Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

THE CONCEPT OF SHIP'S POWER PLANT ARRANGEMENT INVOLVING BIOMASS FIRED BOILER

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Abstract

The article presents the results of the analysis of the possibilities of the application of the solid biomass in the form of pellets as the fuel for ships in consideration of the environment protection as well as due to increase of the liquid fuel prices and decreasing resources of the crude oil. As the object of investigation a ship of minor cruising range of river – sea type has been assumed, chiefly intended for the service on the Baltic Sea. The ship's power system solution has been discussed. A simplified comparative analysis of the fuel costs for a ship with power plant including biomass fired boilers and a ship with the conventional solution of the motor power plant supplied by Diesel oil has been demonstrated. The advantage of the application of the fluidised bed biomass fired boiler has been indicated and the research trends have been presented.

***Key words**: ship's power plant, environment protection, alternative fuels, biomass, fluidised bed boiler*

1. Introduction

The modern ship's power systems generating mechanical energy for the main propulsion needs, electrical energy and heat are dominated by Diesel engines and boilers. The basic kind of fuel applied are still the liquid fuels originating from crude oil – mainly heavy fuel oil. The exhausting resources of crude oil and growing prices of the fuels cause to search for the new solutions of power plants, eg such where unconventional energy sources might be utilised including the renewable energy sources.

Another argument for the abstaining from the liquid fuels originating from crude oil is the marine environment protection. It is estimated that the share of the ships in the worldwide emission of sulphur oxides (SO_x) resulting from the combustion of the mineral fuels amounts to approximately 7%, and the share of the nitrogen oxides (NO_x), subject to the source, amounts to ca 13-17% [1, 4, 9]. The worldwide shipping trade is also responsible for the emission to the atmosphere of the significant quantities of carbon dioxide (CO_2), constituting 3.3% of the global emission of this gas causing in the largest degree the occurrence of the greenhouse effect. Amongst all the transport means the participation of the ships in the CO_2 emission is however 7% [13].

Such situation causes that there are going to be imposed more and more strict regulations concerning the permissible emission of toxic compounds contained within exhaust gas from the ships. The basic document regulating the emission of toxic compounds are the regulations of the International Maritime Organisation (IMO) formulated in Annex VI to MARPOL 73/78

Convention. The permissible limits of NO_x emission applicable by the end of 2010 (Tier I standard) shall be replaced on 1.01.2011 by the new ones (Tier II standard). In 2016, however, there will be introduced very stringent limits concerning the NO_x emission control areas (Tier III). Beyond the emission control areas still Tier II regulations will continue to apply. The permissible NO_x emission limits – Tier II and Tier III standards are stated in table 1.

Tab. 1. The permissible NO_x emission limits acc to MARPOL convention Annex VI [10]

Engine speed (rpm) [min^{-1}]	**NO_x emission limit [g/kWh]**	
	Tier II	**Tier III**
n<130	14,4	3,4
130 ≤n<2000	$44 \cdot n^{(-0,23)}$	$9 \cdot n^{(-0,2)}$
n≥2000	7,7	1,96

On the other hand with regard to the sulphur oxides the permissible emission has been limited by introducing in Annex VI the Rule 14 that regulates the permitted sulphur content in the fuel. The permissible sulphur limits in the fuel, in the global terms and in SO_x control areas (SECA-SO_x Emissions Control Areas) and the dates of their applicability are shown in table 2. It is permitted to apply, both in the control areas and globally, the scrubbers to clean the exhaust gas of the sulphur oxides. For example, the alternative for the fuel of sulphur content up to 1.5% must be the equipment cleaning down to the level ≤ 6g/kWh (SO_2). It is worth reminding that one of the SECA areas is Baltic Sea.

Tab. 2. The permissible sulphur content in fuel acc to MARPOL convention Annex VI [10]

<table>
<tr><th rowspan="2">Date of limit application</th><th colspan="2">Sulphur limits in fuel (%)</th></tr>
<tr><th>SECA</th><th>Global</th></tr>
<tr><td>by June 2010</td><td>1,5</td><td rowspan="2">4,5</td></tr>
<tr><td>by July 2010</td><td rowspan="2">1,0</td></tr>
<tr><td>2012</td><td rowspan="2">3,5</td></tr>
<tr><td>2015</td><td rowspan="2">0,1</td></tr>
<tr><td>2020 or 2025</td><td>0,5</td></tr>
</table>

The current IMO standards do not comprise the carbon dioxide (CO_2) emission. Nevertheless there are works carried out to implement the regulations aiming to limit its emission. It is anticipated that the Carbon Dioxide Transport Efficiency Index will be applied, defined as the ratio of the mass of the emitted CO_2 to the unit of the carried cargo within 1 mile. As a cargo unit, depending on the ship's type, it is proposed to use eg m^3 (tankers and bulk carriers), a passenger (passenger ships), a vehicle or a unit of the length of the lane occupied (vehicle carriers and ferries), a container (container ships) etc. The application of CO_2 indexing is at first voluntary [7].

