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Application of Computer Based Simulation and Optimization in Waste Heat Utilization for Efficient Ship Propulsion in an Innovative Codlogas Combined Power Plant

Akperhe, O.S[1] and Agbakwuru, J.A[1]
[1]Department of Marine Engineering, Federal University of Petroleum Resources, Effurun, Nigeria.
*Corresponding author's email: theakperheovo@gmail.com

Abstract

Combine power plant for ship propulsion is a multiple means that combines the good features of different plant systems for ship propulsion and power generation. This research introduced a new concept that makes the existing concept of CODLOG/CODLAG (Combine diesel electric and Gas turbine) to be more efficient for ship propulsion. The research employed the formulas of mathematical modelling, analyzing and simulating the operations by considering majorly the plant layout, controls, thermodynamic and electrical characteristics of main engines. This was facilitated by a computer application developed in MatLab Integrated Development Environment. Results showed that the new proposition of "CODLOGAS" (Combine Diesel eLectric or Gas and Steam Turbine) is a power plant that has remarkable attributes in utilizing waste heat, adopting a new plant layout and an increased power and efficiency for ship propulsion. Finally, the research generated an integrated model which accommodates the gas, steam and electric power plant for propulsion. The model is able to run an instant analysis by employing the features of simulation and computer resources, thus, bringing to light the appreciation of a simulators in the area of power plant.

Keywords: Combine diesel electric, Gas turbine, Combine diesel electric, Gas and steam turbine, Combine gas and steam turbine, Variable voltage, Frequency drive

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1. Introduction

According to Elgohary (2013), the marine power plant is that part of the ship responsible for generating both mechanical and electrical power for ship propulsion and for other onboard consumers and usually, these two operations are achieved separately, but in some configurations both are performed together. However, a combine power plant for ship propulsion referred to a mixed or dual propulsion system consisting of multiple means that are employed for the ship propulsion. They are classified into two categories; those in which the cruising engine remains online and can be augmented by another source of power for high speeds, and those that require either the cruising or the sprint speed engine. For simplicity it is referred to as OR/AND configurations (see Table 1).

Table 1: Combined power plant configurations

S/N	Configuration	Description
1	CODOG	Combined Diesel or Gas turbine
2	CODAG	Combined Diesel and Gas turbine
3	CODLAD	Combined Diesel eLectric and Diesel
4	CODLOG	Combined Diesel eLectric or Gas turbine
5	CODAD	Combined Diesel and Diesel
6	COSAG	Combined Steam and Gas turbine
7	COGOG	Combined Gas or Gas turbine
8	COGAG	Combined Gas and Gas turbine
9	COGAS	Combined Gas or Steam turbine
10	CONAS	Combined Nuclear and Steam turbine

11	IEP or IFEP	Integrated Full/Electric Propulsion

The use of these plants is widely adopted in the marine industry majorly because of the need to tackle environmental pollutions, to increase efficiency, flexibility in general for ship operability. Ship combined power plants. cannot be overlooked because of its huge benefits, with the shipping industries being a principal contributor to the global pollutant and emissions. The International Maritime Organization puts forward that with the increasing of global trade and rapid economic advancement the CO_2, NO_2, PM emission will increase by 50% to 250% by 2050 (International Maritime Organization, 2015) This gives give hedge to the gas turbine being that the shipping industries are now in quest to substitutes the most popular and famous diesel engine with other options such as gas electric, fuel cell and steam for ship power (Benvenuto et al., 2015).

Following the trend of the ship propulsion machinery, there has been an immense improvement and introduction of different concepts in the ship plant systems for propulsion over the past century as described in Table 1. According to Daniel (1997), this is in an attempt to fulfilling several quests of speed, maneuverability, energy efficiency, monopolistic ideas etc. Information extracted from Marine Insight (provide reference) signifies that each sectors are working continuously, looking for ways to be more efficient and proffer better alternatives by making innovative moves.

Existing concept has always combined one or two prime movers directly coupled for ship propulsion (COGAS, CODLAG, COSAG, and CODAG). However only few selected research articles discussed the possibilities of employing more than two plant design concepts to ship propulsion. Dzidal (2009) and Wojciech (2011) presented a concept with two variant that utilizes the waste energy from the exhaust gas of marine diesel engine to power subsystems of power gas turbine and steam turbine that is assumed to drive through a reduction gear of the ship screw propeller. In both concepts, their configuration was to deliver power to the ship propeller. The overall power available for this propulsion is expressed further in Equation (1). Both authors, show that there is a possible introduction to the propulsion system and that as such, is very possible.

$$N_{combine} = N_{diesel} + N_{power\ gas\ turbine} + N_{steam\ turbine} \quad (1)$$

Van (2011) developed and used multiple criteria analysis to reveal the best solution for the specific ship requirement. It evaluates different configuration of ship power plant for propulsion, including configuration that takes into account two or more distinct prime movers (CODLADAD and CODLADOG) per se. Van (2011) emphasized that the act of combining different plants system is a smart solution, especially when it combines the good features of each piece, for overall ship operability. Sebastian et al. (2017) describes that all vessel regardless of engine power can employ the gas turbine as their prime mover successfully. Thus, the gas turbine plant is generally accepted and this could benefit the energy saving technique of COGAS system. The implication is that a steam turbine can further be integrated into existing plant. In the work of Sirus et al. (2014), they compared and emphasized the relevance of hybrid propulsion plant for ship in terms of various concept/layout/mode of operation and energy utilization. It is possible that a plant system that comprises a gas turbine as main prime mover such as CODLOG could benefit the system of COGAS which Sebastian et al. (2017) supports and extends that such system involving COGAS is with a transmission efficiency of 98-99 percent. This is to say, if properly configured any waste heat can be harnessed and fedback into the shaft system to increased torque and power for ship propulsion.

The marine power plant is an architecture of engines configured to achieve a primarily goal. According to Gurvin (2017) and Torstein et al. (2015), these parts maybe physically separated. However, they can be interconnected by a system of power distribution system, which are controlled and supervised by the control system. This is to achieve a safe operation and improved overall efficiency. Therefore, to carry out a simulation study is to ensure that there is sufficient amount of information available for an actual operational condition, thus simulation is a valuable tools for investigating and acclimatizing oneself with all stages involved in design, implementation and operation. (Torstein et al., 2015).

Yutao et al. (2018) and Martelli and Figari (2019) worked on marine propulsion plant analysis and simulation. Here their works were of logics and control system with some mathematics and thermodynamic behaviors of main engines. In the work of Rahman et al. (2011), the author presented a parametric study for thermodynamic performance of gas turbine power plant, showing variation of operating conditions on the performance of gas turbine. For framework purposes the work of Skjong et al. (2017), modeled and simulated the marine power plant (operation of main generators). The work simulates the electrical concepts of the power plant which are load sharing, synchronizing voltage, currents and speed controls. This author in his work presented a generic framework for modeling and simulating electrical machines (generators) in the marine power plants under transient operations. Ogbonnaya (2012) developed a Visual-Basic.Net program to aid the study of parameters of interest of a gas and steam plant (COGAS). Jefferson et al. (2003) carried out analysis using computer simulation. The work simulated the dynamic characteristics of gas and steam turbine plant for marine propulsion with introduced values for each parameter of the system using MatLab software as tool. Benvenuto et al. (2015) analyzed the gas and steam plant with mathematical model and presented its findings regarding the choice of layout for different steam cycle of that can be operated. In the assessment of Sebastian et al. (2017), COGES was used for study after consideration of various combined systems. The work focused on investigating the effect of varying operating parameters on the weight and efficiency of the system. The scope of Sebastian et al. (2017) was limited to the gas and steam cycle of COGES excluding the electrical sections.

