

Where I_E the input energy in kilo watts or kj/sec, SFC is the Fuel rate in g/bkw-hr, P is the brake power kilowatts in CV is the calorific value of the fuel in kj/kg.

The heat carried away by the exhaust gas can be calculated using the equation

$Q_E = m \times C_P \times \Delta T$ (4)

Where Q_E is the heat carried away by the exhaust gases in kj/sec, m is the mass flow rate of the exhaust gas in kg/sec, Cp is the specific heat of the exhaust gas in kj/kg, and ΔT is the temperature difference between the stack temperature and a value which is higher than the dew point temperature.

The exhaust gas density can be obtained by using the equation

$\rho = {}^{352.5}/_{(273 + T_S)}$ (5)

Where ρ is the exhaust gas density in kg/m3, T_S is the stack temperature in ºC.

The mass flow rate of the exhaust gas is obtained by using the equation

$m = vol_{exh} \times \rho$ (6)

The temperature difference is given by the equation

$\Delta T = T_s - T''$ (7)

Where T" is a safe value usually about 10 degrees above dew point so that condensation is avoided.

$\%\ of\ heat\ lost = Q_E/I_E$ (8)

12.Recoverable Heat Energy From Exhaust Gases

The maximum temperature of the medium used to recover heat will always be less than the temperature of the source, a difference called the terminal temperature difference (TTD) ,which will be determined largely by the size of the heat exchanger involved. The terminal temperature difference (δ) values for various medium are given in Table-1 [12]

Medium	δ (^{0}C)
Gas or air to/from water	10
Gas or air to/from Steam	20
Water to water	5
Oil to/from water	10

Table-1: Terminal temperature Difference for different mediums

Using equation (4) the recoverable heat energy can be obtained by using the equation

$$Q_{ER} = m \times Cp \times \Delta T_R \qquad (9)$$

Where Q_{ER} is the recoverable heat energy from exhaust gases in kj/sec, ΔT_R is the temperature difference in ºC for heat transfer to take place.

The recoverable temperature difference is given by the equation

$$\Delta T_R = (T_s - \delta) - (T'') \qquad (10)$$

Where T_s is the stack temperature in ºC , δ is the terminal temperature difference in ºC.

It is well known that for a heat engine operating between two temperature limits T_H & T_C, the maximum efficiency attainable (Carnot Cycle efficiency) is given by

$$\eta_c = 1 - \left(\frac{T_C}{T_H}\right) \qquad (11)$$

If a Stirling engine is designed to operate between the exhaust gas temperature (T_H) and the ambient engine room temperature (T_C), the Maximum Recoverable Energy is

$$E = \eta_c Q_{ER} \qquad (12)$$

Where

$$T_H = (T_S - \delta) \qquad (13)$$

$$T_C = (T_{AMB} + \delta) \qquad (14)$$

Where T_{AMB} is the ambient Engine Room temperature

13.Estimation Of Power Of A Stirling Engine

A simple formula for Stirling Engine Power output could use the overall plant efficiency factor η_o and Q_{ER} as follows

$$P_s = \eta_o Q_{ER} \qquad (15)$$

When only the engine is considered this can be written as

$$P_s = \eta_H \eta_M \eta_c \eta_s Q_{ER} \qquad (16)$$

Where η_H is the heat source efficiency, η_M is the mechanical efficiency, η_C is the Stirling Coefficient and η_S is the Stirling Cycle efficiency. The range of values for η_H, η_M & η_C are (0.85-0.95), (0.75-0.90) and (0.55-0.88) respectively [13]. The equation (16) is also known as the Malmo Formula

With perfect regeneration, the ideal Stirling Cycle efficiency is same that of Carnot cycle efficiency operating between the same temperature limits, Due to regenerator effectiveness, the Stirling cycle efficiency is below that of the Carnot cycle efficiency. The Malmo Formula is very simple to use but is dependent on a number of variables and empirical factors which vary over a wide range. The non ideal Stirling cycle efficiency can be determined [13] as

$$\eta_s = \frac{\eta_C}{\left[1 + \frac{\{(1-e)\eta_C\}}{\left\{(K-1)\ln\frac{V_{max}}{V_{min}}\right\}}\right]} \qquad (17)$$

Where T_H & T_C are the source and sink temperatures in Kelvin, e is the regenerator effectiveness, in % K is the Specific Heat ratio of the Gas & V_{Min} and V_{Max} are the Minimum and maximum volumes in the cycle. It can be seen that if the regenerator effectiveness is 100%, then the efficiency of the Stirling cycle equals that of Carnot cycle. Other advanced methods have been developed to estimate the power output from a Stirling engine such as the mean pressure formula, Beale Number and Schmidt theory. These would however require some of the dimensions and volumetric ratios to be determined first before proceeding further. Since the objective of this paper is to highlight the feasibility of the concept the advanced analysis has not been undertaken.

14.Case Study

A case study is attempted to estimate the energy available from the exhaust gas of a 500-600 KW propulsion engine and also to estimate the recoverable energy from a Stirling Engine .

