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PROGNOSIS OF MARINE PROPULSION PLANTS DEVELOPMENT IN VIEW OF NEW REQUIREMENTS CONCERNING MARINE FUELS

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Abstract

Corrected VI Annex to MARPOL Convention requires from January 1st 2015 the use of low sulphur fuels on seagoing ships. The target of requirement is reduction of environment harmful substances in exhaust gases coming from marine fuels combustion. Areas of sea trade are divided into two zones: special Sulphur Oxide Emission Control Areas (SECA) for example Baltic Sea and areas outside SECA. On SECA sea areas the contents of sulphur in marine fuel should not excess 0.1% and on outside SECA the same is 3.5%. In the future i.e. from January 1st 2020, the maximum contents of sulphur in marine fuels on outside SECA areas should be 0.5%. These requirements create serious problems for ship owners operating worldwide. The first problem is considerable higher price of low sulphur fuels, which affects operational costs of fleet. The second problem is adaptation of ship engines to be fuelled with low sulphur fuels. At present, the heavy fuel oils being in common use on ships does not fulfil environ protection requirements. As a result, the use of new grades of marine fuels becomes necessity to fulfil environment protection requirements as well as price requirements to keep merchant fleet operation profitable. The wide use of "ecological fuel" i.e. natural gas as marine fuel is expected. The type of ship propulsion plant, which can be used in the future, will effect on the course of marine energetic plants development. The development of hybrid propulsion, electric propulsion, diesel engines fuelled with natural gas and turbine propulsion driven by natural gas. The paper includes proposal of combined turbine propulsion plant fuelled with natural gas, which according to authors can be leading type of marine propulsion plants in the future.

***Keywords**: low sulphur marine fuels, ecological propulsion of seagoing ships*

1. Introduction

Nowadays, the protection of sea environment is a very important problem in view of intensive sea trade development. International Convention for the Prevention of Pollution from Ships MARPOL 73/78 determines conditions to be fulfilled by sea trade and seagoing ships in aspect of sea environment protection. Revised VI Amendment for MARPOL Convention assigns conditions to be fulfilled by marine fuels regarding emission of environment harmful substances in exhaust gases after their combustion in marine engines and energetic plants. Especially the VI Amendment introduces from January 1st 2015 obligation of use low sulphur fuels on seagoing ships. Sea trade areas are divided into two zones: special Sulphur Emission Control Areas (SECA) for example for example Baltic Sea and areas outside SECA. On SECA sea areas the contents of sulphur in marine fuel should not excess 0.1% and on outside SECA the same is 3.5%. In the future i.e. from January 1st 2020, the maximum contents of sulphur in marine fuels on outside SECA areas should not excess 0.5%. Marine fuels fulfilling these requirements are named low sulphur fuels. Application of low sulphur fuels considerable increases operational costs of seagoing ships due to higher prices of these fuels and necessary of marine engines adaptation for such a fuels combustion. It creates the question: what kind of fuel and what kinds of ship energetic plants will be used on ships in the future. The problem is to be solved by new technologies and new designs applied to seagoing ships. Shipbuilding industry, sea trade and Classification Societies are characterised by conservative attitude in application of new technologies thus accepting designs verified in long-term operational experience. At the moment, it seems necessary to apply design solutions of on shore energetic industry where modern designs are successfully introduced during last twenty years. Analysis is to be carried out should take into consideration environment protection aspects as well as economic effects and costs of new designs. Actually, *Triple E* (*Economy, Environment, Efficiency*) standards are obligatory in sea trade and shipbuilding. They consist in assumption that seagoing ships are to be operated with high economy (low operational costs) using high efficiency engines operated in the lowest burdensome for environment manner.

2. Marine fuel in the future

Regarding environment protection, researches of harmful effect of exhaust gases from combustion of different kind's fuels are carried out. An ideal solution can be energetic plants running without exhaust gases at all. Electric propulsion using accumulators or fuel cells meet such a requirements. Still electric propulsion plants are characterised by limited range and relatively low power. Nowadays they are not fit for high propulsion power of large seagoing ship sailing worldwide. These ships should have large sailing range and autonomous propulsion plant. Today high power marine engines are fuelled by heavy fuel oil (HFO) stored in proper capacity storage tanks. Marine HFO as a residuum from crude oil refining does not fulfil requirements of exhaust gases cleanness due to harmful components mainly sulphur, vanadium, catalytic fines etc. The effect of HFO combustion is emission to atmosphere exhaust gases containing carbon dioxide, carbon monoxide, sulphur oxides, nitric oxides and solid particles.