The above discussions have shown that there is freedom in combining plant system for propulsion especially whenever a need is perceived. However, it is noted that many of these literatures did not take into account in-depth mathematical analysis nor simulation and the concept of CODLOGAS especially and other possible arrangement. There are various numbers of combined power plant, with either combined or separate analysis needed for plant assessment (electrical/mechanical/thermodynamic). Many of the literatures have shown the importance of simulation studies to providing an in-depth understanding of power plant systems. However there has not been any research that tends to discuss CODLOGAS as a probable extension to CODLOG which tends to analyses and simulate the combine action of the power plants which comprises of three distinct main primary power plant.

Thus, this study is aimed at extending the configuration of CODLOG power plant by integrating a steam turbine. This is achieved by modelling and performing simulation analysis with the interest of utilizing the waste heat from the gas turbine to power a steam turbine whose power is to be fed back into shaft system for ship propulsion. The work considered both electrical and thermodynamic parameters of the plants, thereby developing a software with adequate graphic user interface to simulate the whole operation for a concrete understanding and assessment of the extension CODLOGAS. Hence, can provide insight into system design, operations and performance prediction of the Marine Plant system.

Table 1 indicate the number of combine power plant for ship propulsion. However, in line with the focus of this paper, two of the enlisted combine propulsion plant (CODLOG and COGAS) is described below, with the interest of bringing about and simulating a new mix which is termed, Combined Diesel Electric or Gas and Steam (CODLOGAS). CODLOG is power plant that runs in the OR mode. This mode allows either electric drive (motor) or the gas turbine to operate the propeller shaft at separate time. Figure 1 depicts the basic configuration of the plant.

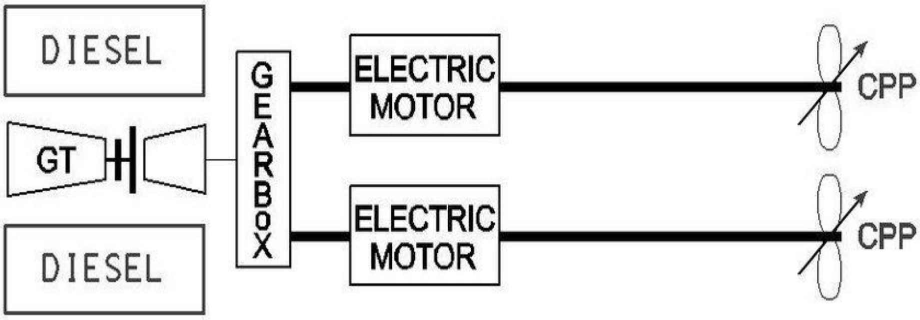


Fig. 1: Layout of CODLOG

COGAS is power plant that runs in the AND mode and this mode allows both the gas turbine (GT) and steam turbine (ST) being powered by heat recovery steam generator (HRSG), operates the propeller at the same time. Figure 2 depicts the basic configuration of the plant.

CODLOGAS is a power plant that is borne out of the combination of COGAS and CODLOG. This plant runs in the "OR" mode and this mode allows either diesel electric drive or gas and the steam turbine thermodynamically connected, to operate the propeller part time. Figure 3 depicts the configuration of the plant. The goal of this work is to improve the performance of waste heat recovery system, by contributing to mathematical modeling of the design and simulation of combine power plants.

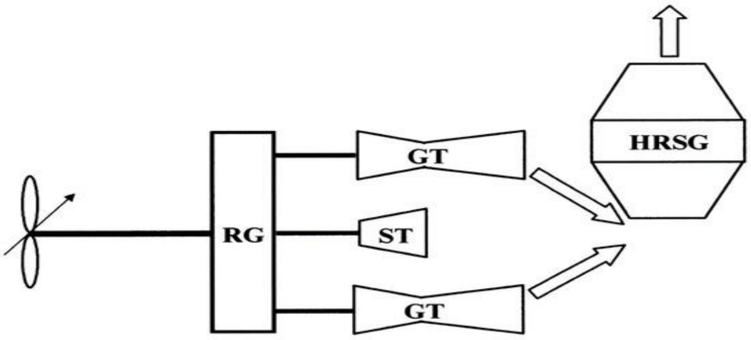


Fig. 2: Layout of COGAS

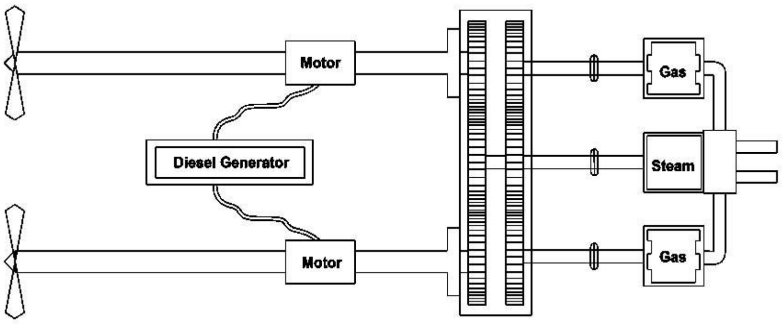


Fig. 3: Layout of CODLOGAS

2. Materials and methods

2.1 Research design

This research employed parametric study to model and run simulation and analysis on the proposed combine power plant of CODLOGAS. Parametric analysis blends into modelling and simulation where the relationships between several key requirements are linked together and can be manipulated to produce outputs indicative of system effectiveness. In CODLOGAS, the section which operates in COGAS is an upgrade of power plant having gas as one of its main prime movers as seen in CODLOG. According to Weerasiri (2014), the steam turbine in this configuration has a thermodynamic cycle and a bottoming one that is thermodynamically dependent on the toping cycle which is of gas type.

According to Weerasiri (2014) the initial stage of designing a HRSG, fitting and sizing a steam turbine in a combine power plant of Gas and Steam, is borne out of the need to make use of the waste heat which is usually of high quality, as high as 600 deg. The first necessary step, is to evaluate the known parameter of the desired engine (gas turbine in this case) such as the power, speed and temperature etc. The second necessary step is the mathematical evaluation of the theoretical maximum waste heat expressed in joules per hour or its equivalent heat rate in watts. With these known values an appropriate steam turbine and HRSG can therefore be derived.

In this presentation, the industrial gas turbine SGT-500 shown in Table 2, which is regularly used for marine propulsion is used as a basis for this modeling, from where other plants (Steam Turbines) will be derived and matched. According to Pathirathna (2013), the above parameters and values for specifying a gas turbine by the manufacturer are not sufficient to make a proper and in-depth thermodynamic analysis of the gas turbine. Thus, other engineering and analytical approach is applied to reveal other hidden parameters and values that contribute to overall system operation.

Table 2: SGT-500 marine/industrial gas turbine parameter

Parameter	Value
Output	17.40 MW
Efficiency	32.8 %
Exhaust gas flow	92.3 kg/s
Turbine rotor speed	3450 rpm
Speed range	0-100%
Exhaust gas temperature	375 °C
Gaseous fuel LHV	46,798 kJ/kg

The procedure employed, reverse engineering approach also known as backwards engineering in order to reveal hidden details and simulates the system. A reverse engineering is a process or method, through which one attempts to understand through deductive reasoning how a device, process, system, or piece of software accomplishes a task with very little (if any) insight into exactly how it does so. This method is applied to numerous fields of software engineering, mechanical engineering, marine engineering, design, system biology, chemical engineering etc. Fig. 4, 5 and 6 are the flowchart showing the design process for the combine cycle. Where the speed is used to simulate and analyse the combine plant of gas and steam turbine.

