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THE SELECTED METHODS OF UTILISING THE WIND POWER AS THE AUXILIARY SOURCE OF ENERGY ON DIESEL ENGINE POWERED SHIPS

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Abstract

In the article there are presented some selected methods of the wind power conversion for the purposes of supplementing the ship's main propulsion or supporting the electric energy production which provide the opportunities to improve the ship's energy effectiveness ratio. The wind energy has been characterised in terms of its application on ships. A proposal has been made to apply the arrangement including the wind turbine with horizontal axis for the electric energy production and the fuel savings have been estimated during its operation.
A concept has been discussed involving a special kind of thruster [towing kite] in the form of the towing kite connected by means of a rope with the ship and supporting her main propulsion. Also the arrangements such as Flettner rotors and turbine with vertical axis have been referred to.

Key words: *environment protection, renewable energy sources, ship's power plant, energetic effectiveness*

1. Introduction

The ships are considered as belonging to the most effective transport means in terms of the CO_2 emissions calculated per unit of the cargo transported at the distance of 1 km. Despite this fact as well as despite the fact that the ships participation in the anthropogenic emission of this gas worldwide at present amounts to as little as approximately 3%, this sector is nevertheless required to implement actions to reduce the emissions of the greenhouse gases [6]. The issues related with the limitation of the greenhouse gas emissions by the ships, after a couple of years of discussions, have become reflected in the regulations stipulated by the International Maritime Organisation (IMO). The decision taken in July 2011 about the introduction of the new chapter 4, regulating the ship's energy effectiveness, to the Annex VI of the MARPOL Convention has been a significant step. Thus since 1 January 2013 the determination of the Energy Efficiency Design Index (EEDI) shall apply to all the newly built ships larger than 400 GRT whereas all the ships, ie the newbuildings and the existing ones built prior to this date shall be covered by the Ship Energy Efficiency Management Plan (SEEMP) that allows the ship optimum operation [13].

It is possible to achieve the small value of EEDI, which is, to put it simply, defined as the total CO_2 emissions from the fuel combustion in main and auxiliary engines and in the boilers in reference to the transport work, in the effect of all the undertakings favourable to the reduction of the ship's fuel consumption. The transport work is here determined as the product of the ship's design deadweight (DWT) and the design speed measured for the ship's maximum loading with 75% of the nominal power on the shaft [13]. The basic actions to reduce EEDI include eg the utilisation of the exhaust gas waste heat. The application of the wind power or solar energy also helps to diminish this value.

The selected manners of the utilisation of these energy sources on the ships have been presented inter alia in the author's works [10, 11]. On account of the new situation resulting from the EEDI implementation the issue of utilising the wind and solar energy on the ships gets more meaningful and it is reflected by the appearance of the new or modernised arrangements of the wind utilisation on the ships. In the further course of the paper the selected methods of wind utilisation as the supplementary energy source for the purposes of aiding the main propulsion or generation of the electric energy will be presented.

2. General Characteristics of the Wind Energy

The wind power is the energy coming from the solar radiation. The temperature differences which appear due to unequal heating of the earth and atmosphere cause the appearance of the air motions which, carrying the heat, tend to equalise the temperatures. The Earth spherical shape causes that the biggest difference in the energetic potential is formed in between the equatorial zone and the poles. Two basic air circulations are thus created, one in the zone between the tropics and the other between the tropics and the poles. The heated air from the equator areas rises upwards and flows towards the poles of both hemispheres. In the areas of the tropics the air masses start to drop down which leads to the formation of the tropical high-pressure areas. From these areas the air flows closer to the earth surface, partly towards the poles and partly back towards the equator. In the effect of the Coriolis force action, which is the effect of the Earth rotation, and also due to the friction force at the Earth surface, the direction of these currents is not compatible with the direction of the pressure horizontal gradient. Thus the horizontal air currents moving nearby the Earth surface towards the equator, called trade winds, have the north-easterly direction on the northern hemisphere and south-easterly on the southern one. The velocities of the trade winds at the earth surface amount to 5-8 m/s on the average. In the moderate zone the air masses circulation is not as orderly as that due to the existence of many moving high and low-pressure areas causing that the wind may practically blow from any direction. However, on the northern hemisphere the south-westerly and west winds prevail whereas on the southern hemisphere the north-westerly and west winds prevail [4]. Besides this global circulation the monsoons or the season winds should be mentioned that change the direction twice a year and which are caused by the differences in the heating of the lands and oceans. In the summer they blow from over the ocean towards the land (the summer monsoon – oceanic), and in the winter from the land towards the ocean (the winter monsoon – continental one).

