Combined Gas And Steam Cycle For Marine Propulsion

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Abstract

This paper focuses on the implementation of combined cycle using Gas and Steam for propulsion and power requirement on board marine vessels. In this concept, Gas turbine works on Brayton cycle. Exhaust from the Gas Turbine is used to generate steam in a Heat Recovery Steam Generator, which is then used to run a steam turbine working on Rankine cycle. The efficiency of the combined cycle lies between 45-55% and is proved in the paper. Emission of harmful gases is negligible due to the use of natural gas hence; the paper concentrates on the use of natural gas as fuel.

Keywords: Combined Cycle, HRSG, Efficiency, Emissions.

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Introduction

In todays world “green technology ”is the buzzword. In every industry including the marine industry there is an increased effort to reduce emissions partly because of increased environmental concerns but also due to rising production costs. Hence there is a necessity to use leaner, cleaner and more efficient processes. According to MARPOL Annex VI SOx and NOx emissions have to be greatly reduced by the year 2020. Cost of operation plays a vital role in the Marine industry. In recent years, an advance in technology has led to large reserves of natural gas becoming commercially viable for extraction. This has led to natural gas becoming available in large quantities at cheap rates. Also use of Natural gas has negligible SOx and greatly reduced NOx emissions. This paper focuses on the development of the combined cycle using gas and steam turbines for propulsion and power requirements for marine vessels.

Combined Cycle

A combined cycle consists of two separate thermodynamic cycles combined together to give an increased power output at a better plant efficiency. The two cycles are the Brayton cycle and the Rankine Cycle. The higher temperature cycle is the ‘topping cycle’ while the lower temperature cycle is the ‘bottoming cycle’.In this system the Brayton cycle is used as the topping cycle while the Rankine cycle is used as the bottoming cycle.

Consider a ship equipped with only a Gas turbine plant. Air is taken at the inlet and then compressed, combustion of fuel increases its energy and this is then use to drive the turbines which are used to produce work and also to drive the compressor.this air is then exhausted through the vents. However, Gas Turbine exhaust gases have enough amount of enthalpy which can be used for steam generation. Hence using this exhaust to produce steam becomes a viable option onboard a ship. This is where a combined cycle comes into picture, the exhaust from gas turbine is led to a shell and tube type heat exchanger. This is referred to as Heat Recovery Steam Generator (HRSG).The high pressure steam generated is then passed through a steam turbine and finally into the condenser. The steam turbine alongwith the gas turbine act as prime movers for the generators. These generators are responsible for serving the power and propulsion requirements onboard the ship.

To meet the power demands during port stay and to provide redundancy while the ship is out at sea, the Heat Recovery Steam Generator (HRSG) discussed in this paper is also capable of self-firing.

In this system gas turbines function as the primary source of power and its exhaust is used to generate steam and run a steam turbine which acts as the secondary source of power.

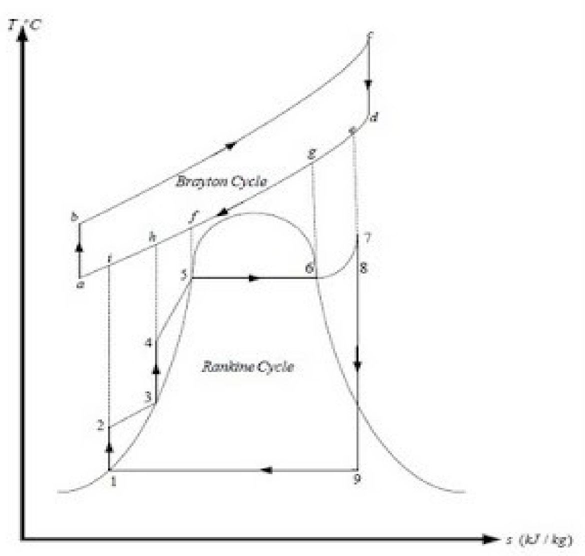

T °C
c
d
e
g
Brayton Cycle
b
f
h
7
i
6
8
5
a
4
Rankine Cycle
3
2
1
9
s (kJ / kg)

Fig.(1.1)