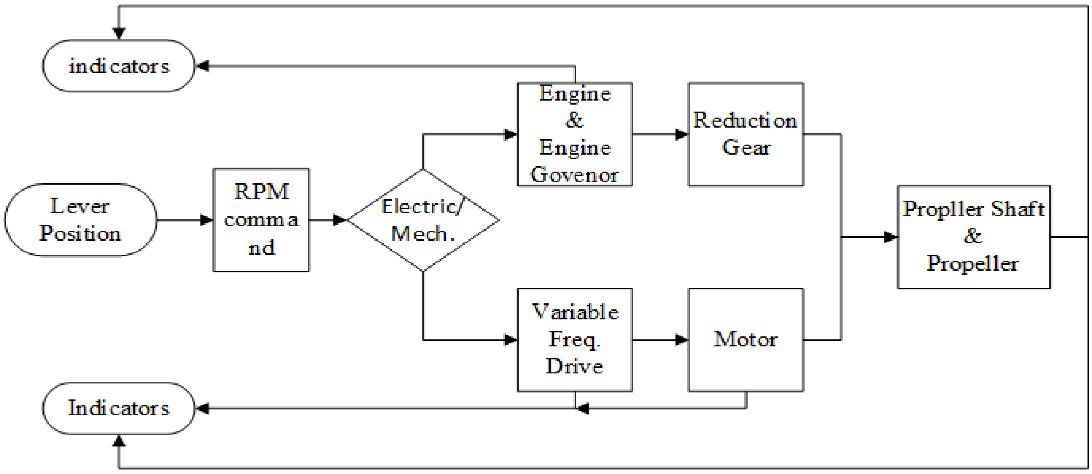


Fig 4. Control flow chart of plant

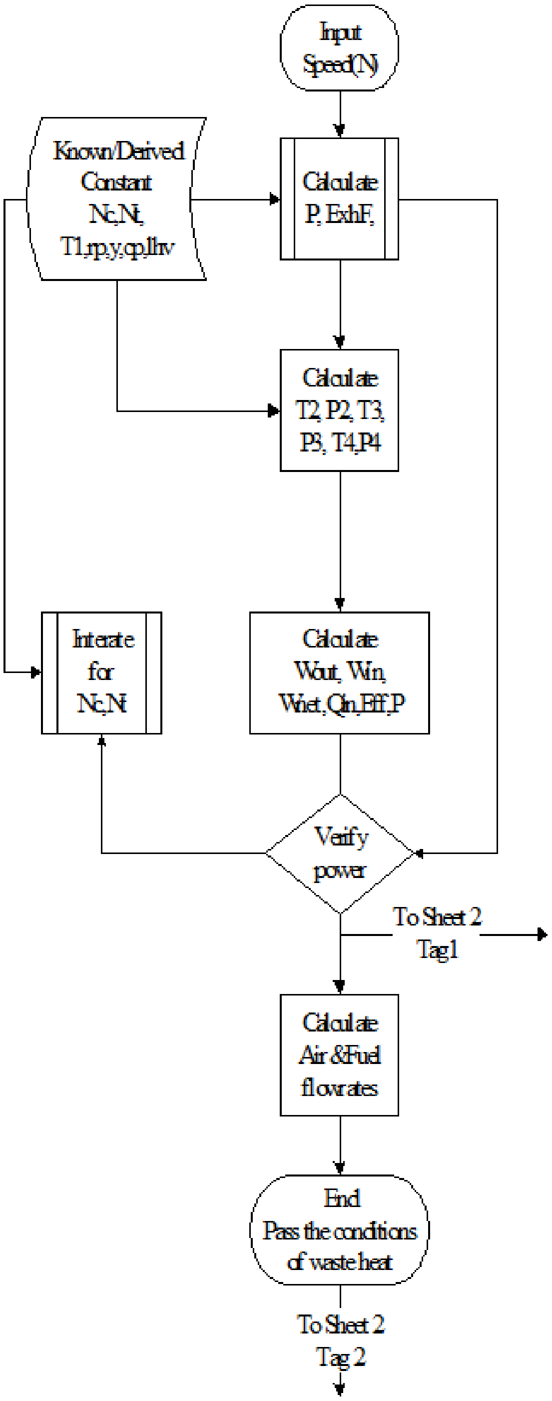


Fig. 5: Sheet 1, simulation flowchart for combine cycle

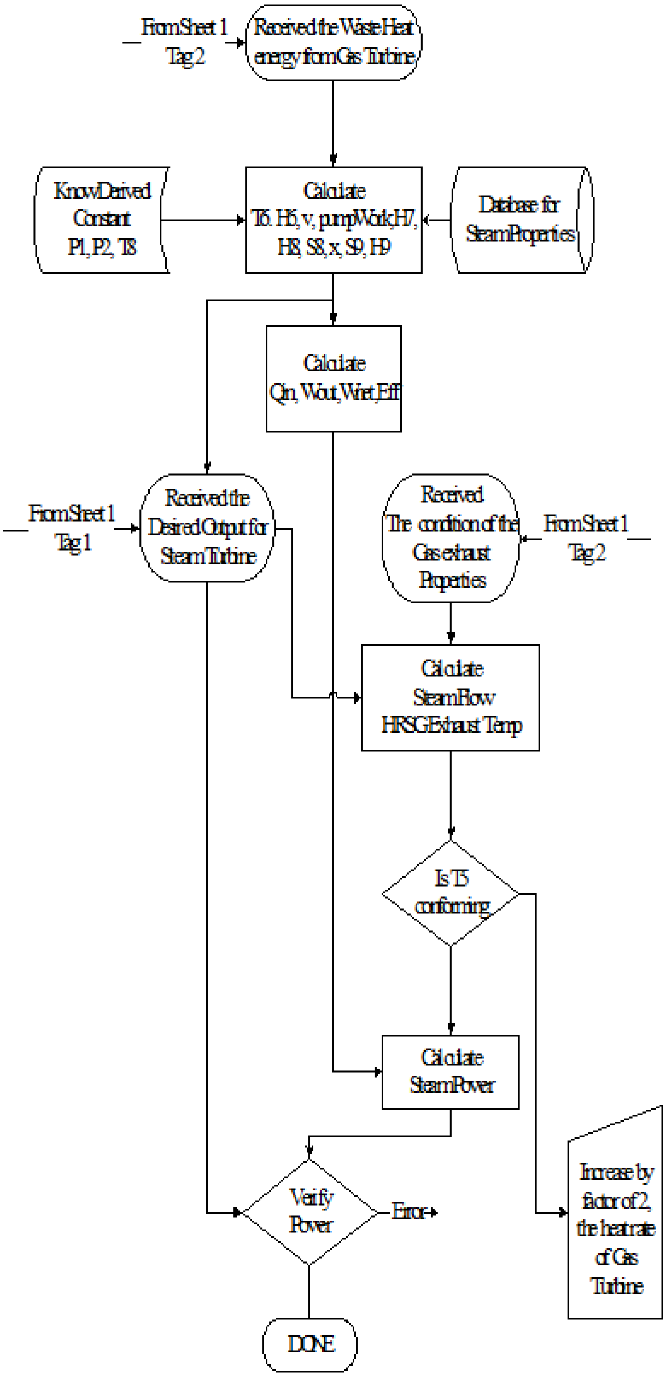


Fig. 6. Sheet 2, simulation flowchart for combine cycle

2.2 Analysis of combine gas and steam plant

The Fig. 7 and 8 describe the thermodynamic cycle of a typical combine gas and steam turbine alongside the working diagram of these two combine cycles.

Combine cycle gas-steam is considered.

