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C O N T E N T S

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COMPARISON OF FUEL COSTS BETWEEN COGES AND DIESEL-ELECTRIC PROPULSION SYSTEMS FOR CONVENTIONAL PASSENGER CRUISER PROPULSION

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Abstract: *The paper presented a comparison of fuel costs between COGES and Diesel-electric propulsion systems for large conventional cruise ship. COGES propulsion system installed on the analyzed cruise ship saves ship's space in comparison with Diesel-electric propulsion system. Diesel-electric propulsion system uses much more fuel for additional steam production and therefore, the additional fuel costs of this propulsion system are much higher in comparison with COGES system. Net profit of 50 additional cabins cannot compensate the difference in COGES system total annual fuel costs throughout the observed time period when compared to Diesel-electric propulsion system. The COGES propulsion system has much lower exhaust gas emissions in comparison with equivalent Diesel-electric system and therefore, in presented comparison, COGES could become profitable in the future if the emission regulations become more rigorous.*

KEYWORDS: FUEL COSTS, COGES, DIESEL-ELECTRIC, PROPULSION, PASSENGER CRUISER

1. Introduction

Advanced marine propulsion systems which combine several prime movers at the same ship were investigated by many authors so far, from the various different aspects.

Geertsma et al. [1] presented a complete review about the design and control of hybrid power and propulsion systems. Techno-economic and environmental risk analysis for advanced marine propulsion systems was investigated by Doulgeris et al. [2]. The method comprises several numerical models which simulate the life cycle operation of marine gas turbines installed on marine vessels. The economic model predicts net present cost over the operating life of the vessel by using stochastic analysis.

The different propulsion systems used on board vessels for the transport of Liquefied Natural Gas (LNG) were described and analyzed by Fernández et al. [3]. The analysis describes main characteristics of the propulsion systems used on LNG carriers along with its advantages and disadvantages, from its very beginnings up to the systems installed to date. The described propulsion systems include gas and steam turbines, combined cycles, two and four stroke internal combustion engines, as well as re-liquefaction plants, while encompassing mechanical, electrical and Dual Fuel (DF) technology systems.

Marine electric propulsion system was investigated by Yutao et al. [4]. Investigation of a tanker with twin podded propulsion was presented by Taskar et al. [5]. The effect of various factors that influenced ship propeller is quantified. Propeller performance in waves in terms of cavitation, pressure pulses, and efficiency is compared with the performance in calm water.

Fuel efficiency study based on the overall ship propulsion model was investigated by Zhao et al. [6]. An overall ship propulsion plant involves marine engine, propeller and ship dynamic model, which are completely included in the presented analysis. The whole ship voyage model was used to predict fuel consumption and exhaust emissions under different sailing conditions.

Unlike above, in this paper was presented an economic and profitability aspect of two complex and advanced marine propulsion systems - COGES and Diesel-electric systems which can be used for propulsion of a large conventional cruise ship. Comparison of annual fuel costs and additional fuel costs provides an insight into the proper selection of propulsion system. Total annual fuel costs were calculated for both propulsion systems and for thirteen different fuel prices in the period from 07.11.2016. up to 07.11.2017. In calculation was also taken the real saving of ship's space when COGES propulsion system was selected.

2. Description of COGES propulsion system installed on passenger cruiser

Passenger cruise ship Celebrity Millennium is one of several cruise ships which use COGES (COmbined Gas and Steam Electric) propulsion system [7]. Most of other passenger cruise ships use Diesel-electric propulsion systems due to its several advantages.

Celebrity Millennium COGES propulsion system is equipped with a pair of General Electric aeroderivative gas turbines with power of 25 MW each and a single steam turbine with a power of 8 MW. Each of those three prime movers drives an AC (Alternating Current) electric generator. Produced electric power is directed into two electrically driven podded propulsion units' Rolls-Royce/Alstom Mermaid azimuth thrusters with a power of 19 MW each. As each pod can be rotated horizontally through 360° if required, the need for rudder shaft lines, stern thrusters, steering gear bossing and brackets is eliminated. Gas turbines are the main propulsion devices and the steam turbine is used to produce additional electricity if needed. A steam turbine recovers heat from both gas turbine exhausts to produce steam. Electricity produced with steam turbine is not used only for additional drive of azimuth thrusters; it is also used for heating and cooling throughout the ship as well as for several other purposes. Depending on the amount of steam required for the electricity production, the entire COGES propulsion system has efficiency between 45 % and 50 %.