Main Engine Particulars

Marine engine performance data From Caterpillar 3508B		
Engine Speed	1200	rpm
Engine Power	578	kW
Fuel Rate	202.5	g/bkwh

Exhaust Stack Temperature	335.1	°c
Exhaust Gas Flow	113.6	m3/min
Calorific Value for Marine diesel fuel [14]	39240	kJ/kg (approx)
Specific heat of` Exhaust gas	1.0	kJ/kg k

Based on the performance data calculating the Exhaust gas losses

Exhaust stack temperature T_S =		335.1^0 C = 608K
Dew point temperature T_{dew} =		160^0C = 433K
T''	=	170^0 C = 443K
δ	=	20^0C

The Input Energy/Heat supplied by the fuel from (3) I_E = 1275.79 kj/sec
The exhaust gas density from (5) = 0.57 kg/m3
The mass flow rate from (6) = 1.10 kg/sec
ΔT is obtained from eq. no. (7) = 165 ^{0}C
The heat carried away by the exhaust gas from (4) = 181.5 kJ/sec
The percentage of heat loss from (8) = 14.22 %

If T'' is considered as ambient temperature (35^0C), then the heat lost expressed as a percentage of energy input is 25.8%.

The recoverable temperature difference is given is obtained from the equation (10) assuming δ = 20^0C

$\Delta T_R = 145^0$ C

The recoverable energy from Exhaust gases from (9) is =159.5 KJ/Sec

From equations (13 & 14), $T_H = 315^0$C & assuming Ambient Engine Room Temperature as 45^0C, $T_C = 65^0$C

The Maximum energy recoverable in a heat engine cycle assuming no other losses is given by the Carnot cycle efficiency η_{Carnot}.

$$\eta_{carnot} = 1 - \frac{(65 + 273)}{(315 + 273)} = 0.42$$

From Equation (12) the maximum recoverable energy is 67.8 KW.

However since perfect Carnot (Stirling) Efficiency cannot be achieved, The power output can be determined from equation (17) . The effect of volumetric ratio and regenerator effectiveness for a constant temperature ratio is shown in Figure 11.

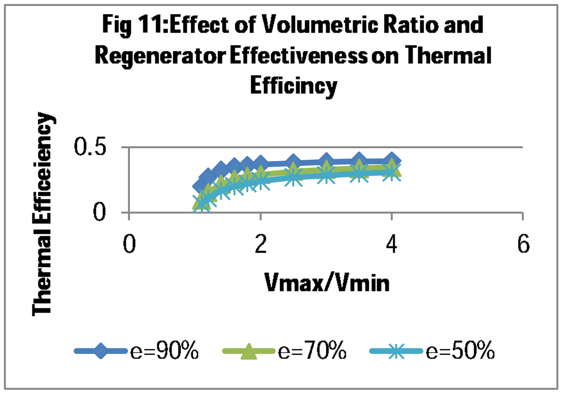

Figure 11

Taking a regenerator effectiveness as 0.7 , and the specific heat ratio for air as 1.4 and the volumetric ratio as 3.0, the value of η_S = 0.35. The power output of the Stirling engine system can now be estimated approximately from equation (16)

P = 0.85 * 0.75*0.55*0.33*159.5 = 18.45 KW

This gives a total conversion efficiency of 11% which is realizable for current low temperature differential Stirling engines.

From the above the saving in fuel can be determined as follows:

Fuel Saved = 18.45 * 202.5 *24/1000000 = 0.09 Tons/day or approximately 18tons per year considering 200 days of operation. The reduction of CO2 Emissions is 56 tons/year.

A schematic Arrangement of the WHR plant is shown in Figure 12

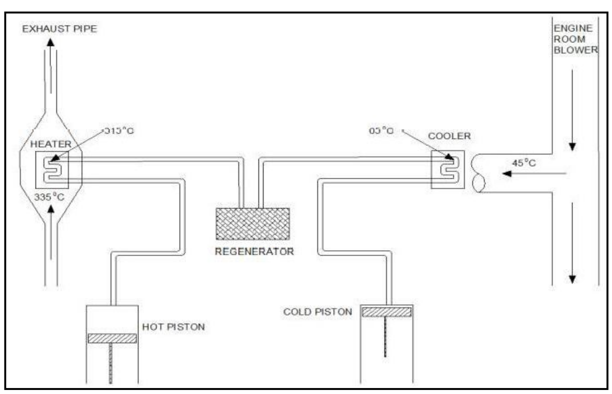

Figure 12:Schematic arrangement of WHR Plant

15. Conclusion

This paper provides an introduction to alternative ways of recovering waste heat energy from exhaust gases other than the traditional way of conversion to steam as employed usually on large ocean liners. Various technologies which are being developed typically for solar and thermal generation systems using external heat sources can be adapted to recover energy from exhaust gases from small and coastal fleet thereby leading to saving in fuel and reduce global warming. Heat balance studies are not often carried out in the development of a design except to the point of ensuring that adequate heat recovery is made to meet the demand of fuel heating / fresh water generation in large ocean liners. This paper stresses the need to undertake such studies at the basic design stage for every ship to identify various losses so that improvements can be undertaken to minimize such losses. Using Stirling Engines in the exhaust stream can recover some part of the lost energy. However more detailed analysis using second order and third order methods will need to be carried out before finalizing the design. Practically, a single Stirling Engine of 20Kw rating would also require that the heat exchanger inside the exhaust trunk should not add undue backpressure thereby preventing the flow of the gas. This could impose restrictions on the installation or in the capacity. Compact Stirling Engines in the range of 2-5 Kw are commercially available and may be installed on board for power generation. As there are a number of ships where steam based WHR mechanism is not fitted, Stirling Engine based system could result in substantial savings in fuel. It is intended to conduct experiments in an engine laboratory to test this concept further.

16.Acknowledgement

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