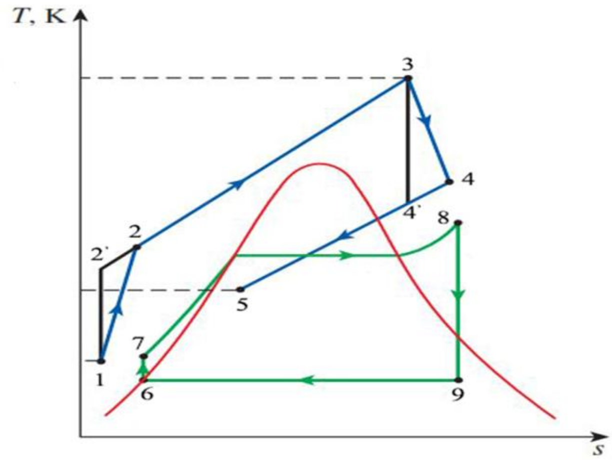


Fig. 7. T-s Diagram (Cengel et al. (2014))

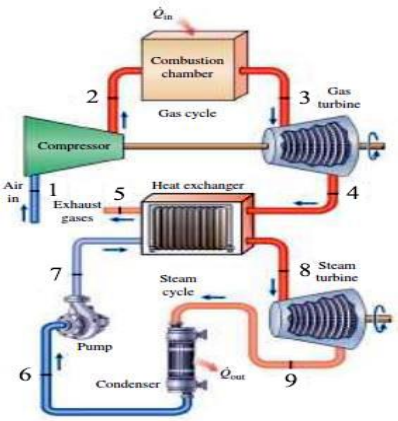


Fig. 8. Working Diagram (Cengel et al. (2014))

Working principle:

A typical combine gas and steam turbine is schematically represented in Fig. 7 and 8.

Section 1: Gas Turbine

A key component of combined power plants, the gas turbine operates within Section 1 (process 1 through 4), known as the topping cycle. Its working principles are delineated below:

1. The system is an open cycle which means the working fluid is not refreshed but discharged.
2. The initial stage of the gas turbine begins with the compressor (process 1-2). As the name implies it draws in air at ambient condition of temperature and pressure and compresses it to a higher temperature and pressure per design limitation.
3. Afterwards the charged air enters the combustion chamber (process 2-3) with fuel continuously administered. Inside the combustion chamber is a continuous combustion and a control volume as the mass in is equal to mass out.
4. The result of combustion brings about a further increased in pressure and temperature where the enthalpy of gas is utilized at the turbine inlet to do work (process 3-4) which is usually a rotary action of turbine blade turning the output shaft as gas is expanded and finally ejected as exhaust gas as waste heat at end of process 4.

Section 2: Steam Turbine

The second section of the combined plant, referred to as the bottoming cycle (process 6 through 9), incorporates the steam turbine. Its working principles are delineated below:

1. The heat exchanger also known as heat recovery steam generator produces steam during process 7-8, by the action of the heat energy from the gas exhaust. Which is been used to heat up, evaporate and superheat water at saturated temperature and pressure supplied by the feed pump (process 6-7).
2. Process 8-9 is a steam turbine that uses heat energy in form of steam to produced mechanical work by the action of pressurized steam and controlled flow through the steam blade which produces a rotary action of an output shaft, describe by (Petrotech Incorporation, 2017)
3. While process 9-6 the steam is condensed by a condenser unit after work is done and brought back to saturated condition, which is reused as the working fluid continuously without disposing

2.2.1 Analytical modelling

It's imperative to show the basis of mathematical modelling behind the algorithms shown in latter section.

$$\text{Pressure ratio } r_p = \frac{P_{2'}}{P_1} = \frac{P_3}{P_{4'}} \quad (2)$$

Process 1-2' (isentropic compression)

$$\frac{T_{2'}}{T_1} = r_p^{\frac{\gamma-1}{\gamma}} \quad (3)$$

Process 3-4' (isentropic compression)

$$\frac{T_3}{T_{4'}} = r_p^{\frac{\gamma-1}{\gamma}} \quad (4)$$

The actual temperature changes for this cycle corresponding to T_4 and T_2 are influenced by the compressor and turbine efficiencies. Where these efficiencies are expressed as follow

$$\eta_c = \frac{T_{2'} - T_1}{T_2 - T_1} \tag{5}$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4'}} \tag{6}$$

The efficiency of the gas cycle can be determined using Equation 7

$$\eta_{GAS} = \frac{W_{net}}{Q_{in}} \tag{7}$$

Where;

$$W_{net} = W_{turb,out} - W_{comp,in} \tag{8}$$

$$W_{turb,out} = c_p\,(T_3 - T_4) \tag{9}$$

$$W_{comp,in} = c_p\,(T_2 - T_1) \tag{10}$$

$$Q_{in} = c_p\,(T_3 - T_2) \tag{11}$$

The power of gas turbine can be expressed as follow

$$P = W_{net} \times m_e \tag{12}$$

Also, for gas turbine, the relationship between power, speed and mass of exhaust flow rate are given by Equations 13 and 14, extracted using regression tool, from standard gas turbine performance curve shown in appendix A.

$$P = f(N) = -N1.4122 \times 10^{-13} + N1.0234 \times 10^{-2} - N^2 1.8923 \times 10^{-6} + N^3 3.7964 \times 10^{-10} - N^4 1.3118 \times 10^{-13} + N^5 1.5574 \times 10^{-17} \tag{13}$$

$$P = f(m_e) = -3.7014 \times 10^2 + m_e 5.6393 \times 10 - m_e^2 2.7636 + m_e^3 4.5921 \times 10^{-2} \tag{14}$$

Where the unit quantity P is express in Mega Watt and N is expressed in RPM

According to Rahman et al. (2011), the energy balance in the combustion chamber is expressed as

$$m_a C_{pa} T_2 + m_f \times LHV + m_f C_{pf} T_f = (m_a + m_f) C_{pg} \times TIT \tag{15}$$

Where TIT is turbine inlet temperature (T_3), and the contribution of T_f is negligible.

The above equation is reduced to

$$f = \frac{m_f}{m_a} = \frac{C_{pg} \times T_3 - C_{pa} \times T_2}{LHV - C_{pg} \times T_3} \tag{16}$$

Where the parameter f is the ratio of mass flow rate of fuel to air.

For a controlled volume,

$$m_e = m_a + m_f \tag{17}$$

Analyzing the heat exchanger

The ratio of mass flow rates, y is determined from an energy balance on the heat exchanger.

$$E_{IN} = E_{OUT} \tag{18}$$

$$m_s(H_8 + H_7) = m_g c_p (T_4 + T_5) \times 2 \tag{19}$$

(The factor of "2" introduced in the above equation signify that there will be two gas turbines in this power plant. This is done to balance the steam turbine against insufficient exhaust energy of gas turbine and minimum temperature for sulfuric action)

Thus, y is expressed as

$$y = \frac{m_s}{m_g} \tag{20}$$

Analyzing the bottoming cycle (steam turbine cycle)

The steam turbine is a good example of a heat engine, bearing in mind it uses heat energy in form of steam to produced mechanical work by the action of pressurized steam flowing through the steam blade which produces a rotary action of an output shaft. The steam turbine.

$$Pump\ work_{in} = (P_7 + P_6) v_6 \tag{21}$$

Enthalpies along the cycle are read from Steam Tables. The enthalpies are expressed as;

$$H = U + Pv \tag{22}$$

$$H_{sat\,mix} = H_f + xH_{fg} \tag{23}$$

The entropy S of steam is expressed as

$$S = S_f + xS_{fg} \tag{24}$$

Thus, dryness fraction is given as

$$x = \frac{S_f - S}{S_{fg}} \tag{25}$$

Efficiency of the steam cycle is given by the following equation

$$\eta_{Steam} = \frac{W_{net}}{Q_{in}} \tag{26}$$

Where;

$$W_{net} = W_{turb,out} + W_{pump,in} \quad (27)$$

$$W_{turb,out} = \Delta H = H_8 - H_9 \quad (28)$$

$$Q_{in} = \Delta H = H_8 - H_7 \quad (29)$$

The power of steam is thus,

$$\mathrm{Pow_s} = \mathrm{m_s} \times W_{net} \quad (30)$$

This steam turbine will be configured to match the power of the gas turbine by controlled mass flowrate of the heat recovery steam generator system.