Gas turbines use clean distillate fuel (Marine Gas Oil - MGO) what significantly reduce exhaust emissions. The used propulsion technology has been a factor that Millennium is the first ship built to Det Norske Veritas' voluntary class notation, Clean Design. In year 2000 ship was awarded with ISO14001 certificate.

General specifications and characteristics of Celebrity Millennium, which are not related to the propulsion system, are presented in Table 1.

Table 1. *General specifications and characteristics of Celebrity Millennium*

Builder	Chantiers de l'Atlantique
Owner/Manager	Celebrity Cruises
Length	294 m
Breadth	32.2 m
Draught	8.3 m
Deadweight	8500 t
Gross Tonnage	90228 t
Passenger Capacity	2449

3. Fuel costs comparison between Celebrity Millennium COGES and equivalent Diesel-electric propulsion system for the year 2000. (the year when Celebrity Millennium was launched)

Fuel cost comparison between COGES propulsion system installed on Celebrity Millennium can be performed in relation to equivalent Diesel-electric propulsion system. So, COGES propulsion system installed on Millennium with the total electrical power output of 58 MW is compared with Diesel-electric propulsion system. Comparable Diesel-electric propulsion system consists of five medium-speed diesel engines along with the corresponding generators and electric motors with total electrical power output of 61 MW. These two propulsion systems are compared from the basis of annual fuel costs firstly for the cruiser launch year, 2000.

Author [8] proposed the correct way of comparison in the annual fuel cost calculation for these two systems and also appropriate load scenario of cruise ship Celebrity Millennium. Annual fuel cost calculation is based on a typical weekly load scenario of 60 hours per week in ports (electrical power requirement 10 MW) with one medium-speed diesel engine in operation, which is equivalent to the operation of one gas turbine along with a steam turbine from COGES system. Proposed scenario includes 3840 working hours per year for each of the five diesel engines or 6150 working hours for each of the two gas turbines from COGES system. It should be noted that COGES system operates with MGO (Marine Gas Oil), while medium-speed diesel engines operates with IFO 380 cSt (Intermediate Fuel Oil with a kinematic viscosity of 380 cSt). For these two propulsion systems and for described load scenario, calculation of fuel consumption is performed in [9] and the results of that calculation are presented in Table 2.

Table 2. *Comparison of annual fuel consumption between COGES and equivalent Diesel-electric propulsion system*

Annual fuel consumption for COGES (58 MW) and Diesel-electric (61 MW) propulsion systems	COGES	Diesel-electric
Fuel	MGO	IFO 380 cSt
Fuel consumption, ton	45120	39540
Additional fuel for steam production (17 ton/h), ton	1000	7050

Average fuel prices for the year 2000, from the Rotterdam bunker market were 300 USD per ton of MGO and 145 USD per ton of IFO 380 cSt [10]. Based on those prices, for the year 2000 were calculated annual fuel costs for each of two propulsion systems and presented in Table 3.

Table 3. *Comparison of annual fuel costs between COGES and equivalent Diesel-electric propulsion system*

Annual fuel costs for COGES (58 MW) and Diesel-electric (61 MW) propulsion systems	COGES	Diesel-electric
Fuel	MGO	IFO 380 cSt
Annual fuel cost, million USD	13.54	5.73
Annual fuel cost for additional fuel, million USD	0.3	1.03
Total annual fuel cost, million USD	**13.84**	**6.76**

At the moment when cruiser Celebrity Millennium was launched the difference in annual fuel cost between COGES and Diesel-electric propulsion system was approximately 7 million USD. The appropriate question is how is intended to compensate such big difference in the annual fuel cost between COGES and Diesel-electric propulsion systems.

The COGES propulsion system needs less ship's space than Diesel-electric system, so the selection of COGES on cruiser Celebrity Millennium allow installation of 50 additional double-passenger cabins on lower cruiser decks, which will not be installed if the Diesel-electric system were selected for propulsion. The selection of COGES propulsion system arises from the idea that additional cabins will compensate the difference in total annual fuel cost in comparison with equivalent Diesel-electric propulsion system.

If assumed that 90 % of capacities in 50 additional cabins are continuously sold out 50 weeks a year and if it is taken the real price of accommodation of about 200 USD per person per day, income from additional cabins will be approximately 7 million USD annually. Based on a practical experience [11], the net profit of 7 million USD income can be estimated on about maximum of 35 % or approximately 2.5 million USD. The remaining 65 % are costs for additional cabins building and furnishing, cost of food, staff, cabin cleaning, laundry, taxes, etc.

