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Ivica Krmek
E-mail: ivica.krmek@unidu.hr
University of Dubrovnik, Maritime Department, Ul. branitelja Dubrovnika 29, 20000 Dubrovnik, Croatia
Vedran Mrzljak
E-mail: vmrzljak@riteh.hr
University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka, Croatia
Igor Poljak
E-mail: ipoljak1@unizd.hr
University of Zadar, Maritime Department, Mihovila Pavlinovića 1, 23000 Zadar, Croatia

Analysis and Comparison of Ship Propulsion Systems

Abstract

One of the highest cost of building the ship refers to the ship's propulsion system. It is therefore very important to know all the types and specificities of propulsion systems for the optimal selection. This paper presents the conventional and the combined propulsion systems, where are briefly given their characteristics and specificities. Special attention is given to the combined propulsion systems, whose extensive use is still under expectation. At the end, the paper discusses the cost calculation of a marine propulsion system of selected passenger cruiser and comparison to the possible alternative system.

Keywords: engine propulsion system, efficiency, economics

1. Introduction

The main propulsion enigne is part of the overall ship propulsion system where is included power transmission, bearings, propulsion (one or more of them), the gearbox and clutch (optional).

In this paper it is given overview of the following class of propulsion engines, which the authors considered the most complete:

a) **Conventional**, which include:
1) Diesel-engine propulsion engines
2) Steam-turbine propulsion engines
3) Gas-turbine propulsion engines
4) Electric propulsion engines

b) **Combined**, which include:
1) CODOG (Combined, diesel-engine or gas-turbine)
2) CODAG (Combined, diesel-engine and gas-turbine)
3) CODLAG (Combined, diesel-electric propulsion and gas-turbine)
4) CODAD (Combined, diesel-engine and diesel-engine)
5) COSAG (Combined, steam-turbine and gas-turbine)
6) COGOG (Combined, gas-turbine or gas-turbine)
7) COGAG (Combined, gas-turbine and gas-turbine)
8) COGAS (Combined, gas-turbine and steam-turbine)
9) CONAS (Combined, nuclear and steam-turbine)
10) Other combined drives

The distribution shows that the combined propulsion engines represent a combination of two or more conventional propulsion engine, and each combination has its own peculiarities.

2. Conventional propulsion engines

2.1. Diesel-engine propulsion engines

About 90% of today's ships, using diesel-engines as the main propulsion engines. The striking advantage of these propulsion systems is reflected in their efficiency (from 0.49 ~ 0.53), [1], and economical consumption of fuel. Propulsion, diesel can develop power up to 82440 kW per shaft according to the MAN engine selection catalogue Figure 1, [2]. In that sense they become a serious rival of steam-turbines in the field of high power. In the ship's propulsion, it is necessary to distinguish two types of diesel-engines: slow speed on the one and medium or fast speed on the other side.

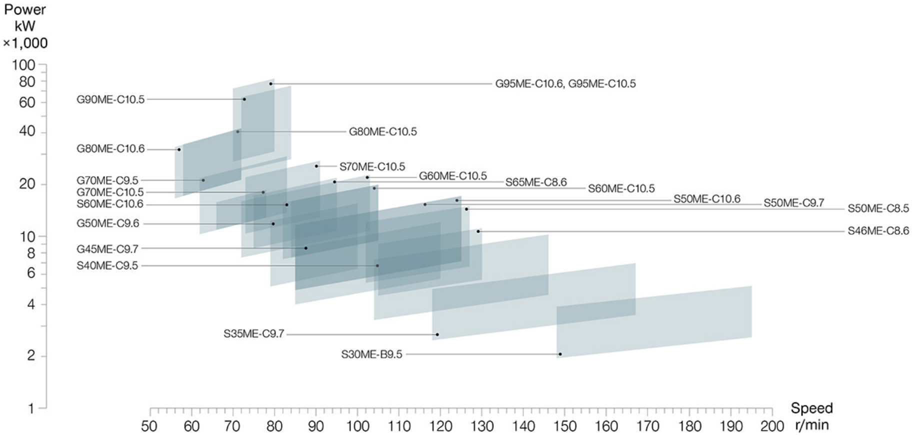

Figure 1. MAN Portfolio of two-stroke propulsion engines.

2.1.1. Slow speed diesel-engines

Slow speed diesel-engines are in most cases, two-stroke, and their main advantages are high efficiency, a relatively cheap fuel which they use, they can run different types of propellers (fixed geometry or pitch propeller), produce high permanently power (up to 90 MW) and typically they are without a gearbox.

Disadvantages of slow speed two-stroke diesel-engines are reflected in their massiveness and complexity, creating high intensity of noise and vibration, they require complicated piping of work and extra media, their work is unreliable at low speeds (old type), and produces higher emissions of nitrogen oxides (NO_x), which has extremely harmful effects on the environment.

Precisely, due to high emissions of nitrogen oxides, there are being introduced increasingly stringent environmental regulations which these propulsion engines must comply with.