Thus,

$$\mathrm{Pow_s} = \mathrm{Pow_g} \quad (31)$$

Thermal efficiency of the combine plant

$$\eta_{\mathrm{Combine}} = \frac{\mathrm{W_{net}}}{\mathrm{Q_{in(GAS)}}} \quad (32)$$

Where;

$$\mathrm{W}_{net} = \mathrm{W}_{net,gas} + y\mathrm{W}_{net,steam} \quad (33)$$

2.4 Analysis of electric motor – power speed and torque

Electric motors for propulsion are categorized into two DC drive and AC drive. However, the choice of motor depends on the operator and the power requirement of the ship, but marine propulsion motors are almost universally AC. In some cases, the chosen configuration is induction motor (synchronous) running on a constant voltage and frequency. Fig. 9 shows an AC Motor driven by variable voltage and frequency drive.

Operating the motor requires that the power from the generators is stepped down by the propulsion transformers feed into the converter. The converter is the equipment under a computer control switching, which convert a fixed frequency input usually 60 Hz to a variable frequency output for example 0 to 29 hertz, which will drive a 24pole synchronous motor and between, 0 to 145 rev per minutes.

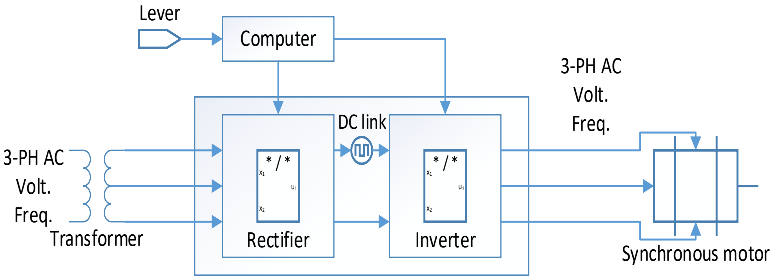


Fig. 9: A motor driven by variable voltage and frequency drive

For an AC induction motor, the speed of the motor is given by

$$N_s = \frac{120f}{p} \quad (34)$$

However, the motor rotor speed is quite below the synchronous speed. This is due to a constant slip which is between 2 to 6 percent of synchronous speed. Thus, the slip is expressed as.

$$s = \frac{N_s - N_r}{N_s} \times 100 \quad (35)$$

Carrying out substitution, the rotor speed is given as

$$N_r = \frac{(1-s)120f}{p} \quad (36)$$

From electrical equivalent, the torque of this machine is given by

$$T_{max} = \pm k \frac{\left(\frac{V}{f}\right)^2}{2\pi(L_s + L_r)} \quad (37)$$

Using regression tool for the volts per hertz chart in appendix A, the relationship between the voltage and frequency for constant torque operation is given as.

$$V = 7.6667f \quad (38)$$

For ship propulsion which requires maximum torque, the ratio of voltage and frequency must be constant (Van, 2011). Therefore, torque is directly proportional to the square of the ratio V/f. More specifically for a given motor, controlling the voltage and frequency in a constant ratio makes the motor operate at constant torque. The relationship between mechanical power and torque of this machine is given by Equation (39).

$$P(kW) = \frac{2\pi NT}{60} \tag{39}$$

According to Van (2011), the efficiency of electric motors is generally above 90% and this nominal efficiency is given as.

$$Eff = \frac{1}{1.026 + \frac{0.003162}{\sqrt{P}}} \tag{40}$$

where Power (P) is given in (MW).

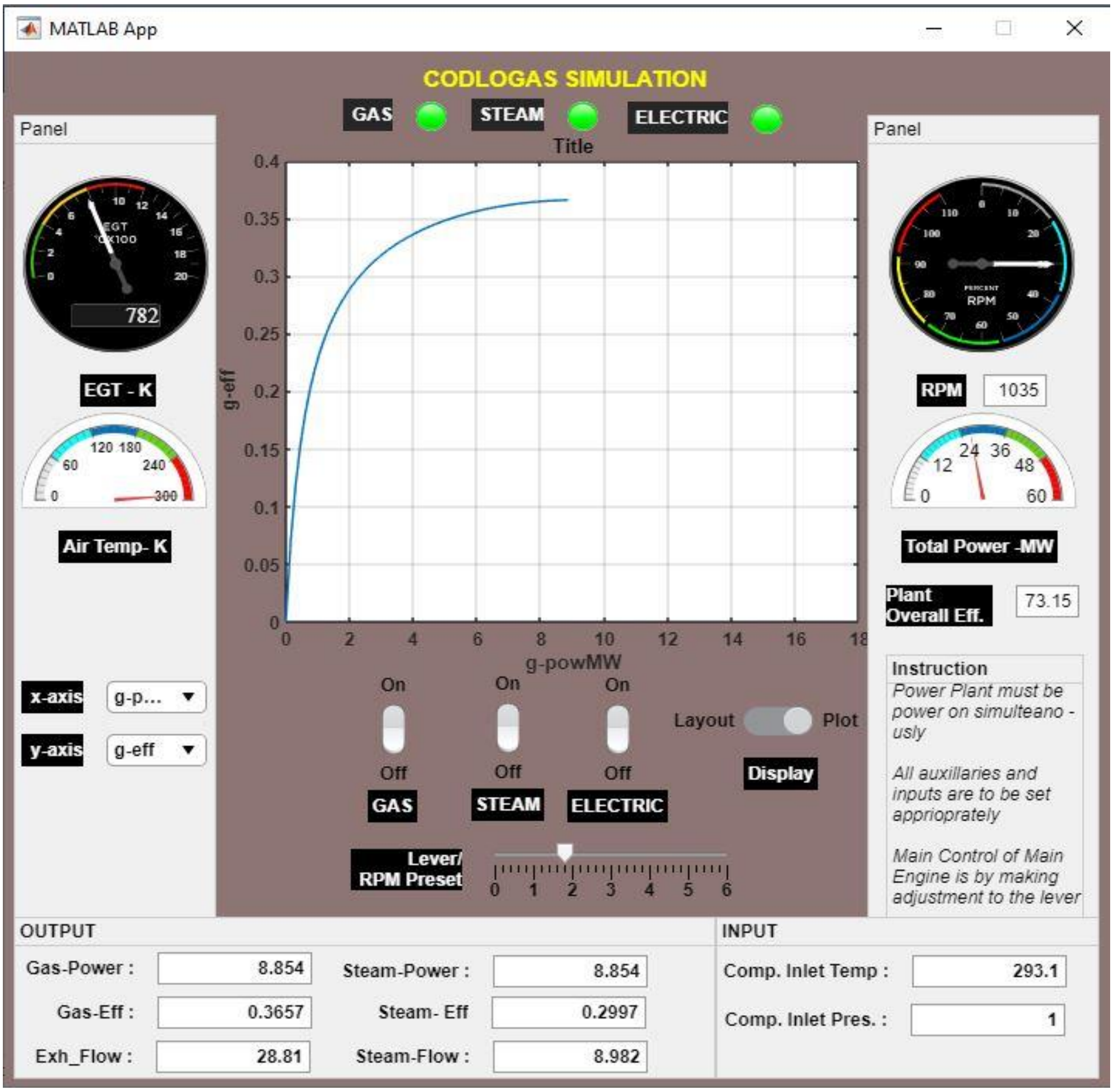
3. Results and discussion

3.1 Results description

The simulation conducted in this study investigates the influence of ship speed on the thermodynamic and electrical characteristics of the power plant. Utilizing a MATLAB Integrated Development Environment, the graphical user interface provides instantaneous visualization of the plant's behaviour, as depicted in Fig. 10. Additional visual materials are available on the attached CD.

The analysis commences with a thorough sizing of the two dissimilar powerplants (steam and gas turbine), detailed in Tables 3 and 4. This sizing process is conducted iteratively to ensure adherence to specifications of the gas turbine as shown in Table 2. Subsequently, the findings are presented, incorporating a comparative evaluation between an established marine gas and steam turbine and the developed Model in MATLAB program. Sensitivity analysis is then implemented to discern the effects of adjustments in the speed of the marine propulsion plant, designated as the input variable, on a spectrum of parameters encompassing power output, efficiency, fuel-air ratio, temperature, mass flow rates, and motor characteristics, delineated as the output variables. Methodically adjusting the speed input and scrutinizing resultant alterations in these output variables offer profound insights into the propulsion system's performance under varying operational conditions.