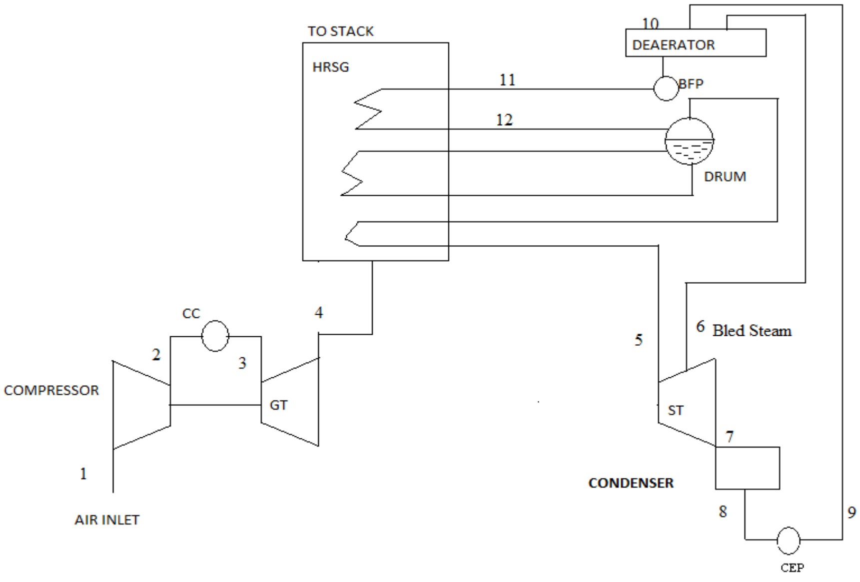

10
DEAERATOR
TO STACK
HRSG
11
BFP
12
DRUM
CC
4
2
3
COMPRESSOR
GT
1
AIR INLET
5
6 Bled Steam
ST
7
CONDENSER
8
9
CEP

Fig.(1.2)

Why A Combined Cycle?

In this design natural gas in the form of LNG is used as the fuel to fire the gas turbine. LNG is a fuel which has no particulate matter, hence wear due to erosion is greatly reduced. Also LNG is a clean burning fuel as it produces a negligible amount of toxic gases. However in the absence of availability of LNG the gas turbine can also run on alternatives such as MGO, MDO, DMA or DMX. Thus the gas turbine has fuel flexibility. The exhaust is used to generate steam which is used to run a steam turbine this helps in increasing plant efficiency. This makes the use of gas turbines commercially viable.

To support the fact that a combined cycle has a better plant efficiency as against the individual gas or steam plants following calculations are done.

Consider a gas turbine with a single stage compressor and turbine alongwith a single pressure HRSG and a single steam turbine without reheat.

System parameters (Refer to fig.(1.2))

A) Gas Turbine

Air Inlet Pressure : $P_1 = 1$ bar.

Air Inlet Temp. : $T_1 = 33^{o}C$ (308 K)

Compression Ratio : - 18:1

Maximum temp. : $T_3 = 1500^{o}C$ (1773 K)

Outlet Pressure : $P_4 = 1.08$ bar

Specific heat of Air : $c_{pa} = 1.005 kJ/kgK$

Specific heat of Gas : $c_{pg} = 1.15 kJ/kgK$

Lower Calorific Value of Natural Gas : LCV = 42MJ/kg

Stack Temp. : $T_{stack} = 140^{o}C$ (413 K)

Isentropic efficiencies :- a) Compressor: $\eta_{comp} = 0.82$

b) Turbine: $\eta_{turbine} = 0.88$

Combustion Efficiency: $\eta_{cc} = 0.98$

Mechanical Efficiency : $\eta_{mech} = 0.99$

B) Steam System

Boiler Pressure = 60bar

Condenser Pressure = 0.05bar

Maximum Temp : $T_6 = 550^oC$ (823 K)

Isentropic efficiency of Turbine : $\eta_{turb} = 0.88$

HRSG Effectiveness : $\varepsilon = 0.92$

Bleed for Feed heating = 2bar

Calculations

A) Gas Turbine

Temperature at end of compression : $T_2 = T_1 \times (P_2/P_1)^{(\gamma-1)/\gamma} = 308 \times (18)^{0.4/1.4} = 703.4$ K