The air circulation in the poles area is of no practical meaning for the ocean trade and therefore it will not be discussed. The local winds being the effect of the local differences in the temperatures are independent of the global circulation and overlap it. For the offshore trade the breezes as having the daily cycle and the nature similar to that of the monsoons, although in a small scale may be significant as well as the boras blowing from over the law mountain ridges towards the warm sea.

In the wind power engineering the major significance has the annual average wind velocity on a given area at the specified height over the earth surface in terms of the available wind energy for the use by the wind power plant. The increase of the height over the earth surface is generally accompanied by the wind average velocity.

The wind velocity profile or in other words the graph showing the average velocity of the wind blowing from a given direction as a function of height over the earth or water area, is strongly dependent on the area shaping and surface roughness as well as time of velocity averaging. The research shows that the friction effect on the air horizontal movements is significant in the air layer in direct contact with the earth, of the thickness around 1 km [4]. According to all the classifications of the surface roughness the water surface, as the open sea, belongs to the areas of the lowest roughness values. The velocity profile with the large averaging times are presently recommended to be defined by use of the logarythmic formula while earlier it was the power formula. The logarythmic formula (1) gives the results closer to the reality in the earth adjacent layer up to 200 m:

$$\frac{\overline{v}_2(z_2)}{\overline{v}_1(z_1)} = \frac{\ln\left(\frac{z_2 - z_0}{s_0}\right)}{\ln\left(\frac{z_1 - z_0}{s_0}\right)} \qquad (1)$$

where:

z_1, z_2, – the heights where the average 10 minutes velocities are measured (determined),

z_0 – parameter characteristic for the wall-adjacent layer related to the surface roughness,

s_0 – Earth surface roughness measure (determines the height where the wind velocity gets down to zero,

$\overline{v}_1$, – average 10 minutes velocity measured (assumed) at the height z_1=10 m,

$\overline{v}_2$ – average 10 minutes velocity determined for the height z_2 [2, 4].

In case of the surface like the sea z_0 =0 m, and s_0= 0,0002 m [2]. The velocity profiles calculated basing on the relation (1) for the various average velocities $\overline{v}_1$, assumed as those measured at the height of 10 m above the sea level are shown in figure 1.

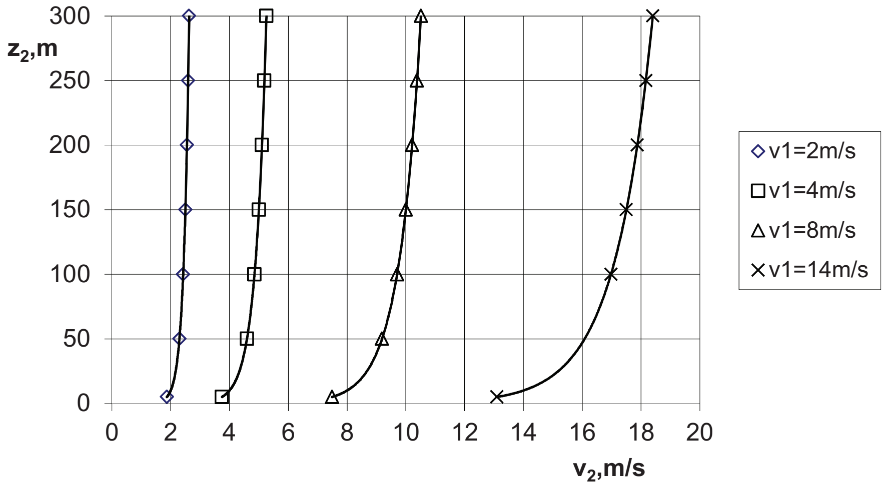

Fig 1.Vertical profiles of the wind calculated on the basis of the velocity value $\overline{v}_1$, at the height of 10 m

For the surfaces of bigger roughness the bigger velocity gradients would occur along given height. This is of large significance in the land wind power engineering for the selection of the location of the wind power plant. In case of the offshore wind farms this is a useful information for the establishing of the tower heights and wind force at a given height. The power of the wind stream $\dot{m}_A$ flowing through the surface A perpendicular to its direction depends on the velocity in 3rd power and can be determined from the relation:

$$N = \frac{1}{2}\dot{m}_A v^2 = \frac{1}{2}\rho v^3 A \qquad (2)$$

where:
N – wind power,
A – surface area where the wind flows,
$\dot{m}_A$ – wind mass stream flowing through the surface,
ρ – air density,
v – wind velocity.