Control and the regulation of these engines is complex and must be implemented with the aid of electronic control devices. Figure 2. shows a schematic control loop of the exhaust valve, fuel injection and referral systems on slow speed, two-stroke diesel-engine which manufacturer is Wartsila.

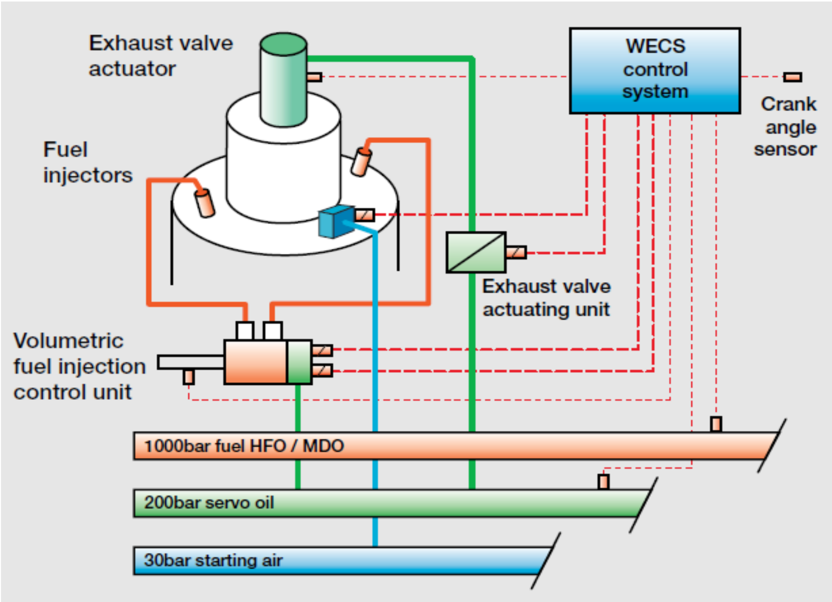

Figure 2.: Controll loop of exhaust valve, fuel injection and referral systems, [3].

2.1.2. Medium and fast speed diesel-engines

This type of diesel-engines are often used in the propulsion of smaller size ships. The benefits of this type of propulsion are reflected in a high degree of efficiency, they can run the various types of propellers, engines are smaller so their accommodation requires less engine room space compared to slow speed diesel-engines. Often, the propulsion system used is composed of a few medium speed or high speed diesel-engines, which ensures greater security.

The main disadvantages, compared to slow speed diesel-engines are greater complexity of design, the more expensive fuel, required the use of gearing, vibration, noise, and significant nitrogen oxide emissions. Two of the world's leading manufacturers of these propulsion engines are Wartsila and MAN. One of the major problems that they noticed is the overheating of the exhaust valve. The company Wartsila has solved this problem with a special cooling system of exhaust valves, visible in Figure 3., where is 01 Cylinder head, 02 Exhaust seat ring, 03 Exhaust valve and 04 O-ring.

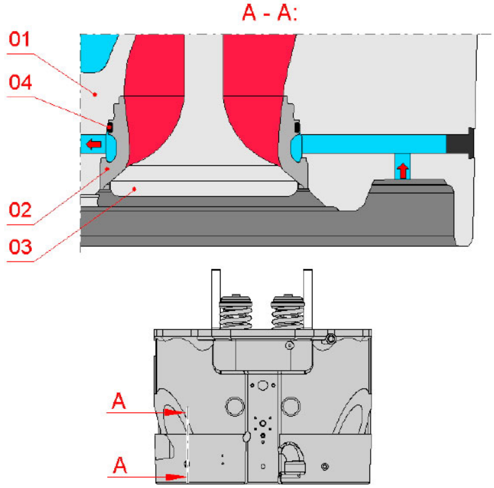

Figure 3.: Exhaust valve cooling system using cooling ring [4].

2.2. Steam-turbine propulsion engines

Based on figures for the last several years, steam-turbine drive is present in the world's merchant navy but limited mostly to the LNG fleet, where it's shear decreases from 2010 on, but is still present in the some of the largest shipping companies. For example K Line share of steam ship in their LNG fleet is 67% in total [5]. The biggest advantage of steam-turbines, compared to other propulsion systems consists in the fact that these engines are suitable for getting maximum output power. Marine steam-turbines are built for the power up to 100 MW, while on the warships were built for the power up to 300 MW. Steam-turbine, therefore, have the advantage on the field of very large power supply.

2.2.1. Conventional steam-turbine propulsion engines

The advantages of steam-turbine propulsion engines are reflected in a very quiet and peaceful work, low maintenance costs, high drive security, high durability and good torque at low revolutions. They offer the possibility of the ship propulsion with slow steaming, and are more elastic in running conditions then diesel-engines. The disadvantages are their higher fuel consumption, compared to diesel engines, the need for a separate turbine for astern drive, the time required to start astearn (turbine can be rotated in one direction only), and poor maneuverability of the ship. Steam reciprocating engines was long ago thrown out of use due to the fact that with the efficiency from 0.15 to 0.20 can not compete with other propulsion engines.