Actual temp at end of Compression : $T_2' = (T_2 - T_1)/\eta_{comp} + T_1 = (703.4-308)/.82 + 308 = 790.2$ K

Work done on compressor: $w_c = c_{pa} \times (T_2' - T_1)/\eta_{mech} = 1.005 \times (790.2-308)/0.99 = 489.5$kJ/kg

Ideal outlet temp : $T_4 = T_3 \times (P_4/P_3)^{(\gamma-1)/\gamma} = 1773 \times (1.08/18)^{0.333/1.333} = 877.96$ K

Actual outlet temp : $T_4' = T_3 - (T_3 - T_4) \times \eta_{turb} = 1773-(1773-877.96) \times .88 = 985.4$ K

Mass of fuel required : $\dot{m}_f = (c_{pg} \times T_3 - c_{pa} \times T_2')/(LCV \times \eta_{cc} - c_{pg} \times T_3)$

$= (1.15 \times 1773 - 1.005 \times 790.2)/(42000 \times 0.98 - 1.15 \times 1773)$

$= 0.0318$ kg/kg

Actual heat supplied $q_A = (1+\dot{m}_f) \times c_{pg} \times T_3 - c_{pa} \times T_2' = (1+0.0318) \times 1.15 \times 1773 - 1.005 \times 790.2$

$= 1309.63$kJ/kg

Work done by turbine : $w_{gt} = c_{pg} \times (T_3 - T_4') \times (1+\dot{m}_f) = 1.15 \times (1773-985.4) \times (1+0.0318)$

$= 934.54$kJ/kg

Actual Gas cycle efficiency : $\eta_{gtc} = (w_{gt} - w_c)/q_A = (934.54-489.5)/1309.54 = 0.3398 = 33.98\%$

B) Steam Cycle

From Steam tables

Points	P_i (bar)	T_i (°C)	h_i (kJ/kg)	s_i (kJ/kg-K)	x_i
5	60	550	3541.2	7.03	-
6_s	2	120.21	2668.36	7.03	98.8%
6	2		2773.1		
7_s	0.05	32.87	2143.54		82.78%
7	0.05		2311.26		
8	0.05	32.87	136.5		0
10	2		504.7		

Fig.(1.3)

Heat Absorbed by HRSG : $q_{HRSG} = (1+\dot{m}_f)\times c_{pg}\times(T_4'-T_{stack})\times\varepsilon$

$= (1+0.0318)\times1.15\times(985.4-413)\times0.92$

$=624.85$kJ/kg

Mass flow rate of Steam : $\dot{m}_s = q_{HRSG} /(h_5 - h_{10}) = 624.85/(3541.2-504.7) = 0.2058$kg/kg of air

Mass Fraction bled : $x = (h_{10} - h_8)/(h_6 - h_8) = (504.7-136.5)/(2773.1-136.5) = 0.1533$

Work output of stream turbine : $w_{st} = \dot{m}_s \times[(h_5-h_6)+(1-x)\times(h_6-h_7)]$

$= 0.2058\times[(3541.2-2773.1)+(1-0.1533)\times(2773.1-2311.26)]$

$= 238.55$kJ/kg

Efficiency of steam plant : $\eta_{sp} = w_{st}/q_{HRSG} = 238.55/624.85 = 0.3817 = 38.17\%$

Overall efficiency of Combined Cycle: $\eta_{ccp} = (w_{gt}+ w_{st} -w_c)/q_A$

$= (934.54+238.55-489.5)/1309.63$

$=0.522 = 52.2\%$

Redundancy

Gas Turbines do not require maintenance while the ship is out at sea. However there may be functional issues that may come up in the Heat recovery boiler during its operation. These problems may be soot build up, Scale formation on the water tubes in the boiler. To resolve these issues, HRSG should be shut off and hence steam generation is stopped which means the total power generation is reduced. For this, a baffle arrangement alongwith a bypass duct can be used thus enabling independent operation.