Table 4 summarized the parameter of interest of an electric motor, driven by a variable voltage and frequency drive, which is conform with ship propeller shaft.



x-axis: g-p...

y-axis: g-eff

RPM: 1035

Plant Overall Eff.: 73.15

Instruction

Power Plant must be power on simulteano - usly

All auxillaries and inputs are to be set appriopriately

Main Control of Main Engine is by making adjustment to the lever

Gas-Power : 8.854

Gas-Eff : 0.3657

Exh_Flow : 28.81

Steam-Power : 8.854

Steam- Eff 0.2997

Steam-Flow : 8.982

Comp. Inlet Temp : 293.1

Comp. Inlet Pres. : 1

Fig. 10. GUI of the MATLAB model, running

Table 3: Derived steam turbine properties

Parameters	Boundary Value	Control/Fixed
Pressure limit	5kPa – 0.6MPa	Fixed
Superheated temperature	500^{o}C	Fixed
Saturated temperature T_6	32.8^{0}C	Fixed

Table 4: Constant and constrain in modeling of VVFD

Parameters	Boundary Value	Control/Fixed
Phase	3 phase application	Fixed
Voltage	0-460volts	Control
Power	3 mega watts	Fixed
Pole	24 poles	Fixed
Synchronous speed	300 rpm	Fixed
Slip	0.06	Fixed

3.2 Results interpretation

The sensitivity analysis, depicted in Figures 11 through 18, elucidates the impact of plant speed on a range of selected parameters including power output, efficiency, fuel-air ratio, temperature, mass flow rates, and motor characteristics. Notably, the incorporation of a steam turbine as in CODLOGAS results in augmented power output and efficiency in contrast to individual gas turbine configurations.

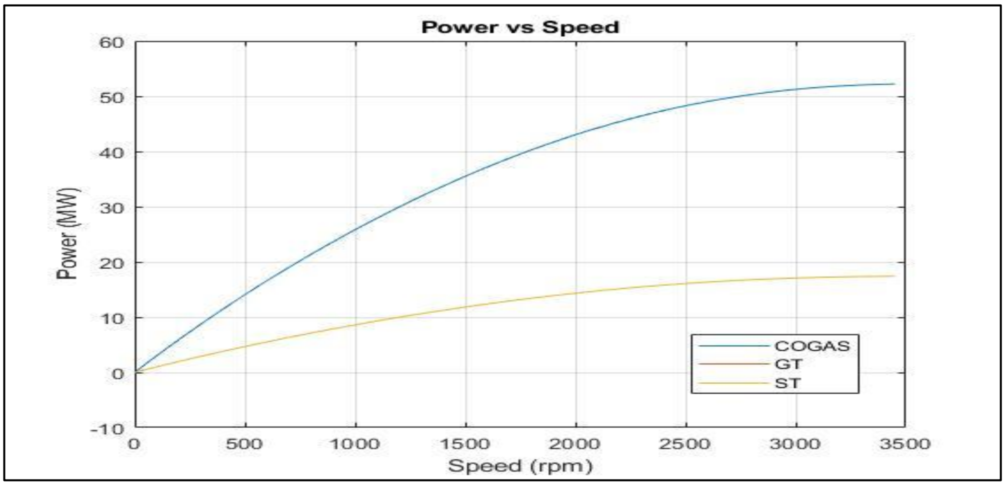


Fig. 11: Plot of power against speed

3.2.1 Effect of plant speed on power output

Fig. 11 is a plot of power against speed. The legend with their respective colours are used to distinguish various plots. Note that the plot for GT is overlaid by the plot of ST, tracing same path. The plot of GT and ST describes a plant running separately, a gas turbine and steam turbine as their main engine. Fig. 11 indicates that the power is less when it runs only the gas turbine compared to the boost when it is optimized by the introduction of steam turbine that uses the waste heat from the gas turbine to produces additional power. The boost in power is shown in the plot of COGAS which is configured to operate both gas and steam. There is a boost in power from approximately 34MW (2 x 17MW of 2 gas turbine) to about 50MW (combine mode). It is noted that power increases as speed increases in. The curve tends to be flat at peak values (say from 80%). At these peak values, an appreciable change in speed is followed by a negligible change in power.

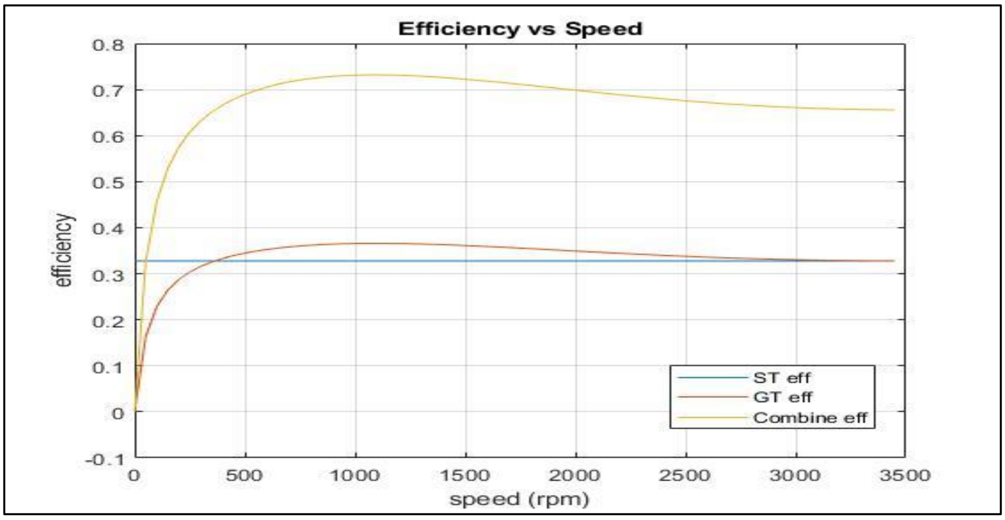


Fig. 12: Plot of efficiency against speed

3.2.2 Effect of plant speed on efficiency

Fig. 12 shows a plot of efficiency vs speed of the power plant with legend used to distinguish the plots. The plot of GT turbine shows that the efficiency rapidly increases as the speed of the engine is increasing gradually and reaches its peak value of 0.35 at about 1/3 of the max speed, then gently decreases as it approaches a constant value of 0.32 at max speed. An inference of these plots is that at low speed the gas turbine tends to be less optimum in terms of efficiency. The plot of Combined Plant shows that the efficiency rapidly increases as the speed of the engine is increasing gradually. This reaches its peak value of 0.73 at about 1/3 of the max speed, then gently decreases as it approaches a constant value of 0.65 at max speed. The plot of ST turbine shows that the efficiency of this plant remains fairly constant at approximately 0.33 as the speed increases. This constant, is as a result of the derived steam turbine operating at constant enthalpy around its cycle thus thermal efficiency is constant.