In terms of general efficiency, steam-turbine becomes a rival of diesel-engines in the field of power over 20 MW and its prominent advantage is greater with greater strength. An overview of the marine steam-turbine propulsion plant for operation of LNG tanker can be seen in Figure 4. More deep insight to these plants are given in literature [6-8], where is noted that the turbines are highly efficient engines, however main boilers are the primary dsource of exergy destruction what is degrading efficiency of such plants. Positive aspect of such plants is that less maintenance investment is requiered comaring to the other propulsion systems.

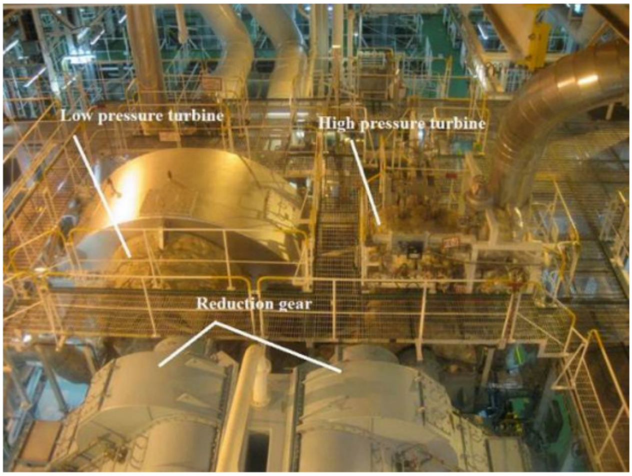

Figure 4.: Main steam-turbine propulsion system [9].

2.2.2. Nuclear propulsion engines

Nuclear drive is a specific type of the steam-turbine system because it ultimately produces water vapor which runs steam-turbine rotor. Difference compared to conventional steam-turbine drive is that the heat needed to create water vapor is produced from nuclear reactor, therefore there is no fuel combustion, and the entire process of generating heat is performed without the presence of oxygen.

This steam turbine dominantly operates with wet steam. HPC of this turbine has two steam extractions. After HPC, it is performed process of steam reheating, which in the case of nuclear power plant consists of moisture separation and reheating. LPC of steam turbine from nuclear power plant has three steam extractions. After LPC, remaining steam mass flow rate is delivered to steam condenser. Figure 5.

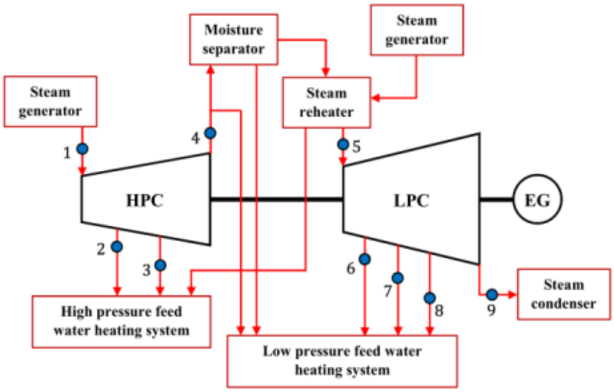

Figure 5.: Nuclear system in two circulating circuits [10]

If the main propulsion engine, in addition with the nuclear system, used electric propulsion, we get a combined system called CONAE or CONOE (Combined Nuclear And / Or Electric). CONAE system is applied in the case of simultaneous operation of nuclear propulsion and electric-motor, while CONOE system is used only in the case of a nuclear or in the case of the electric drive. These combined systems are often encountered in submarines due to additional security and the need for extremely quiet propulsion, while the ships are not used this systems for objective reasons (the size of electric motors), Figure 6.

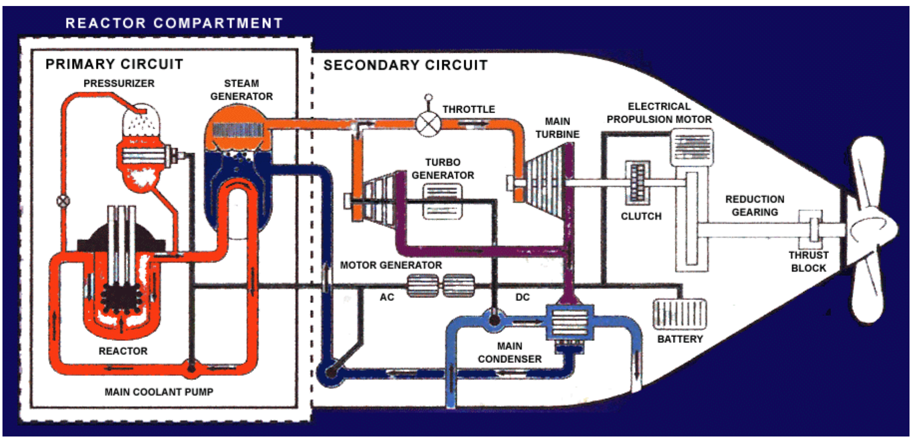

Figure 6.: Nuclear system in two circulating circuits [11]