Thus the arrangements enabling the utilisation of the winds blowing at big heights should be preferred.

In case of ships using the wind energy the knowledge of the wind velocity profile is also of big importance for the application of some technologies.

3. Wind as the Energy Source on Ships

3.1. Introduction

The energy of wind, besides the heat from wood burning, has been the renewable energy used by the humans as the earliest. The history of the application of the wind has begun from the sail boats and goes back as far as approximately 8,000 years. The Egyptians used the wind force for the propulsion of the boats by means of the simple square sail; the boats having been used to transport people and goods on the Nile [8].

Nowadays there are different shape sails still in use either in sports and recreation boats. In a minor scale they have also been used as the supporting propulsion means on the motor ships. During the fuel crises the interest in such ideas has been growing. The primary deficiency of the sail propulsion is the necessity to tack if the wind direction is not as desired. Therefore on account of the very much stable wind direction and its velocities the trade winds would be most preferably utilised by the sailors.

There have been the attempts made to eliminate the inconvenience of the sails by the application of the other arrangements such as eg Flettner rotors utilising the Magnus effect or even wind turbines which were mechanically coupled with the propeller [8].

Recently the interest in the wind energy results from the reasons presented in the introduction. Apart from the improvement of the earlier solutions such as Flettner rotors [5] or wind turbines, in Germany there has been developed the concept originating in the beginnings of the XIX century where the kite was applied for the boat propulsion. The contemporary towing kite is constructed as a kite connected to the ship by means of a rope, the kite bearing the structural resemblance to paraglider. This solution utilises the bigger wind velocities blowing at the heights within 100 and 500 m above the sea level which has been presented in figure 1.

Besides supporting the main propulsion the wind energy may also be successfully utilised to drive the electric energy generators. For this purpose the most useful seem to be the horizontal axis turbines. Still a solution applied in 2011 by Stena Lines is also worth mentioning – that consisting in placing on the fore deck of the ferry Stena Jutlandica of the two wind turbines with the vertical four metres Darrieus' type axis of the total power of 8 kW. Within a year they generate 23 MWh of the electric energy which is used for the lighting of the vehicle deck. The most significant merit of the applied turbines is not so much the generation of the electric energy, but rather the reduction of the front air resistance to allow the fuel savings of approximately 80 to 90 Mg by main engines in a year [9].

3.2. The Application of the Wind Turbine with the Horizontal Axis on Ship

The wind turbine power P can be represented by the relation (3).

$$P = C_p \frac{\pi D^2}{4} \cdot \frac{\rho \cdot v_0^3}{2} \tag{3}$$

where:
D – turbine rotor diameter,
C_p – wind power utilisation coefficient (theoretical maximum value amounts to 0,59),
v_0 – wind velocity before rotor.

Since the power increases together with the square value of the rotor diameter, the largest possible diameters should be aimed at. In Europe the biggest diameter, 127 m, is that of the turbine type Enercon E126 with the 7.58 MW power. The height of the tower is 135 m [14]. The dimensions of the turbines on board the ship must be however significantly smaller in view of the ship's stability. If several turbines are installed, the distance to be kept in between them shall be not less than 4 diameters of the rotor in order to prevent the mutual interfering of the wind jet which means the necessity of the selection of the rotor diameters adapted to the ship's main dimensions. Thus it is purposeful to install the wind turbines on large vessels allowing to select the turbines with rotors of bigger diameters.

One of the biggest ships built at one time in Stocznia Szczecińska was the product tanker B573 of the length overall 183 m and breadth 32.2 m. While complying with the aforesaid criteria and assuming the installation of the wind turbines in the most favourable area, ie on the superstructure it would be possible to apply eg 2 turbines with the 8 m diameters rotors. The example of the arrangement of two turbines is shown in figure 1.

To determine the turbine power in relation to the wind force the formula (1) has been used. For the calculations there has been assumed the power coefficient that characterises the most efficient turbines with the special blade profiles C_p = 0,5. The diagram representing the relation of the power of the single turbine and the wind velocity is presented in figure 3.