From calculations done earlier in the paper it is clear that power developed by gas turbine alone is sufficient for propulsion (at reduced speed) and power requirements of the ship. When the ship is at port, gas turbine may be shut down for overhauling. Now the HRSG which is capable of self firing takes the responsibility of power requirements. The fuels used for combustion can be MGO or LNG itself (depending upon the availability).

This ensures that failure of any one cycle will not affect the general performance of the ship as the plan is redundant.

Emissions

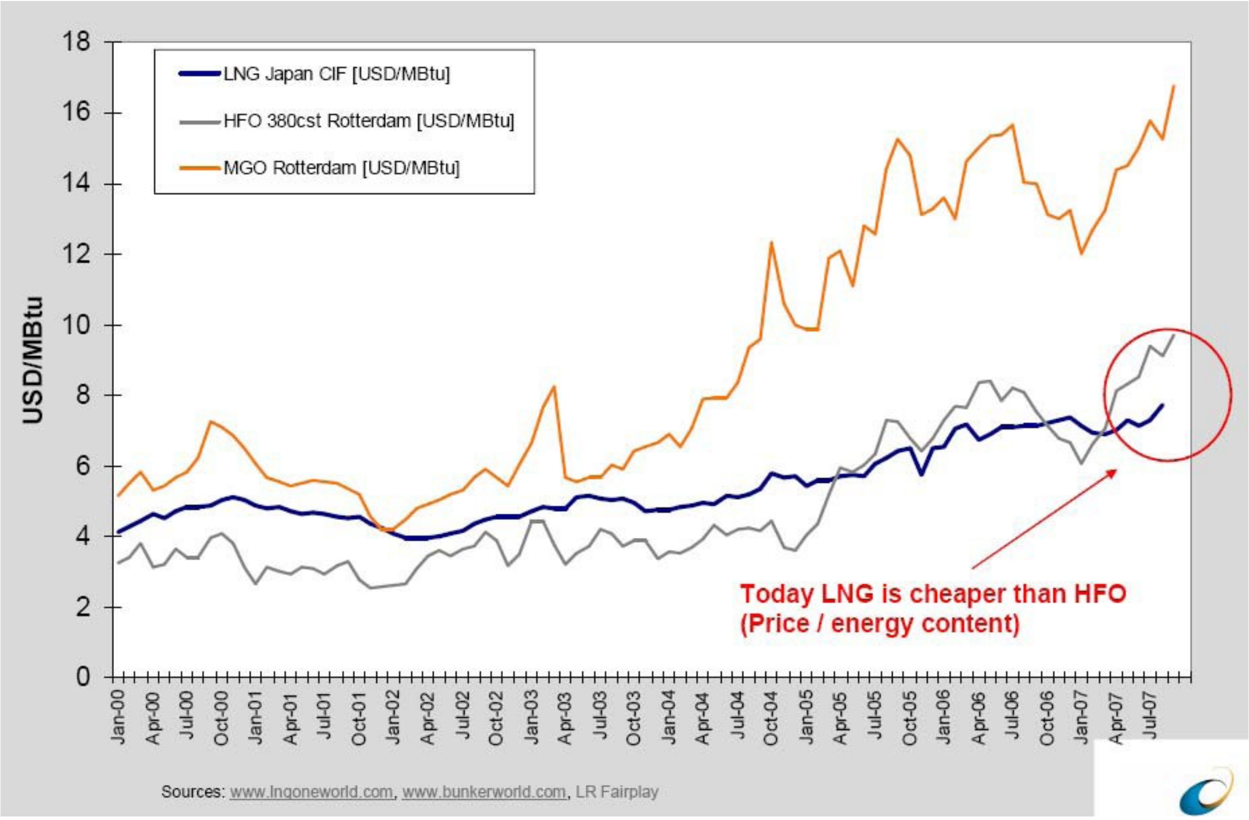
There are strict regulations for control of emission of harmful gases in landbased plants. However the marine industry has been slow to adopt these restrictions as it entails restriction on the use of HFO, which is a byproduct of the refining process of crude oil and hence available in large quantities at cheaper rates. However, according to MARPOL Annex VI there is a great focus on the reduction of SOx and NOx gases emitted by the marine industry. This will lead to the reduction of HFO for fuel requirements.