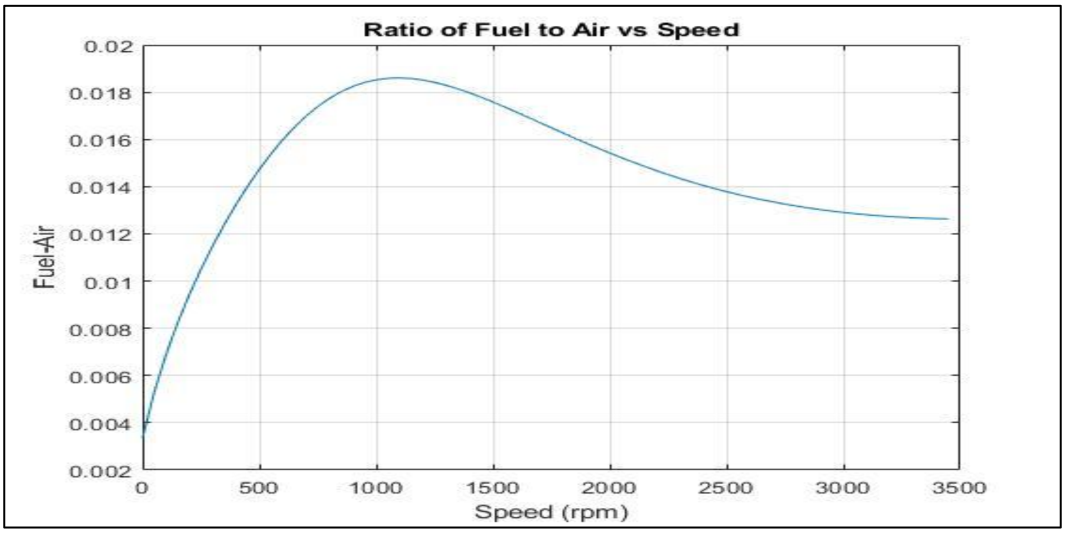


Fig. 13: Plot of fuel-air ratio against speed

3.2.3 Effect of speed on ratio of fuel to air

Fig. 13 shows a plot of fuel-air ratio vs speed. It is observed that for the gas turbine this ratio increases rapidly to a peak value of approximately 0.018 and gently trace a negative slope to maintain and approach an approximate value of 0.012. Indicating that engine performs best by consuming least fuel at high speed which is more economical from fuel consumption point of view.

3.2.4 Effect of temperature on efficiency

Fig. 14 shows a plot of efficiency vs temperature of plant. It is observed that the efficiency of the plant follows a logarithmic growth with increase in temperature. Where combustion chamber temperature is maximum and minimum at approximately 1400 K and 800 K respectively that of exhaust is maximum and minimum at approximately 800K and 400K. Also, temperature at the exhaust of the heat recovery steam generator is considered a vertical rise with fairly change in temperature which may be negligible as it is closer to 400 K. Inference here is that plant efficiency is greater at higher temperature which conformed to the second law of thermodynamics which literally states that the higher the temperature the more useful work the system can do.

3.2.5 Effect of speed on mass flowrates

Fig. 15 is a plot of mass flowrate against speed. The legends with their respective colours are used to distinguish various plots containing four set of data. The plot of gas turbine exhaust mass flow rate and that of compressed air for combustion are identical. They both increases as speed increases. The plot of mass of steam and fuel flow rate, traces a logarithmic curve, which gently increases with speed and then tend to be constant as the speed is further increased. The inference here is that for this configuration, the gas sections have the highest values for flowrates (exhaust gas) while the fuel supply is lowest.