The fuel, which can fulfil requirements of autonomous, large sailing range ships and requirements of marine environment protection, is natural gas (LNG – Liquefied Natural Gas). The natural gas is now widely used in onshore applications e.g. transport or power stations. A comparison of harmful substances contents in exhaust gases from diesel engine fuelled with heavy fuel oil and natural gas according [9] is shown in Fig. 1. The amount of emitted harmful substances from diesel engine fuelled with HFO is stated as 100%. Accordingly, the same engine fuelled with LNG emits 25% less carbon dioxide, 85% less nitric oxides, 100% less sulphur oxides and 100% less solid particles.

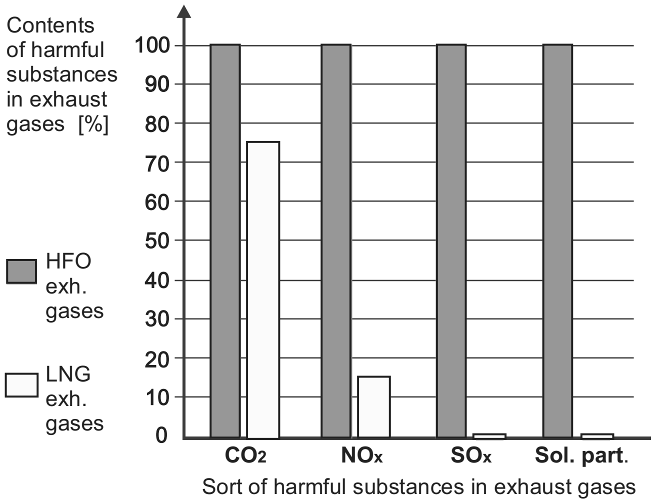

Fig. 1. Comparison of harmful substances contents in exhaust gases of diesel engines fuelled with heavy fuel oil and natural gas [9]

25% less carbon dioxide emission comes from higher calorific value of LNG than HFO. 75% less nitric oxides is achieved in most modern diesel engines with advance combustion process control. There is no sulphur content in natural gas fuel, which results in sulphur oxides zero emission. The same goes for solid particles emission because natural gas does not content components giving soot and ashes in exhaust gases.

Therefore, natural gas as marine fuel fulfils requirements of Revised VI Amendment for MARPOL Convention concerning harmful substances emission to environment after combustion.

Particularly requirement of maximum sulphur contents in marine fuel after January 1st 2020 is maximum 0.5% outside SECA areas.

As a result of analysis, it can be stated that natural gas is the future marine fuel.

3. Type of marine propulsion plant in the future

Nowadays operated marine energetic plants fuelled with natural gas are dual-fuel (DF) medium speed and low speed diesel engines, dual-fuel steam boilers and gas turbines. Dual fuel means they can be fuelled alternatively with LNG or HFO.

Recently many seagoing ships are driven by DF four stroke medium speed diesel engines. DF two stroke low speed diesel engines are still in the phase of construction and operational experiment. It comes from necessity of low speed diesel engines fuelling with natural gas under high pressure (20-26 MPa) injected directly to combustion chambers. Than a very complicated, special and expensive gas, compression plant is needed. Complicated technical system by nature is susceptible to operational disturbances and failures. In contrary four-stroke medium-speed engines, the gas is delivered to suction manifold before suction valves under considerably lower pressure (0.4-0.6 MPa). Thus, the system of gas delivery is simpler.

The prognosis of propulsion plant type tends toward wide use of four stroke medium speed diesel engines fuelled with LNG. Due to good operational experience with medium speed diesel engines, they will be used in mechanical gear propulsion plants on small and medium seagoing ships and in electric gear propulsion plants (diesel-electric) on large ships. It can be forecasted that DF engines will be replaced with spark-ignited engines fuelled only with LNG.