The CO_2 emission level depends mostly on the fuel consumption. In case of the heat boilers and engines, in particular slow-speed engines, there is but a small margin to reduce the emission, if it is assumed to reduce the fuel consumption only by the improvement in the thermal efficiency of the simple cycle and the utilisation of the waste energy.

A significant reduction of CO_2 emission can be achieved by the application on the ships of the renewable energy sources such as eg wind or solar radiation. Their disadvantage is however small density in comparison to the energy from the conventional source, which with the restricted ship's surface makes it difficult to utilise them, and besides they are temporarily inaccessible. Thus the utilisation of the wind or solar radiation is for these reasons restricted to the sport and recreational watercraft or to the role of just auxiliary energy source on bigger merchant ships. On the other hand, it is worth analysing to utilise on the ships the renewable energy in the form of biomass.

2. Biomass General Characteristics

In the most general terms the biomass is the organic matter contained in animal and floral organisms, originating as the product of the photosynthesis. This is a complex process covering various stages of photochemical and biochemical conversion of the electromagnetic (solar) radiation resulting in the formation of the biomass chemical energy. Under the influence of the solar radiation water is decomposed and in the reaction with carbon dioxide the carbohydrates are generated

$$CO_2+2H_2O+hv \rightarrow O_2+H_2O+(CH_2O)+E, \tag{1}$$

where:
h – Planck constant
v – electromagnetic radiation frequency [8].

The energy E synthesised from one mole of CO_2 equals to 470 kJ. Biomass can be therefore regarded as the solar energy storage. The transformation of the biomass chemical energy into heat in the combustion reaction is related with the emission of CO_2. However, this is treated as environment-friendly, not causing the greenhouse effect because it is subsequently absorbed by the next generations of plants in the photosynthesis, thus circulating within closed cycle. The length of such cycle depends on the kind of plant and varies within several months and several dozens of years.

The detailed classification of biomass is hard in view of numerous possible technological processes of biomass production and conversion and the generation processes of secondary biomass in these processes. The concept of biomass comprises many energy carriers of various properties. According to [5] the basis for the floral biomass classification can be the method of its transformation by conversion or the application of the products obtained. The conversion of biomass may take place by direct combustion, gasification or conversion into liquid or gaseous fuels in various processes. The forms of biomass utilised for the energy generating purposes are shown in the diagram in fig 1.

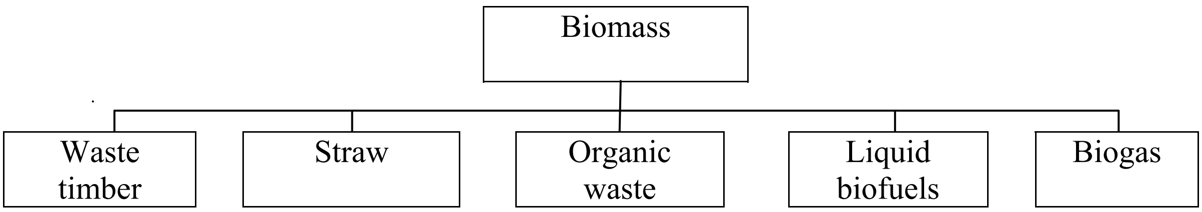


Fig. 1. The forms of biomass used for the energy generating purposes

The table 3 shows the calorific value and densities of various forms of biomass and for the sake of comparison same data for heavy fuel oil, diesel oil and coal. These two parameters determine the volume of the fuel stock for the assumed ship's cruising range.