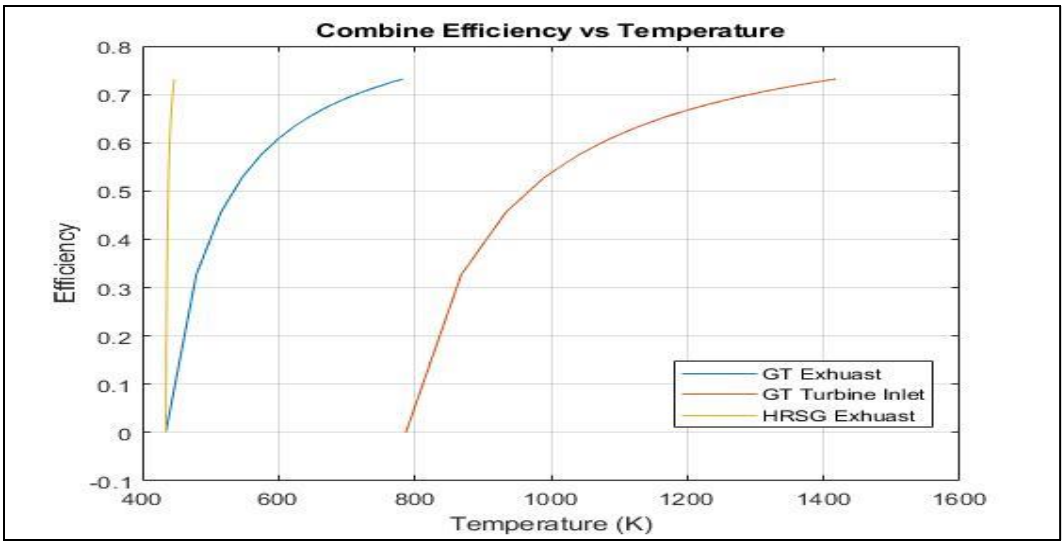


Fig. 14: Plot of efficiency against temperature

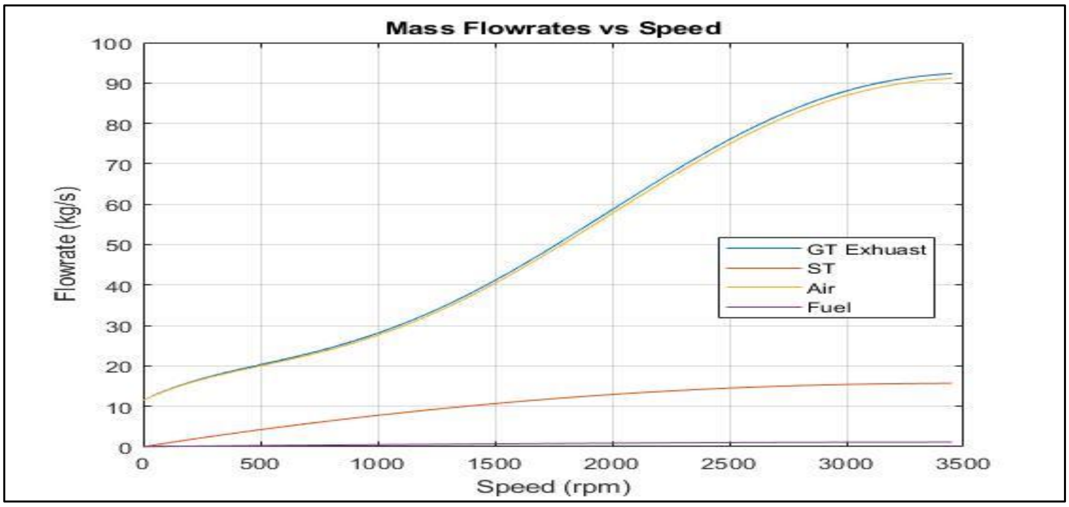


Fig. 15: Plot of flowrate against speed

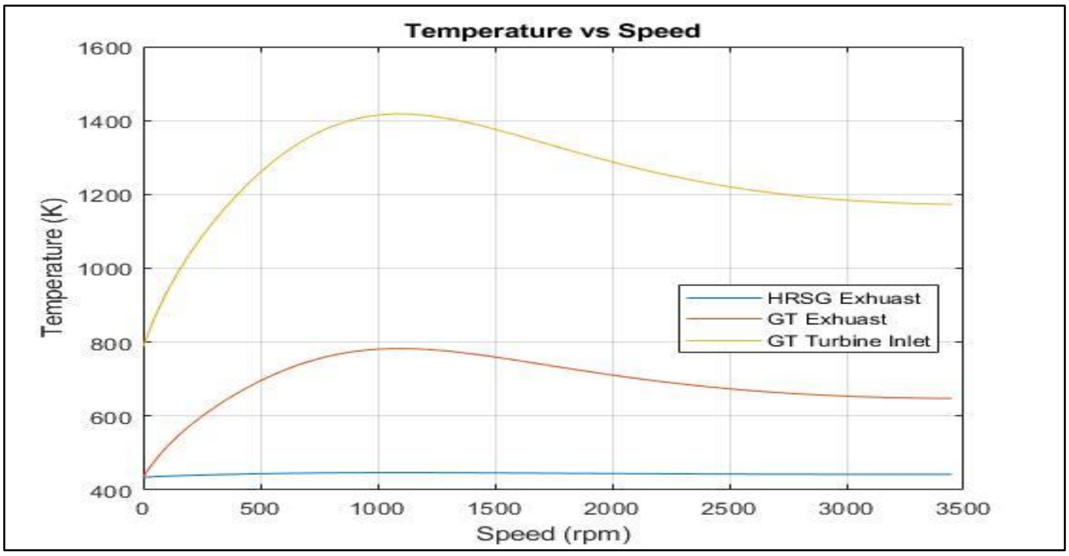


Fig. 16: Plot of temperature against speed

3.2.6 Effect of plant speed on temperature

Fig. 16 is a plot of temperature against speed. The plot of gas turbine inlet temperature and exhaust follow a parabolic curve with a gentle fall as it approaches top speeds. Both plots have a peak value at approximately 1400 K and 800 K respectively at about 1/3 of maximum engine speed, as the speed continue to increase the value gently and slowly fall to an approximate value of 1200 K and 600 K. That of the heat recovery steam generator at the exhaust trace a similar history but a negligible change in temperatures compare to the others two plot. Inference here is that temperature tends to drop a bit as the engine approaches maximum speed.

3.2.7 Effect of motor power on speed

Fig. 17 is a plot that shows the relationship of the power vs speed developed by the electric motor. This is a linear relationship, thus as the speed increases the motor tends to develop more power.

Fig. 17: Plot of motor power against speed

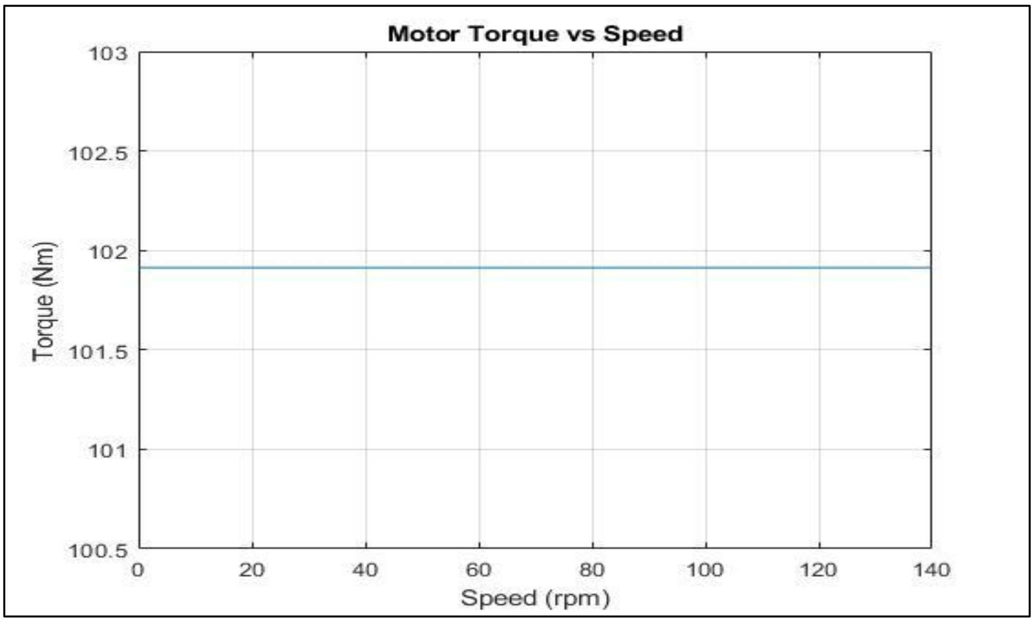


Fig. 18: Plot of motor torque against speed

3.2.8 Effect of motor torque on speed

Fig. 18 is a plot that shows the relationship of the torque developed by the electric motor vs the speed of the motor. The above plot shows a straight-line plot with its no slope. This indicates that as the speed changes the motor torque remain constant. It shows that the motor is operating under the region of constant torque, and it is driven by a constant ratio of voltage to frequency.

3.3 Result comparison

Comparing CODLOG with the new proposed plant, shows that the waste heat from the gas turbine is well utilized by the introduction of steam turbine, which is the configuration of CODLOGAS. Table 5 shows an existing marine/industrial gas turbine produced by Siemens Energy (2005) compare with results from developed program run at full and half the rated speed of SGT-500. Table 6 compares the results of a commercial steam turbine software* with results from steam power plant section of the developed program. This set as benchmark and for validation purposes.

Table 5: SGT-500 marine/industrial vs MatLab model for gas turbine results comparison

Parameter	**SGT-500**	**MatLab Model Run at Full Speed**	**MatLab Model Run at half the Rated Speed**
Output	17.40 MW	17.40 MW	13.05 MW
Efficiency	32.8 %	32.78 %	35.61 %
Exhaust gas flow	92.3 kg/s	92.29	48.66
Turbine rotor speed	3450 rpm	3450 rpm	1725 rpm
Speed range	0-100%	100%	50 %
Exhaust gas temperature	375 ℃	374.59 ℃	463.85 ℃
Gaseous fuel LHV	46,798 kJ/kg	46,798 kJ/kg	46,798 kJ/kg

Table 6: Steam turbine results comparison

Parameters	**Commercialize Software Run at Full Speed**	**Matlab Application Run at Full Speed**	**Commercialize Software Run at Half the Rate Speed**	**Matlab Application Run at Half the Rate Speed**
Turbine Power (MW)	17.40	17.40	8.606	8.606
Specific Consumption. (kg/kW.h)	3.463	3.457	4.155	4.154
Mass flow rate (kg/s)	16.74	16.71	9.932	9.931
Quality	0.9497	0.9508	0.9225	0.9233
Outlet Enthalpy (kJ/kg)	2440.7	2441.5	2399.4	2400.4
Inlet Enthalpy (kJ/kg)	3480.2	3483.4	3265.9	3267.7
Saturated MixtureTemp. (^{0}C)	32.8^{0}C	32.87	45.8	45.81
Inlet Pressure (kPa)	5	5	10	10
Superheated Temp. (^{0}C)	500	500	400	400
Outlet Pressure (MPa)	0.6	0.6	0.8	0.8

From the result interpretation in section 3.2, the following can be made of the proposed combined power plant (CODLOGAS):

i. The CODLOG meant for propulsion has its efficiencies lower than when it configured in CODLOGAS. This is shown in the plot of efficiencies. This is on the assumption that the electrical efficiency is same for both.
ii. The power of the steam turbine matches that of the gas turbines. An optimization for this, is achieved by ensuring that the gas turbine energy at exhaust is sufficient enough to

produce an equivalent power output in a combine mode. Thus, there is need for the double gas turbine in the midst and by adjusting the steam mass flow rate to its optimum level, an equivalent power is then achieved.

iii. There is a boost in power and torque available to the propeller shown in the plot of power vs speed for CODLOGAS plant compare to when it configures in CODLOG.

It is noteworthy that the results obtained from the analysis and simulation indicate that in a combined power plant configuration consisting of both gas and steam turbines for ship propulsion, for the steam turbine to deliver the same power output as the gas turbine, it is imperative that the gas turbine be present in multiple units. This becomes particularly crucial when the steam turbine boiler lacks independence or secondary firing capability. This observation is evident in the proposed layout of CODLOGAS as outlined in this research, as well as in existing COGAS configurations.

4. Conclusion

Comparing the proposed CODLOGAS configuration with existing CODLOG, reveals the efficient utilization of waste heat from the gas turbine through the introduction of a steam turbine. Specifically, improvements in efficiency and power output are notable, emphasizing the optimization potential of combined gas and steam turbine configurations. This research comprehensively addresses the parameters essential for the assessment and operation of combined gas and steam turbine plants, offering valuable insights for both integrated and separate configurations.

Competing interests

Authors have declared that no competing interests exist.

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