In the year 2000 when the Celebrity Millennium was launched, it is obvious that annual fuel cost of COGES propulsion system cannot be compensated with additional cabins.

In general - if the difference in annual fuel cost between COGES and Diesel-electric propulsion systems is 2.5 million USD or less, additional cabins compensate the higher COGES fuel cost. If not, additional cabins cannot compensate the higher COGES fuel cost.

The comparison in this paragraph was made for the year 2000. The authors of this paper were interested how this comparison will look nowadays.

4. Fuel costs comparison between Celebrity Millennium COGES and equivalent Diesel-electric propulsion system for a period between 07.11.2016. and 07.11.2017.

The same calculation and comparison of annual fuel costs between COGES and equivalent Diesel-electric propulsion system is provided for the period between 07.11.2016. and 07.11.2017.

It should be noted that annual fuel consumption and additional fuel consumption of both propulsion systems remain the same as presented in Table 2. The changeable variable is the fuel price between observed periods.

4.1. The change in fuel prices between 07.11.2016. and 07.11.2017.

The change in fuel prices between 07.11.2016. and 07.11.2017. is presented in Fig. 1 (IFO 380 cSt) and in Fig. 2 (MGO). Fuel price in the Rotterdam bunker market was taken as relevant (red curve in Fig. 1 and Fig. 2). It is important that both fuel prices in the Rotterdam bunker market are lower throughout observed period than average price in 20 the most important worldwide trading ports (gray curve in Fig. 1 and Fig. 2).

Fuel price for both observed fuels increases in average during the observed period and in 07.11.2017. the price of both fuels was the highest.

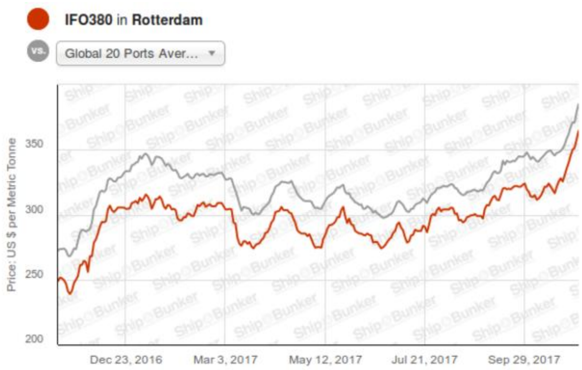

Fig. 1. *IFO 380 cSt price change between 07.11.2016. and 07.11.2017. in the Rotterdam bunker market [12]*

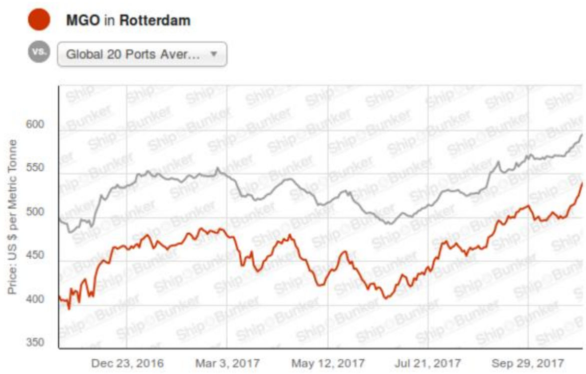

Fig. 2. *MGO price change between 07.11.2016. and 07.11.2017. in the Rotterdam bunker market [12]*

4.2. Annual fuel costs comparison between COGES and equivalent Diesel-electric propulsion system for thirteen randomly selected dates in the period between 07.11.2016. and 07.11.2017.

From the period between 07.11.2016. and 07.11.2017. was randomly selected one day in every month, and it was read the fuel prices for that day from Fig. 1 and Fig. 2. Randomly selected dates and fuel prices on that day at the Rotterdam bunker market was presented in Table 4.