Tab. 3. The calorific values and densities of various forms of biomass and fuel oil, diesel oil and coal

Biomass form	**Calorific value [MJ/kg]**	**Density [kg/m^3]**
Grey straw	15,2	90 -165
Timber debarked	18,5	380 - 640
Rapeseed oil	35,8	886 (at temp. 20 ^oC)
Ethyl alcohol	26,9	790 (at temp. 20 ^oC)
Briquetted timber	17,5	470 [1)]
Timber pallets	19,5	630- 750 [1)]

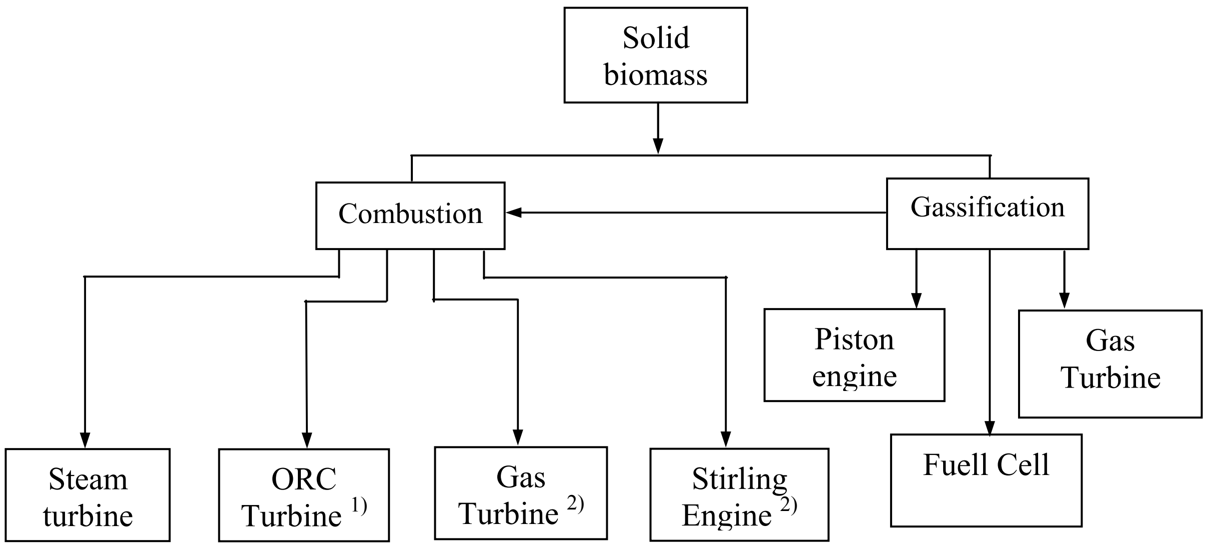
Diesel oil DMA	40	890 (at temp. 15 ^{o}C)
Heavy fuel oil (RMK 700)	39,4	1010 (at temp. 15 ^{o}C)
Hard coal	16 - 29	800 - 1000

1) dump density

3. Biomass as Fuel for Ships

In the shipbuilding relatively the most simple would be to substitute the liquid fuels generated from crude oil by the biofuels on account of the minor differences in the calorific values and densities, similar fuel installations as well as existing experience in engine operation by use of this fuel in shore conditions [9]. The marine engines, both the slow-speed and the medium-speed, manufactured by the major makers in the world, suitable to fire fuel oil are also capable of combusting biofuels (bio-oils). The problems can only be expected in the engines designed for combusting only the Diesel oil on account of the cavitation appearing in the fuel injection pumps [11]. So far the application of the liquid biofuels takes place in a very restricted degree and is related either with research projects or limited to the utilisation of biofuels as only several percent addition to conventional fuel originating from crude oil [2]. One of the barriers for the wider application of biofuels at the current legal status within the permissible CO_2 emission is the high price in calculation onto a unit of energy in comparison with the conventional fuels [11].

In the shore power engineering there are presently many technologies available to use the solid biomass for energy generating; the technologies being more or less complex, referred to inter alia in [5]. The selected technologies which are worth considering in terms of the application in ship's power plant are shown in figure 2.



1 with the application of heating oil as the intermediate medium
2 combustion in outer chamber

Fig. 2. The selected technologies of the solid biomass application in ship's power plants

The synthesis gas (syngas) obtained within the biomass gasification process can be very successfully used as the fuel for heat engines or boilers as well as for the supply of the fuel cells. However, its production is related with the necessity of installing of the gas generator on board the ship; the generator occupying additional space in engine room; as well as the additional energy consumption for the process implementation. The synthesis gas is characterised by relatively low calorific value, i e 4 – 7 MJ/kg. This can be increased by the gasification with pure oxygen or adding the steam within the process which however leads to the enlargement of the installation. On account of its low calorific value it is not economic either to produce this gas on shore in order to compress it and supply subsequently to the ship.