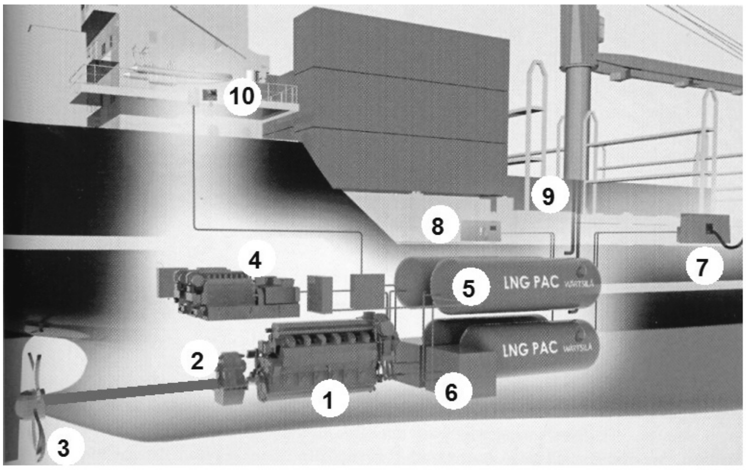

Fig. 2. Diesel engines gas fuelling system on container ship [9], 1 – main dual-fuel medium speed diesel engine; 2 – main gear; 3 – propeller; 4 – diesel generator set; 5 – pressurized liquefied natural gas tank; 6 – gas supply module; 7 – bunker station; 8 – control panel; 9 – vent pipe; 10 – emergency stop box

A Wärtsilä vision [9] of small container ship propulsion plant with gas fuelled medium speed diesel engine and mechanical gear is shown in Fig. 2. Natural gas is stored in liquefied form (LNG) in pressure tanks under pressure about 1 MPa. Main propulsion engine and auxiliary generator sets engines are fuelled by LNG prepared in supply module equipped with vaporisers.

The propulsion plant with electric gear changes engine room configuration. The number of LNG fuelled medium speed engines driving generators deliver electric energy for ship main propulsion and to ship electric network. This way the central on board power station consisting high power generator sets is created. There are no auxiliary generator sets and main propulsion shafting. It makes construction of engine room simpler. The central power station can be located in suitable part of hull, however due to ship stability rather in lower part. The ship is driven by electric motors placed on stern part of hull or by aliped propulsors (Fig. 3).

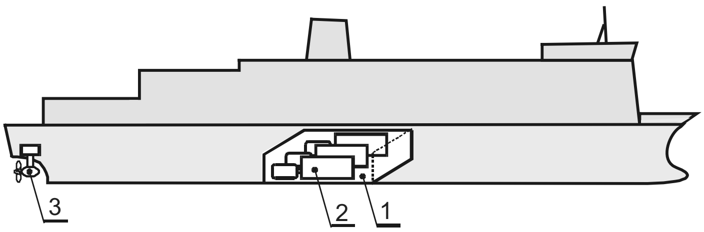

Fig. 3. Ship propulsion by diesel-electric propulsion plant with central electric power station using medium speed generator sets 1 – central power station; 2 – main generator set; 3 – azipod propulsor

Considering future type of large and very large ships propulsion plants the turbine propulsion plant fuelled with natural gas should not be omitted. Nowadays big number of LNG carries (*Liquefied Natural Gas Carriers*) carrying LNG cargo is driven by steam turbines. It comes from relatively easy adaptation of main boilers for operation in dual-fuel system and firing with natural gas. Boilers are fired with vapour of natural gas BOF (*Boil off Gas*) from cargo tanks under low pressure below one MPa. Natural gas is carried, in cargo tanks, in liquefied form at -163 ^{o}C temperature and evaporates due to heat penetration into tanks from outside atmosphere. Fuelling with gas fuel Boilers allow easy management of BOF. The alternative is liquefaction of BOF using energy consuming reliquefaction plant. In addition, LNG carriers are equipped with cargo managing compressors, which can be used for boilers fuel system supply.