2.3. Gas-turbine propulsion engines

Gas-turbines are one of the major propulsion engines. However, due to low efficiency, from 0.25 to 0.30, its application are now found only on battleships, altough General Electric today is building marine gas turbines with efficiency of 0.36 and 25 MW, [6], Figure 7. In recent years the gas-turbine is increasingly built on passengers, so-called H.S.S. (High Speed Ship) vessels. The main impediment to use gas turbine especially on the LNG ships before was the price which was higher comapring to the convetional engines. Today these prices are equalised 1350 $ per kW for the conventional diesel enigine vs 1250 $ for the open gas cycle turbinse [12]. Apparently there is a steel high influence of conventional engine buliers to the marine engine building sector what prevent broader implementation os such solution to the vessels.

The most important advantages are reflected in the fact that these are the least propulsion engines (by dimensions), small dimension engines gets a high power, they creating a minimum of vibration, have a minimum of moving parts, realize high-speed rotation of the output shaft, spend a little oil for lubrication and they have ability for fast-moving operational start.

The disadvantages are reflected in a expensive fuel necessary to drive these engines, they can rotate only in one direction, have the highest production costs of all the propulsion engines because of high quality materials resistant to high pressures and temperatures, it is necessary to use gearboxes and still not sufficiently high efficiency.

For all closed (circular) thermodynamic processes, including the gas-turbine, there is a rule that the higher efficiency of the process can be obtained with the higher combustion temperature of the working fluid in the combustion chamber. Limiting factor is a characteristic of the material in input circuit of gas-turbine. To increase efficiency, many gas-turbines have specific ways to utilize the heat of exhaust gases with the help of recuperator. Recuperators are heat exchangers which waste heat from gas-turbines used to heat the air at the exit of the compressor, respectively, before the entrance to the combustion chamber.

In marine systems it can be used three types of gas-turbines: with an open process, open process with warming air after compression and closed process.

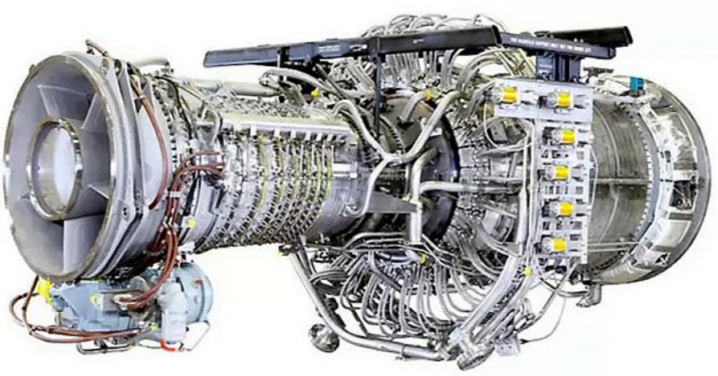

Figure 7.: GE Marine Gas Turbine Engines for Constellation Class Frigates, [13].

2.4. Electric propulsion engines

The first significant application of electric propulsion had the war navy and first in the submarines. The first submarine was driven by electric-motors, fed with energy from the batteries. These propulsion engines were used solely for quiet operation and features of navigation without oxygen. Later, the submarines use nuclear propulsion, with the indispensable electric-motors that are used primarily as safety equipment in failure case of nuclear reactor.

Electric propulsion engines have many advantages over other types of propulsion engines and they are most evident in low fuel consumption, low noise and vibration, reduced emissions (especially NO_x), increased safety of the ship, and the extension of exploitation life of the boat.

The only obvious drawback of electric propulsion engines are high total construction costs of the ship, which will in future increasingly declining due to high competition of manufacturers of such propulsion engines and their equipment.

In Figure 8. visible are the basic elements of the electric propulsion systems, which are (from left to right): the primary mover (diesel-engine, gas or steam turbine); generator; transformer; frequency converter; synchronous or inductive propulsion electro-motor; and at the end, the propeller shaft and propeller. The same figure shows the approximate power losses in each element of electric propulsion system [14].

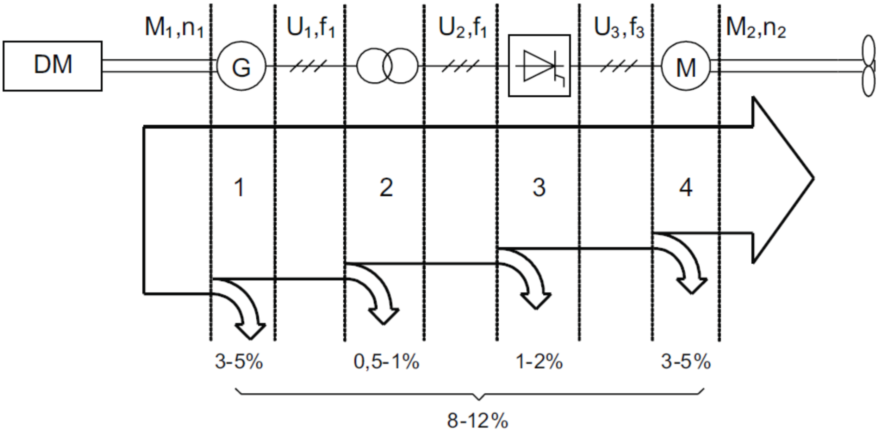

Figure 8.: Electric propulsion system basic elements and power losses.