Table 4. *Randomly selected dates and fuel prices for every month between 07.11.2016. and 07.11.2017. - Rotterdam bunker market*

Date	IFO 380 cSt	MGO
07.11.2016.	249.0 USD/ton	409.5 USD/ton
27.12.2016.	305.0 USD/ton	466.5 USD/ton
24.01.2017.	307.0 USD/ton	467.0 USD/ton
21.02.2017.	308.0 USD/ton	484.0 USD/ton
20.03.2017.	277.5 USD/ton	453.0 USD/ton
13.04.2017.	303.5 USD/ton	473.0 USD/ton
22.05.2017.	298.0 USD/ton	454.5 USD/ton
20.06.2017.	276.5 USD/ton	415.0 USD/ton
19.07.2017.	287.5 USD/ton	434.0 USD/ton
24.08.2017.	299.5 USD/ton	464.5 USD/ton
22.09.2017.	322.0 USD/ton	506.0 USD/ton
20.10.2017.	316.5 USD/ton	498.0 USD/ton
07.11.2017.	364.5 USD/ton	539.0 USD/ton

To make appropriate annual fuel price comparison between COGES and Diesel-electric propulsion systems, it was calculated total and partial annual fuel prices for each date presented in Table 4. That calculation allows comparison of annual fuel prices based on fuel prices for each month. The final intention of this analysis was to calculate can the COGES propulsion system can be cost effective in comparison with Diesel-electric propulsion system.

Change in annual fuel costs for COGES and Diesel-electric propulsion systems for randomly selected fuel prices from Table 4 is presented in Fig. 3. From Fig. 3 it can be seen that COGES annual fuel cost at any selected calculation date is much higher than the annual fuel cost of Diesel-electric propulsion system. During the observed period, annual fuel costs of COGES propulsion system are higher for approximately 9 million USD in average.

It is important to note that at the last observed date (07.11.2017.) annual fuel costs of both propulsion systems are the highest in comparison with the previous calculated ones. This fact arises from the fact that on the last observed date prices of both fuels was the highest, Table 4.

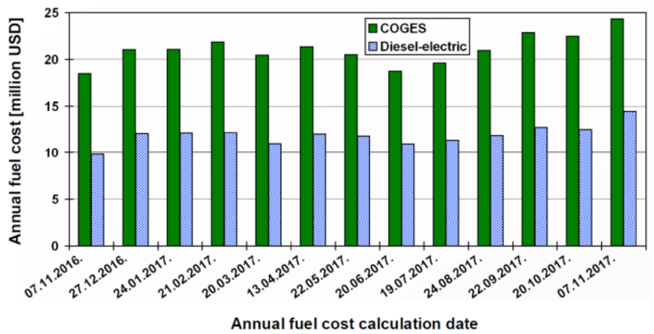

Fig. 3. *Change in annual fuel costs for COGES and Diesel-electric propulsion systems*

Change in annual fuel costs for additional fuel (fuel for steam production, Table 2) of COGES and Diesel-electric propulsion systems are presented in Fig. 4. According to Table 2, Diesel-electric propulsion system uses much more fuel for additional steam production and therefore, the additional fuel costs of this propulsion system are much higher in comparison with COGES system. Throughout the observed period, annual fuel costs for additional fuel of Diesel-electric propulsion system are higher for approximately 1.7 million USD in average.

Annual costs of additional fuel for steam production represents smaller part of total fuel costs; therefore they cannot have a significant influence on total annual fuel costs in presented comparison. Again, the highest values of additional fuel annual costs for both COGES and Diesel-electric propulsion systems are the highest for the last observed date (07.11.2017.) due to the highest fuel prices from the Rotterdam bunker market on that day.

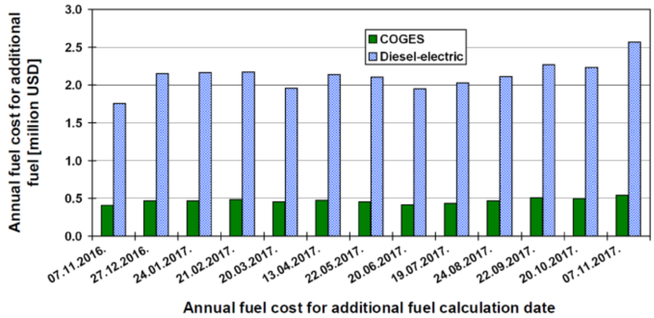

Fig. 4. *Change in annual fuel costs for additional fuel of COGES and Diesel-electric propulsion systems*

Total annual fuel costs change of COGES and Diesel-electric propulsion systems are presented in Fig. 5. Data presented in Fig. 5 were obtained by summing annual fuel costs, Fig. 3, and annual fuel costs for additional fuel, Fig. 4, for each observed propulsion system and for every observed calculation date, Table 4.