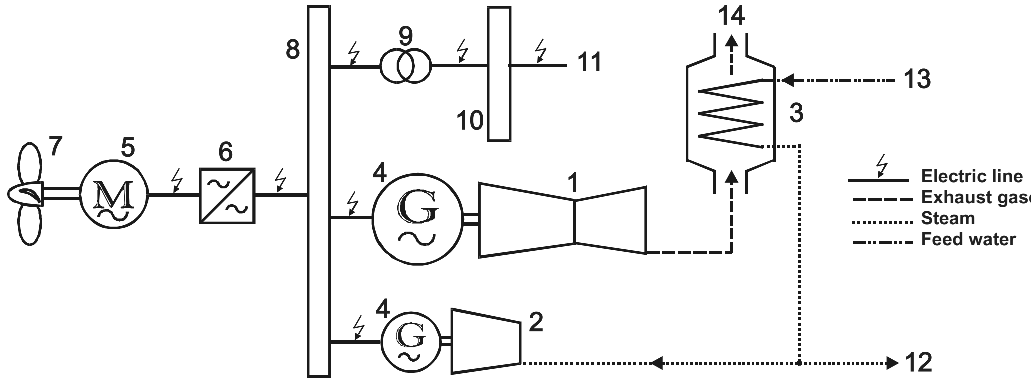

Fig. 4. Marine combined turbine propulsion plant with electric gear 1 – gas turbine; 2 – steam turbine; 3 – waste heat boiler; 4 – generator; 5 – electric motor; 6 – frequency converter; 7 – propeller; 8 – high voltage switchboard; 9 – transformer; 10 – low voltage switchboard; 11 –ship network supply; 12 – heating steam; 13 – feed water; 14 – exhaust gases outlet

Mayor disadvantages of steam turbine propulsion e.g. lower efficiency and large dimension of engine room lean towards gas turbine propulsion fuelled with natural gas. Due to low efficiency of gas turbines caused mainly by high-energy exhaust gases loss, they should be used in combined turbine propulsion system. Combined turbine propulsion system consists in thermodynamic connection of gas turbines and steam turbines in one energetic system (Fig. 4). Gas turbine 1 exhaust gases have high temperature (about 600^{o}C). They are used for steam generation in waste heat boiler 3. The steam is supplied for steam turbine 2 propulsion and for ship heating purposes 12. Both turbines (gas and steam) drive generators 4, which supply ship main propulsion electric motor 5 and ship electric network 11. Thermodynamic connection of gas and steam turbines increases overall efficiency of energetic plant due to minimising exhaust loss of gas turbine. Combined turbine energetic plants fuelled with natural gas nowadays are widely used in onshore power stations. They achieve 60% overall efficiency which is the highest value among contemporary energetic plants.

The use of fuelled with natural gas combined turbine propulsion plants with electric gear on large seagoing ships is very likely in the future. It is determined by many advantages in comparison to classic engine room equipped with low speed main diesel engine and diesel generator sets. It is:

– high and even higher overall efficiency,

- less complicated construction and operation of turbines than diesel engines,
- high reliability, long overhaul life, lower overhaul costs,
- lower engine room equipment and system costs (about 40%); according to [5] the ship engine room equipped with 50 MW combined turbine propulsion plant and electric gear consists about ninety important machines less, about thirty pumps less, 5600 meters of pipelines less and about 350 valves less, which gives about 1540 tons of engine room weight less without considering lower weight of turbines than low speed diesel engines,
- lower lubricating oil costs,
- no need of separate diesel generator sets for ship electric network supply,
- possibility of BOF natural gas use as a fuel on LNG carriers,
- considerably smaller engine room dimensions and weight due to high power concentration (according to Rolls-Royce about 30%), as shown in Fig. 5.