Total power losses on all elements of the electric propulsion system is between 8 and 12%, which is much higher compared to diesel-engines, where the power losses from the primary drivers to the propeller is between 2 and 4%, which is one of the advantages of diesel-engine propulsion system.

The latest systems of electric propulsion engines operating with the help of swivel thrusters (AZIPOD), which further increases the advantages of this propulsion. Thrusters don't have shaft-line, they have much smaller moment of inertia, and thus more dynamic. Today electric propulsion, which is based on electric-motors with permanent magnets, due to increased hydrodynamic efficiency, significantly reduces the losses and thus fuel consumption, Figure 9.

Figure 9.: AZIPOD propulsion system, [15].

3. Combined propulsion engines

The combined propulsion engines give an example how a combination of more conventional propulsion engines can achieved optimization. These propulsion engines operating on the principle of interdependence, which means that the disadvantages of one propulsion engine make up by the other and vice versa. The combined propulsion engines called, because of its complexity, the combined systems.

3.1. CODOG (COmbined Diesel Or Gas) and CODAG (COmbined Diesel And Gas)

At each propeller shaft of CODOG system there is a diesel-engine for cruising speed and a gas-turbine with reduction gearbox for maximum sailing speed, Figure 10. At the time of inclusion of gas-turbine, diesel-engine are excluded from drive. Boats for which applies CODOG system are mainly a warships.

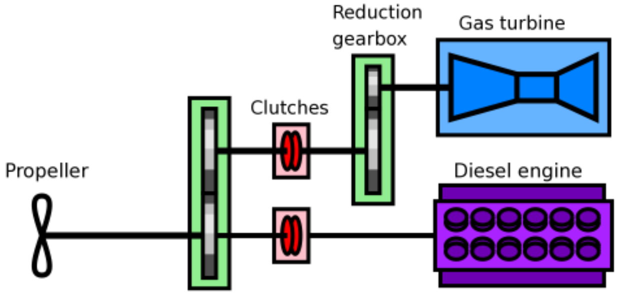

Figure 10.: CODOG propulsion system with a single propeller driven, [16].

CODAG system for sailing at a cruising speed use diesel-engines, while achieving maximum speed of navigation includes the gas-turbine in a joint work with diesel-engines. Simultaneous propulsion with two types of conventional propulsion engines requires a complex system of gearing, Figure 11., in order to ensure safe and reliable operation. In this propulsion system is common to use a diesel-engine for each propeller shaft and one gas-turbine at the two shafts.

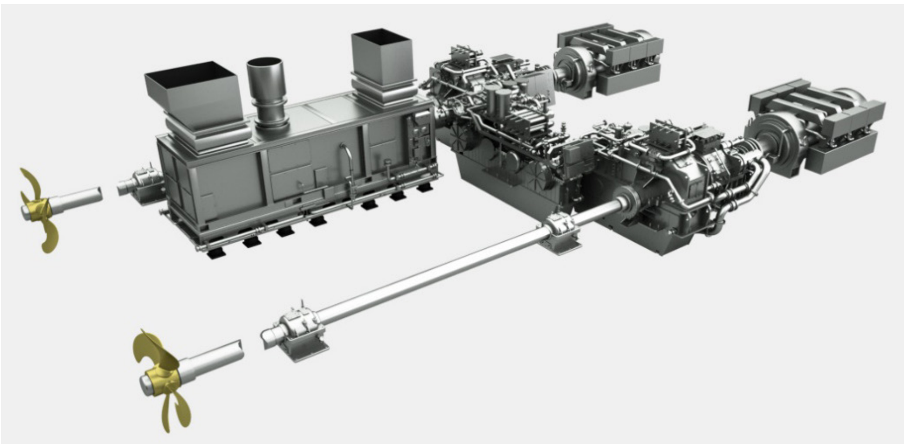

Figure 11.: CODAG system for driving the ship with two propellers, [17].

These systems according to manufacturer could be with following technical specifications:
Diesel engines output: up to 20,000 kW
Gas turbines output: up to 40,000 kW
Electric engines output: up to 15,000 kW
Installed overall output: 100,000 kW or more

3.2. CODLAG (COmbined Diesel-eLectric And Gas)

In the period of usual cruising, the system uses electric-motors drive, while achieving greater speed of navigation requires the inclusion of a gas-turbine in a joint operation with electric-motors, Figure 12. The system offers many advantages in terms of reducing noise and vibration, and represents a modification of CODAG system. The biggest drawback is large number of expensive parts, but the investments may pay off after 2-3 years of the system exploitation.