Natural Gas is a gaseous fuel and mainly consists of methane which makes it a sulphur free and clean burning fuel. Therefore there is negligible SOx emissions due to the use of Natural gas. Natural gas also burns at a lower temperature therefore there is a great reduction in the emission of NOx. Also as it is a gaseous fuel it has no particulate matter thus there is a reduction in erosive wear of the turbine.

Due to technological advancement in drilling techniques, In recent years, the extraction of natural gas especially the shale reserves have become commercially viable. This has led to natural gas being commercially available in large quantities at cheaper rates. Thus Natural gas can be used as an alternative to HFO which makes it a cheap and clean fuel.

Economic Aspects

Fuel used in the combined cycle is mainly LNG. Fig () gives the general trend of LNG price variations over the years.



Sources: www.lngoneworld.com, www.bunkerworld.com, LR Fairplay

Fig.(1.4)

As of 2011 the LNG prices are

USA : 4 USD/MMBTU

EU :8-10 USD/MMBTU

ASIA :13-15 USD/MMTU

While the cost of HFO is around 16 USD/MMBTU

Thus cost of fuel reduces when compared to conventional plants or even the diesel engines Emissions SOx , NOx and CO2, on the other hand are considerably lower. Following table gives a general idea regarding the emissions from various fuels.

Fuel Type	SO_x g/Kwh	NO_x g/Kwh	PM g/Kwh	CO_2 g/Kwh
Residual Oii,3.5%Sulphur	13	9-12	1.5	580-630
Marine Diesel Oil,0.5%Sulphur	2	8-11	0.25-0.5	580-630
Liquefied Natural Gas(LNG)	0	2	~0	430-480

Fig(1.5)

Thus using LNG proves to be an advantage in terms of economic as well as environmental aspects.

Since the overall plant efficiency increases compared to the conventional power plants Power output increases keeping the cost low. Since the 2/3 of the power output is produced by Gas Turbine plant and rest by steam turbine plant, the investment cost are much less than a conventional steam plant. As the share of steam plant is less in the total power output, water requirement greatly reduces thus reducing the cost of operation of the plant.

Conclusion and Recommendations

Using combined cycle we improve on the overall plant efficiency. Considering the fuels used and plant dimensions, a combined cycle propulsion system can be implemented in LNG carriers.

It makes sense to use gas turbines onboard LNG carriers as they can use the LNG boil off gasses (BOG) as fuel. Other applications of this type of propulsion system include cruise ships.

As the IMO regulations will be become stringent, it will become necessary for all ships to switch over to LNG or any other economically and environmentally valid fuel. The weight (of the combined cycle plant) issues can be resolved by using low weight materials for construction of hulls.

Following are the advantages of the combined cycle plant in general:

- Gas and Steam Turbine plant offer greater flexibility in terms of start up and shut down processes.
- The installation of gas turbine plant is much quicker due to relatively less dimensions and low weight (as against diesel engines). This allows to generate electricity while installation of steam plant is under construction
- The combined cycle plant makes it possible for increased duration between routine maintenance thereby reducing the time spent for maintenance in port. This increases the availability of the ship for commercial use.
- Aero-engine reliability and availability for minimized off-hire;
- Lower newbuilding cost for the vessel, due to lower equipment and installation cost;
- Flexibility due to real dual-fuel capability;
- No visible smoke, NOx or SOx emission issues, compliance with strictest IMO guidelines;
- Maintainability:
- Gas Turbines are “mass”-produced; engines, spares and services are available worldwide immediately from a number of sources;
- Engines are overhauled while vessel is sailing with spare or lease engine;
- Engine exchange can be accomplished within 24 hours, without dry-docking;
- Lower engine room crew requirements;
- High thermal efficiency and increased cargo capacity translate in lower transportation cost per delivered MMBTU of LNG and higher revenues from the each vessel

Appendix

- Fig(1.1) - T-S diagram of a general combined Cycle
- Fig(1.2) - System diagram of combined cycle discussed in the paper
- Fig(1.3) - Table showing calculated parameters of the steam plant
- Fig(1.4) - LNG price comparisons

- Fig(1.5) - Table showing emissions due to combustion of various grades of fuels

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