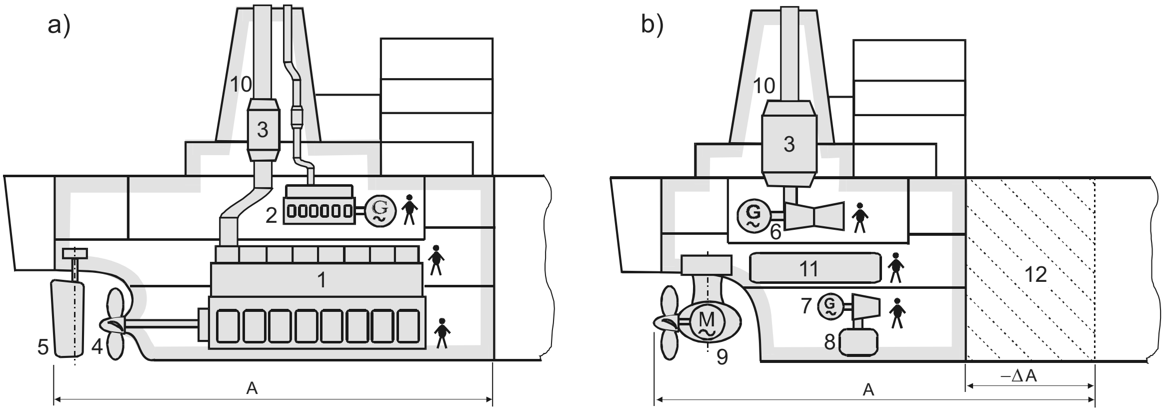

Fig. 5. Comparison of engine room dimension for ship driven with low speed diesel engine and with combined turbine propulsion plant with electric gear a) low speed diesel engine; b) combined turbine plant 1 – low speed diesel engine; 2 – diesel generator set; 3 – waste heat boiler; 4 – propeller; 5 – rudder; 6 – gas turbine generator set; 7 – steam turbine generator set; 8 – condenser; 9 – azipod propulsor; 10 – exhaust gas pipe; 11 – gas fuel reservoir; 12 – engine room space saving

Minimising of engine room space allows building smaller ship of the same cargo space but smaller power of propulsion plant. It results in smaller emission of environment harmful substances in exhaust gases.

4. The problem of propulsion plant efficiency

Nowadays *Triple* ***E*** (***E****conomy,* ***E****nvironment,* ***E****fficiency*) standard is hold in shipbuilding and ship operation. *Triple E Standard* results in use of most modern propulsion engines consuming smaller amount of fuel and in configuration of ship propulsion plants allowing the highest overall efficiency and the smaller emission of environment harmful substances in exhaust gases.

Considerations in points 1 – 2 determined the kind of future fuel and future type of ship propulsion plant. The use of natural gas fuel seems obvious. Regarding efficiency of ship energetic plants, the calorific value of gas fuel is important.

Types of dominating kinds of future ship propulsion plants are gas fuelled medium speed diesel engines and gas fuelled combined turbine propulsion plants both with electric gear. The first one is on smaller and medium ships, the second on large ships. In both case energetic plants will be based on central onboard electric power station supplying ship main propulsion and ship electric network. Separate diesel generator sets will not be used.

Considering overall efficiency of ship propulsion plants, in the future the present state of efficiency of different propulsion plants is worth to be noticed. Results of analysis carried out by [9] in the year 2000 are shown in Fig. 6. The diagram shows that diesel engines have higher efficiency in the range of power below 60 MW. In the range above 60 MW, the advantage of combined turbine propulsion plant can be observed. Nowadays the largest container ships need about 70 MW propulsion plants for main propulsion and ship electric network. According Fig. 6, combined turbine propulsion plants achieve overall efficiency about 60% in onshore power station having power 400-500 MW. The development of combined turbine propulsion plants allows achieving 60% efficiency from 40 MW marine propulsion plants used for large seagoing ship propulsion.

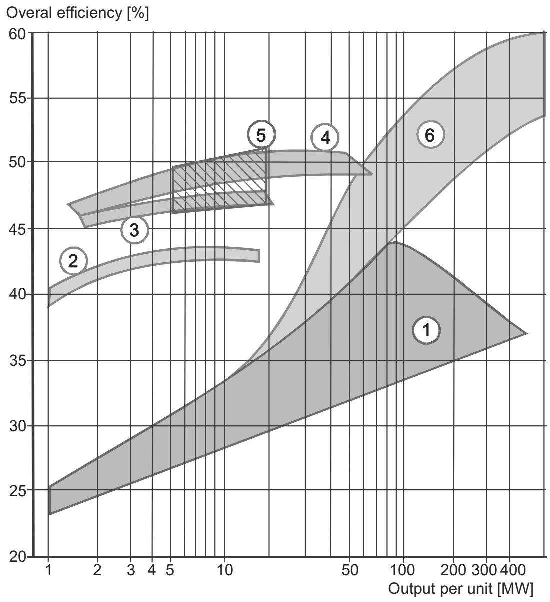

Fig. 6. Overall efficiency of different type propulsion plants [9], 1 – gas turbine, 2 – petrol engine, 3 – medium speed four stroke diesel engine, 4 – low speed two stroke diesel engine, 5 – medium speed four stroke diesel engine in combined system with steam turbine driven by steam from waste heat boiler, 6 – combined turbine propulsion plant

According to analysis carried out in Marine Power Plants Department of Gdynia Maritime University, the most important is to achieve maximum power of steam turbine connected with gas turbines. It is presented in Tab. 1 [4].