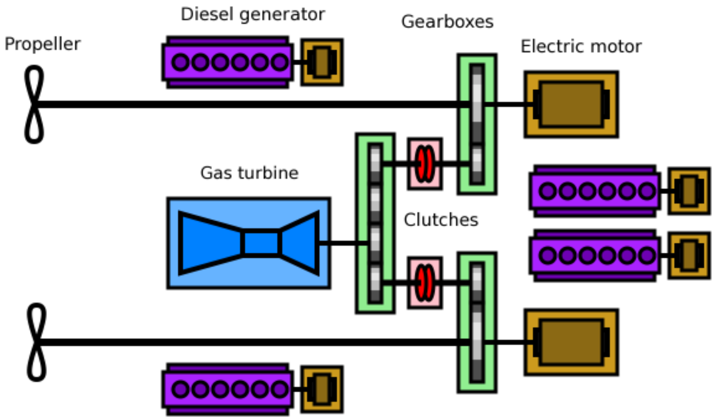

Figure 12.: The basic scheme of CODLAG propulsion system, [16].

3.3. CODAD (COmbined Diesel And Diesel)

The system consists of two diesel-engines, and propulsion can be achieved with only one or two diesel-engines simultaneously. Diesel-engines are small or medium size, so it requires less engine rooms, and produces less noise and vibration, Figure 13.

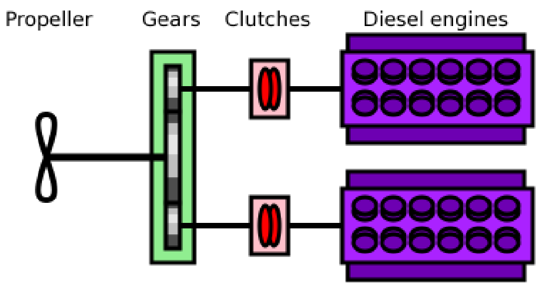

Figure 13.: Combined CODAD propulsion system, [16].

3.4. COSAG (COmbined Steam And Gas)

Gearboxes and couplings allow this system to perform self-propulsion with gas-turbine engine, with self-steam-turbine engine or gas-turbine and steam-turbine engine at the same time, Figure 14. COSAG system has the advantage because of the reliability of steam-turbine engine at cruising speed of navigation, and, on the other hand, due to very high accelerations and quick start thanks to gas-turbine engine.

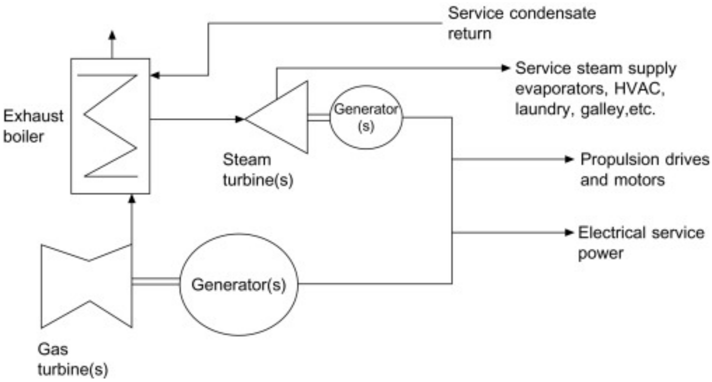

Figure 14.: COSAG propulsion system, [18].

3.5. COGAG (COmbined Gas And Gas)

COGAG is a propulsion system that mostly uses two or four gas-turbines as propulsion system, Figure 15. Small turbine have higher efficiency, but provides less power, and it is used for crusing speed of navigation. If the need for achieving higher sailing speed arise, smaller turbine are running both with a larger turbine. Two gas-turbines operates in a joint operation, so advantage of this system is that there less fuel consumption during crusing speed of the ship.

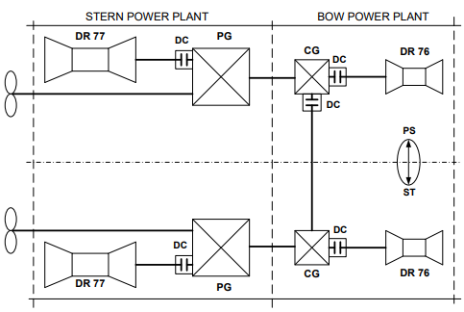

Figure 15.: COGAG propulsion system, [19].

3.6. COGAS (COmbined Gas And Steam)

This is a combined process in which the propulsion system involved in gas and steam-turbine systems, Figure 16. COGAS system can realized independent propulsion only with gas-turbine, but not with the steam-turbine system due to the fact that the steam-turbine system using the heat of exhaust gases from gas-turbine to create superheated steam that drives a steam-turbine.