Among the technologies utilising directly combustion of biomass the most simple and at the same time well-proven in a sense in marine conditions, at the time when coal was commonly used as fuel, is the technology of firing biomass in the boiler and the application of steam circulation. The dump density of biomass is however much lower than coal dump density which makes the storage facilities for biomass larger than for coal. For this reason the most adequate fuel from amongst various biomass forms pellets should be considered as characterising by the biggest dump density. An additional argument for the choice of this kind of ecological fuel is also significantly lower price than bio-oil in terms of the unit of the obtained energy. The pellets are also easily transported from the receiver to the boiler, eg by pneumatic method.

Pellets contain not more than 0.08% sulphur and not more than 0.3% nitrogen [5]. Therefore the problem of sulphur oxide emissions practically does not exist. The generation of NO_x from nitrogen contained in fuel is of minor importance as well. With the typical for pellet combustion surplus of air (λ=1.1-1.3) the generation of NO_x shall mainly take place in the thermal manner from the nitrogen contained in air. The formation of NO_x strongly increases in the temperatures exceeding approximately 1300°C. The reduction of NO_x emission can be obtained in this situation by gradually supplying the air for combustion or the application of the fluidised bed boiler allowing the firing in lower temperatures.

4. The Choice of the Ship and the Concept of Power Plant Arrangement

From the comparison of the dump densities and their calorific values (table 3) it ensues that for the same cruising range of a ship the volume of the fuel stock in the pellet form would have been only slightly bigger that the coal stock. The comparison with fuel oil or Diesel oil looks much worse as their stock needs several times smaller volume than that in case of pellets. The large volume of fuel stock limits the cargo space. In this situation naturally the preferable type of a ship where pellets would act as fuel should be a ship of small design cruising range.

In order to verify these relations there has been selected as an example of the design object – the power plant of the river – sea type ship of 2,900 DWT and 12 knots contract speed which would operate in the Baltic area and the inland waters connected [6]. The Baltic Sea is the area covered by the strict regulations concerning the emissions of toxic compounds, which in particular justifies the choice of the ship of such type, and where biomass would be utilised as fuel. An important argument is also an excellent availability of pellets within Baltic Sea area [12].

The power of the ship's main propulsion of 1,500 kW is divided between the two azimuth propellers with AC electric motors, each of 750 kW. Considering other electric energy consumers on the ship, including bow thruster of 280 kW and the heating needs satisfied by the application of the electrical power, there has been assumed the required power plant rating of 2,320 kW. It has been assumed that the total electric energy is generated by turbogenerator supplied with steam generated in the pellet fired boiler. The proposed power plant arrangement is an alternative solution for the design of Diesel electric power plant with the high-speed engines presented in [6]. The cruising range for the ship has been assumed as for the model ship, ie 4,000 nautical miles.

One of the key questions arising from the application of the pellets as the fuel is to determine the volume of its stock for the assumed ship's cruising range. To determine the stock it has been assumed that in the engine room a simple steam cycle is assumed. The assumed parameters of the cycle and the results of calculations are presented in table 4.

The calculations of the required stock of Diesel oil conducted on the basis of the same assumptions regarding the components of the time of voyage duration for the model vessel with the Diesel electric power plant have rendered the result determining its needs as 250 Mg. The capacity of the Diesel oil storage tanks equals for that purpose 309 m^3. Evidently these are the values more than three times less than for the pellets.

Tab. 4. The assumed parameters of the cycle and the results of calculations of fuel stock

Parameter	Value	Unit
Steam temperature at the turbine inlet	530	°C
Steam pressure at the turbine inlet	9	MPa
Pressure in the condenser	0.006	MPa
Turbine internal efficiency	0.9	-
Turbine mechanical efficiency	0.97	-
Boiler efficiency	0.85	-
Turbogenerator power	2,320	kW
Steam flux directed to turbine	2.49	kg/s
Hourly pellet consumption	1,789	kg/h
Stock weight	795	Mg
Volume of the pellet stock for the 4,000 nautical miles range	1,060	m^3

On account of the very good availability of the pellets within Baltic Sea region and the meridional stretch of Baltic as 1,300 km and the parallel stretch being ca 600 km in its widest place, the ship's cruising range could be shortened by half and thus reduce the pellet stock volume down to ca 530 m^3. These are already acceptable figures.

Definitely more advantageous for the power plant with biomass fired boiler on the other hand is the comparison of the fuel prices. The table 5 shows the specification of the fuel costs for the assumed cruising range of 4,000 sea miles for both solutions of power plant with the average prices applicable in June 2010 [14, 15].