Tab. 1. Efficiency of 49.1 MW natural gas fuelled combined turbine propulsion plant depending on power distribution between gas turbines and steam turbine [4]

Power distribution between gas turbines and steam turbine [%]	85/15	80/20	75/25	70/30	65/35
Gas turbines power [kW]	41736	39280	36826	34370	31916
Steam turbine power [kW]	7365	9820	12275	14730	17185
Specific gas fuel consumption [kg/kWh]	0.157	0.148	0.139	0.130	0.120
Overall efficiency of plant [%]	44.0	46.8	49.9	53.5	57.6

Raise of steam turbine power is possible by application the most modern constructions for example Semi-Curtis control stage introduced by Kawasaki [6], which increases stage efficiency by 4%. Also, application of vacuum condenser considerably increases steam turbine efficiency in relation to the same with atmospheric condenser. Steam turbine should be driven by superheated steam. In the steam-condensate system, a number of feed water heaters should be used to increase system efficiency.

Regarding nitric oxides emission to atmosphere DLN (Dry Low NO_x) [1] systems should be applied in gas turbines. They consist in water or steam injection into combustion chambers or else variable number of nozzles delivering gas to combustion chambers at different turbine load.

The proposal of marine combined turbine propulsion plant with electric gear is shown in Fig. 7. Such a plant is classified as COGES type (*Combined Gas Turbine and Steam Turbine Electric Drive System*). COGES type propulsion plant creates central on board electric power station supplying ship main propulsion and ship electric network. The system also provides heating steam covering ship heat energy demands. Central power station consists of two gas turbines 1 and one steam turbine 2 driving generators 4. Gas turbines are fuelled by natural gas and steam turbine uses steam produced in waste heat boiler 3 HRSG (Heat Recovery Steam Generator) heated by exhaust gases from gas turbines. The ship is propelled by azipod thrusters 8, which simultaneously act as steering gear. Heating steam receivers use saturated steam from HRSG (inlet 30). The power of gas turbines is diversified to obtain acceptable efficiency of plant at partly load. Such a system allows three combinations of gas turbines power operating under high load i.e. in the range of good efficiency.