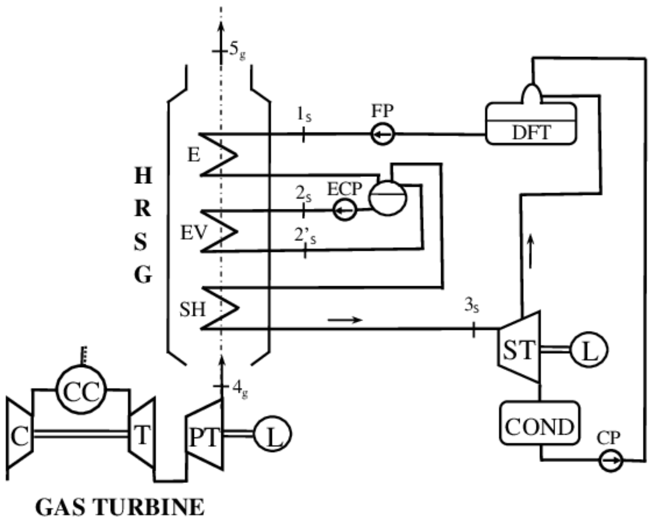

Figure 16.: COGAS propulsion system, [20]

If the propulsion system used COGAS similar to Figure 15, but with electric motors before the propeller shaft, such a system is called COGES (COmbined Gas-Electric and Steam). This system is often used as an upgrade of marine propulsion systems that use gas-turbine engines as the main propulsion system, eg. COGAG system.

The ships, which are used COGAS propulsion system, generally are a large passenger and warships that were in launching only had gas-turbine propulsion system, and it proved too expensive and unprofitable as an independent, so on such vessels made modifications to this system of propulsion.

3.7. CONAS (COmbined Nuclear And Steam)

These systems are used exclusively on military ships, and they are characterized by two additional conventional boiler to produce superheated steam, installed near the nuclear propulsion system [21]. Overheated steam obtained using the two additional boilers allows to run two steam turbines that are connected via gearingbox to the propeller shaft (usually two propeller shafts). Steam propulsion system is extremely safetly, so the crew use it in case of trouble or malfunction of a nuclear reactor.

The most famous ships using CONAS propulsion system have been battlecruisers Kirov class of the Russian Navy's, Figure 17.

Figure 17.: Battlecruiser Kirov class of the Russian Navy's

3.8. Other combined engines

In the list of other combined engines are included the specific performance of, until now presented systems, as well as systems that are still in the experimental stage or adjustments phase.

Systems in an experimental stage or adjustments phase are based on the nuclear propulsion and that are CONAN (COmbined Nuclear And Nuclear) and CONAG (COmbined Nuclear And Gas) propulsion systems. It is known that such systems are used for operation of military vessels by the U.S. and the Russian Navy, and that they are constantly improving them.

4. The efficiency illustration of COGAS propulsion system in relation to diesel-electric same power system for passenger cruise "Millennium"

4.1. Economic cost-based comparison in 2022. year

Proper selection of the main propulsion engine is reflected in the calculation of its efficiency in comparison to other propulsion engine with the same power, and by taking into account the characteristics and specificities of the boat on which it is applied.

According to a study of MAN company in 2000., into consideration was taken COGAS propulsion system of passenger cruiser “Millennium” [22], which consists of two gas-turbines (each with power 25 MW) and one steam-turbine with power of 8 MW, and the whole system has an overall efficiency between 45 and 50%. For propulsion, cruiser used gas-turbines, while the steam-turbine is used to generate additional electrical power. In addition with COGAS system, on cruiser are mounted two thrusters (power of each is 19 MW). Thrusters should provide good maneuverability of the ship, and they can get involved in propulsion together with COGAS system to achieve the greatest speed of navigation.

Selected COGAS propulsion system of the cruiser, with the total power of 58 MW, is compared with diesel-electric propulsion system which consisting of five medium-speed diesel-engines (and the corresponding generators and electric motors), with total power of 61 MW, which could be a major competitor to COGAS system when shipowner choosing a propulsion system. To compare these two systems it should be taken the annual fuel costs.

The calculation of annual fuel costs is based on the following scenario of a typical weekly consumption: 60 hours a week in port (requires 10 MW), enough to work one medium-speed diesel-engine or one gas-turbine with a steam-turbine. This scenario includes the 3840 work hours for each diesel-engine or 6150 hours for each gas-turbine. For this scenario the annual costs of fuel have been calculated at average prices of marine fuel markets of northwestern Europe for the month of May, 2022., and given in Table 1.

Table 1.: Annual fuel costs for COGAS system in relation to diesel-electric propulsion system, for year 2022 as per bunker prices global ports 20 average, [23].

Anual cost for COGAS propulsion system (58) MW and Diesel – Electric propulsion system (61 MW) in million $.		
	COGAS	Diesel - Electric propulsion
Fuel	MGO	HFO 380 cSt
Fuel price, $/ton	927.5	588.5
Fuel consumption, ton	45120	39540
Annual fuel costs, million $	41.84	23,27
Additional fuel for steam production (17 tonnes/h), tone	1000	7050
Additional fuel costs, million $	0.93	4.15
Total annual fuel cost, million $	42.77	27.42

The difference in annual fuel costs between COGAS system and diesel-electric propulsion system is U.S. $ 15.35 million!