Tab. 5. Fuel costs for biomass power plant and motor power plant

Parameter	Fuel type	
	Pellets	Diesel oil
Unit price [zlotys/Mg]	700	4,686
Fuel stock [Mg]	795	250
Fuel cost [zlotys]	556,500	1,217,000

The comparison of the costs shows that the fuel costs for the ship with biomass fired boiler are twice as low. The comparison would have been even more advantageous, if straw pellets are applied instead of the timber pellets which are characterised by similar properties and half the price.

5. Ship's Biomass Fired Fluidised Bed Boiler

CO_2 emission limits applicable in the European Union states as well as the obligations to increase the participation of the renewable energy sources in the generation of electric energy cause that in the shore power engineering industry in Poland there is applied combination of coal with biomass combustion or new biomass fired boilers are built. In many cases these are fluidised bed boilers ensuring the environment friendly combustion. In the proposed power plant arrangement it would be also advisable to apply also the fluidised bed boiler as more environment friendly and also characterised by the smaller dimensions in relation to the classic boiler of the same rating. In view of the shortage of experience in the operation of the boilers of this type in marine conditions, there have been commenced the investigations of the physical model of the fluidised bed boiler, with a part of results presented among others in [16]. These investigations concern the behaviour of the fluidised bed and the conditions of heat exchange during the disturbances originated by the ship's motion on the waves. In the course of further works there has been designed a new construction of fluidising column that will allow inter alia to conduct the examination of the average heat transfer coefficient in the circulating bed subject to the height of the probe location over the grid during the cyclical pendulous motion of the column. The column diagram is presented in figure 3.

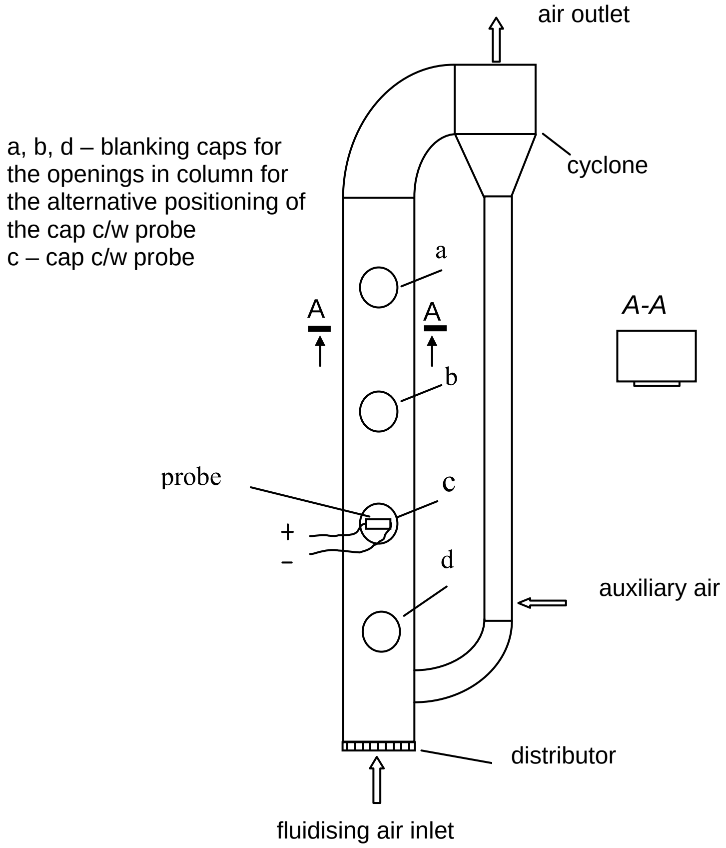


Fig. 3. The diagram of the fluidising column with the fluidised bed material return system

6. Summary

By the example of river-sea type ship intended for the operation within Baltic Sea waters where the strict regulations are applicable concerning the permissible emissions of the toxic compounds it has been demonstrated that it may be justified to utilise turbo-steam power plant with pellets fired boiler. The simplified analysis of the operational costs of the power plant indicates also a possibility of their significant reduction, if instead of motor power plant the proposed arrangement is applied. Although the low emissions level is achievable by use of the classic biomass fired boilers, it would be recommendable to apply the fluidised bed boilers which are characterised by even smaller emissions. This however requires the implementation of the experimental research of such boilers in the actual or simulated marine conditions.

Other positive aspects of biomass application as fuel on ships in the country scale may be the partial getting independent of the imported fuels originating from crude oil as well as the improvement of the environment by the farming of energy generating plants.

However, in consideration of biomass application for the energy generating purposes, some ethical aspects should be duly taken into account. The farming of energy generating plants should not enter into direct competition with the foodstuff production.

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The study financed from the means for the education within 2009 – 2012 as own research project No N N509 404536