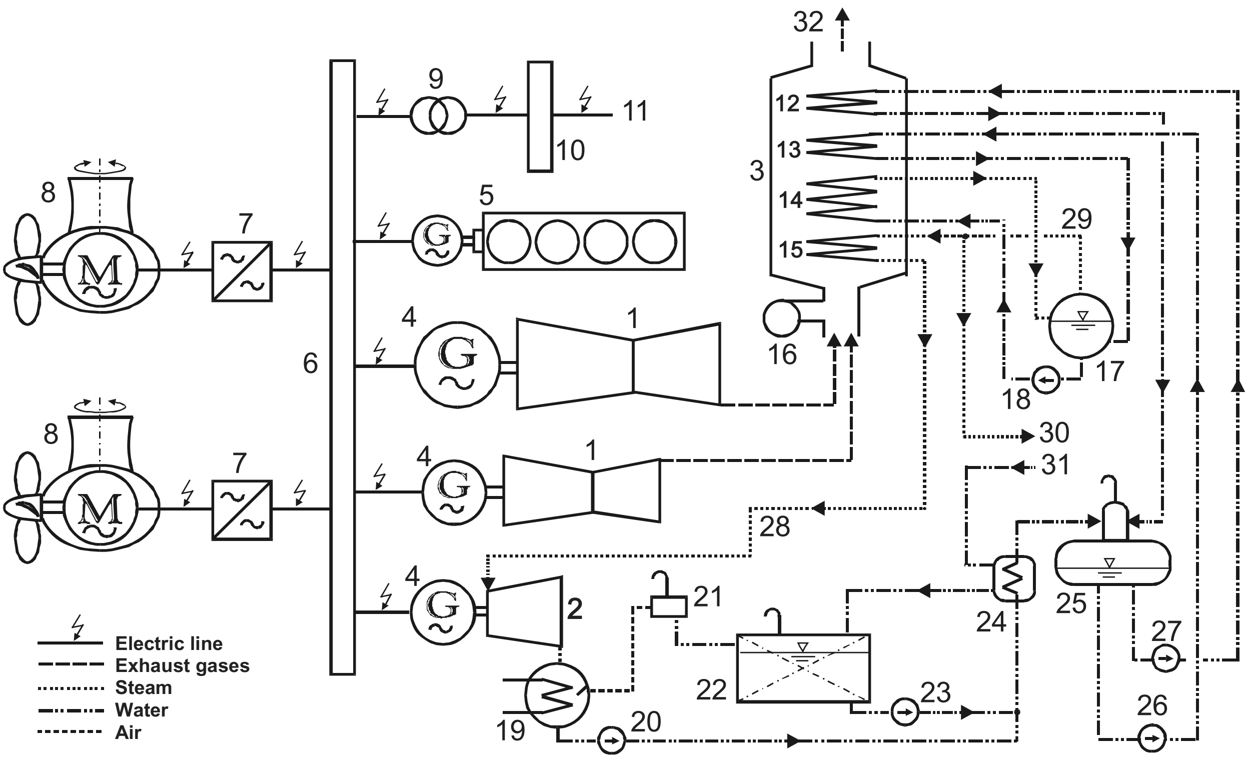

Fig. 7. Proposal of marine COGES type propulsion plant, 1 – gas turbine; 2 – steam turbine; 3 – waste heat boiler HRSG; 4 – generator; 5 – emergency diesel generator plant; 6 – high voltage switchboard; 7 – frequency converter; 8 – azipod propulsor; 9 – transformer; 10 – low voltage switchboard; 11 – ship network supply; 12 – deaerator water heater; 13 – feed water heater (economizer); 14 – boiler evaporator; 15 – steam superheater; 16 – auxiliary burner; 17 – steam drum; 18 – circulating pump; 19 – condenser; 20 – condensate pump; 21 – condenser vacuum system; 22 – drain and condensate tank; 23 – drain tank pump; 24 – low pressure heater; 25 – feed water deaerator; 26 – feed pump; 27 – deaerator heater circulating pump; 28 – superheated steam inlet into turbine; 29 – saturated steam from steam drum; 30 – heating steam delivery; 31 – heating steam condensate return; 32 – exhaust gases outlet

The steam condensate system shown in figure is single pressure type. Higher efficiency can be obtained in double pressure system where turbine is driven by steam under higher pressure than heating steam. However, double pressure system has more complicated boiler and piping construction. It increases investment costs and operation requirements although rise of efficiency is not big. The deaerator 25 utilising heat of gas turbines exhaust gases is installed in the system. Deaerator water heating increases steam-condensate system efficiency and executes water deaeration. Also, application of low-pressure water heater 24 increases system efficiency due to utilisation of condensate heat.

Waste heat boiler is divided into four heating sections: deaerator water heater 12, feed water heater (economizer) 13, evaporator 14 and steam superheater 15.

5. Logistic problems of natural gas use on future ships

Nowadays natural gas is used as marine fuel mainly on LNG carriers carrying LNG as a cargo. The use of natural gas on other seagoing ships creates necessity of worldwide natural gas bunker stations. The problem is analogous to the same in the past when the coal and liquid fuel were introduced on seagoing ships. The problem will be certainly solved if gas fuel will be commonly used on ships.

6. Conclusions

Concerning development trends of marine propulsion plants, in the future the following can be found:
- natural gas will be commonly used as marine fuel,
- central on board electric power station will dominate as seagoing ship engine room configuration,
- natural gas fuelled medium speed diesel engines with mechanical gear will be used on smaller ships,
- natural gas fuelled, spark ignited engines will replace dual fuel-diesel engines,
- natural gas fuelled combined turbine energetic plants with electric gear will be used on large ships,
- computerised engine room control systems will be commonly used on seagoing ships.

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