Fig. 5 presents that total annual fuel costs in the observed period amounts in average 21.5 million USD for COGES propulsion system and 14 million USD in average for Diesel-electric propulsion system.

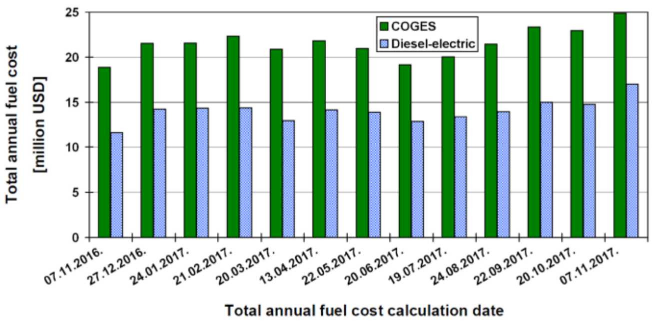

Fig. 5. *Change in total annual fuel costs of COGES and Diesel-electric propulsion systems*

The differences in total annual fuel costs of COGES and Diesel-electric propulsion systems, for all calculation dates (Table 4) are presented in Fig. 6. The fuel costs differences between those two systems amounts from approximately 6 million USD up to 8.5 million USD.

50 additional cabins mounted on Celebrity Millennium with COGES propulsion system bring an annual net profit of approximately 2.5 million USD. Net profit of 50 additional cabins cannot compensate the difference in COGES and Diesel-electric propulsion system total annual fuel costs not only for a year 2000 (when the Celebrity Millennium was launched) but also throughout the observed time period (from 07.11.2016. to 07.11.2017.). The COGES propulsion system at the analyzed cruiser can be profitable only if total annual fuel cost difference, in relation to Diesel-electric propulsion system, amounts 2.5 million USD or less.

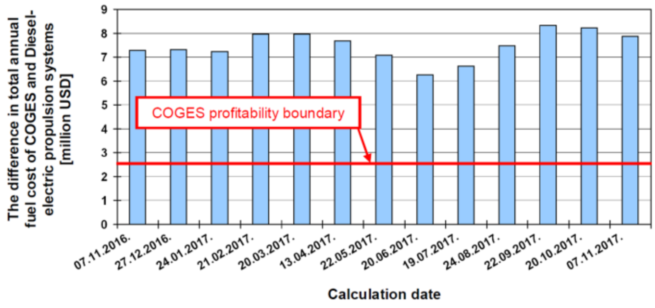

Fig. 6. *The differences in total annual fuel costs of COGES and Diesel-electric propulsion systems*

5. Conclusion

In the paper was presented comparison of fuel costs between COGES and Diesel-electric propulsion systems for large conventional cruise ship, based of known fuel consumption comparison between these two propulsion systems.

COGES propulsion system installed on the analyzed cruise ship saves ship's space in comparison with Diesel-electric propulsion system, so the selection of COGES system allows installation of 50 additional double-passenger cabins on lower cruiser decks. The intention of such propulsion system selection was that additional cabins will compensate the difference in total annual fuel costs in comparison with Diesel-electric propulsion system.

Annual fuel costs of COGES and Diesel-electric propulsion systems were calculated for randomly selected fuel prices at each month during the period between 07.11.2016. and 07.11.2017.

COGES annual fuel costs in any selected calculation date is much higher than annual fuel costs of Diesel-electric propulsion system. During the observed period, annual fuel costs of COGES propulsion system are higher for approximately 9 million USD in average.

Diesel-electric propulsion system uses much more fuel for additional steam production and therefore, the additional fuel costs of this propulsion system are much higher in comparison with COGES system. Annual fuel costs for additional fuel of Diesel-electric propulsion system are higher for approximately 1.7 million USD in average throughout observed period.

Total annual fuel costs in the observed period amounts in average 21.5 million USD for COGES propulsion system and 14 million USD in average for Diesel-electric propulsion system.

Net profit of 50 additional cabins cannot compensate the difference in COGES and Diesel-electric propulsion systems total annual fuel costs throughout the observed time period (from 07.11.2016. to 07.11.2017.).

It should be noted that COGES propulsion system has much lower exhaust gas emissions in comparison with Diesel-electric system. Therefore, COGES propulsion system could become profitable in the future (in comparison with equivalent Diesel-electric propulsion system) if the emission regulations become more rigorous.

6. Acknowledgment

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