Cost of extra fuel used in boilers to produce steam are also included in Table 1. COGAS system needs less extra fuel for steam production, actually only in cases where the ship is berthed in the harbor. One of the most important reasons for spend a lot of extra fuel to produce steam by diesel-electric system is the fact that system consumes more fuel, as the number of diesel-engine running is smaller.

The fundamental question is whether much higher fuel costs of COGAS system in relation to diesel-electric same power system can be compensated with higher income of 50 additional double-passenger cabins on lower decks of cruiser Millennium (additional cabins are built because choosen propulsion system brought a saving of ship space). This question arises after the statement of the shipowner that the additional passenger cabins will justify higher fuel costs of COGAS propulsion system.

If it is assumed that 90% of beds in these 50 additional cabins are always sold out, 50 weeks a year, and if we take the real price of accommodation, about 200 U.S. $ per person per day (for a small cabin with no windows), income from additional cabins will be approximately U.S. $ 7 million annually. The real profit of U.S. $ 7 million income is approximately 30% or U.S. $ 2.1 million (the remaining 70% are the cost of the owner to build and equip the cabins, the cost of food, cabins cleaning, laundry, taxes, etc.).

The difference in fuel price of COGAS system in relation to diesel-electric propulsion system can not be compensated with an additional 50 passenger cabins. If given difference in annual fuel costs of 7 million U.S. $ in favor to diesel-electric system reduced with the yearly earnings of 50 additional passenger cabins, which is U.S. $ 2.1 million, remains a difference of 13.25 million U.S. $ by a year irretrievably lost due to this selection of propulsion system.

4.2. Economic cost-based comparison in 2010. year

One important difference, which occurred before 12 years, is the fact that the price of crude oil on world markets oscilates and the ship's fuel consistently follows the same trend.

According to the stock market of marine fuel in Rotterdam [24] on the day of 05.02.2010., the fuel prices were the following:
MGO (Marine gas-oil) = 587 U.S. $ per ton
HFO (Heavy fuel-oil) = 441.5 U.S. $ per ton.

Profitability calculation of propulsion engines, based on their fuel prices, which was implemented for 2010. year, takes the same basic premise for calculation from 2022. year; a systems have identical consumption of primary fuel, extra fuel consumption is also identical (for steam production), and differ only by fuel prices, according to Table 2.

Table 2.: Annual fuel costs for COGAS system in relation to diesel-electric propulsion system, for year 2010.

Anual cost for COGAS propulsion system (58) MW and Diesel – Electric propulsion system (61 MW) in million $.		
	COGAS	Diesel - Electric propulsion
Fuel	MGO	HFO 380 cSt
Fuel price, $/ton	587	441.5
Fuel consumption, ton	45120	39540
Annual fuel costs, million $	26.49	17.46
Additional fuel for steam production (17 tonnes/h), tone	1000	7050
Additional fuel costs, million $	0.59	3.11
Total annual fuel cost, million $	27.08	20.57

For the observed period can be concluded that the difference in fuel costs for GOGAS and diesel-electric propulsion system is U.S. $ 6.5 million, which means that the expenses of COGAS system, in relation to 2022., and given diesel-electric system, reduce for the U.S. $ 8.85 million.

If we take away from this amount 2.1 million U.S. dollars for the average gross earnings under 50 additional passenger cabin on cruiser Millennium, the result is amount of 6.75 million U.S. $ which will shipowner lose in the 2010. due to the noneconomical choice of propulsion system.

Another trend in this case is very important and it shows that the cost of fuel for ship propulsion during period of 2010. - 2022. rapid increase.

5. Conclusion

The paper provides a comprehensive overview of marine propulsion plants, primarily of conventional, and then combined. While conventional propulsion plants can be found in the most of today's modern ships, combined are particularly interesting because they give the possibility to use more conventional propulsion engines on a one vessel. Although the combined propulsion plants, today, mostly may be found on ships of different military ships where their qualitative characteristics come to the fore most, it can be expected a significant implementation of such power plants also in passenger and cargo ships in the future. It is already proven that open gas turbine cycles have efficiency above 0.35, and with cogeneration these systems are reaching for the stationary plants 0.6 what is the highes current efficiency for the thermal generation systems. The influence of diesel engine builders is still high at the moment and this systems are still not in the wide use. The calculated example for the fuel cost and cabine accomodation income has no ecconomical justification for the selected example, however it is not conducted new generation of the gas and cogeneration plants into consideration where economical results may be different from the one which were presented in this paper. Selecting a propulsion plant for the ship is very complicated and complex task that needs to be done consulting experts, and producing cost-effectiveness calculations. In shown example it can be seen visible approach how to analyze and compare different propulsion systems, in order to ultimately selected the optimal solution. The significance of this paper is deliberation idea of marine engine plants from the conventional to the alternative which are present as a real option today.

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