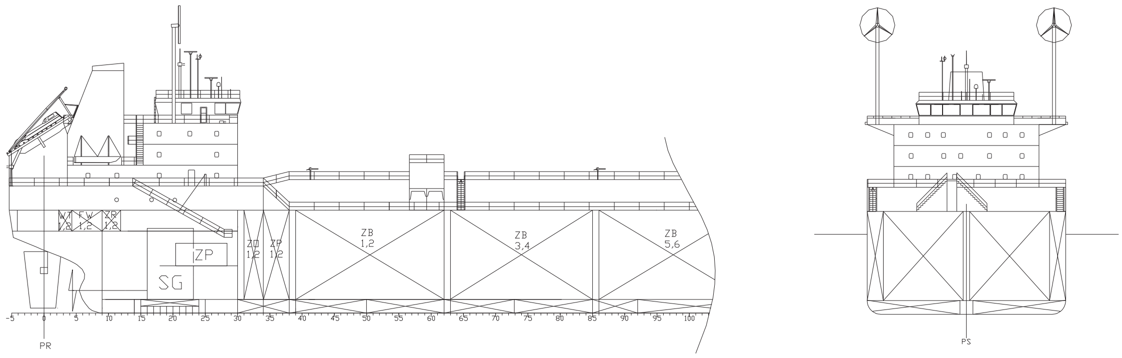

Fig 2. A possible location of the wind turbines on the product tanker

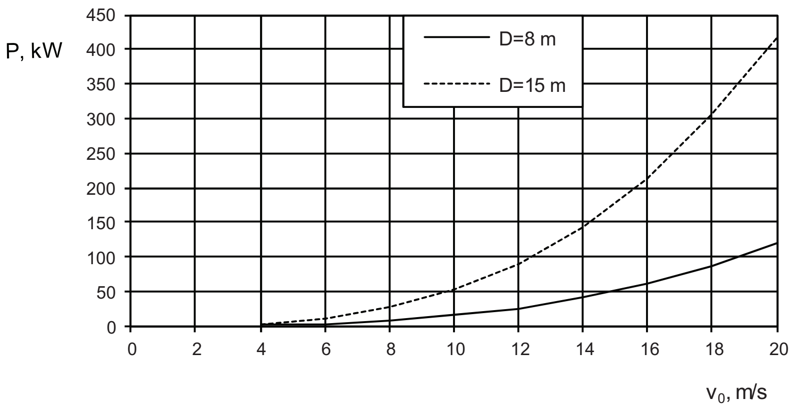

Fig 3.The power outputs achieved from one turbine for various diameters as the function of the wind velocity

As shown in the diagram with the assumed rotor diameter of 8 m the power outputs obtained are not any large ones. From the two turbines and with the wind force corresponding to 6 to 7 Beaufort scale (ca 16 m/s) the power output to be obtained is approximately 120 kW. This consists ca 30% of the electric energy demand during the ship's stay on the roads. Therefore it is possible to achieve a certain relief for Diesel generating set and the savings at the level of 20 kg of Diesel oil within an hour. However, these are not any meaningful values. As shown in the diagram only the application of the rotor of diameter ca 15 m would offer with the same wind force the power output of ca 210 kW from one turbine. With two turbines then the full demand would have been satisfied. Such diameter for the rotor is still acceptable, however it would be necessary to locate the turbines at the bigger distance from each other, eg one in the aft and one in the fore. It is also possible to use bigger number of the turbines, but with smaller diameters that would give similar benefits.

3.3. Towing Kite

A new arrangement is the proposal of using the kite as the auxiliary ship's propulsion consisting in joining it with the ship by means of the towrope of 100 – 500 m length. Should the wind blow favourably from the stern or backstay, the rope with the kite attached at its end is uncoiled from the compartment in the fore, passing through a roller located at the top of a not too tall mast of the height varying by pulling up or down. The most advanced and well tested system is that of Messrs Sky Sails. Here the kite resembles the two-layer inflatable paraglider. Owing to the adequate profile at the kite, similarly as on the aeroplane wing, there appears the carrying force facilitating it rising. Inside the towrope there is the cable supplying the pod placed underneath the kite and incorporating the electronic operating system. While the kite is kept in constant motion doing the figure of eight in the air the carrying force increases and then a large towing force is developed. The entire operation is surveyed by computer [1].

The first attempts with the application of the kite the Sky Sails conducted in 2002 on a small boat weighing 360 kg which has developed the speed of 7.4 km/h. The positive experiences with the other boats made the company conduct the tests on a ship. The first one was 55 m long motor ship Beaufort and the kite mounted thereon, operated still manually, had the surface area of 160 m^2.

The first cargo ship worldwide with the fully automatically operated kite was that launched in 2007 – 475 TEU containership, MS Beluga Sky Sails. The ship developed the speed of 15.5 knots with the main engine power output of 3,840 kW. According to the manufacturer's assurances with the kite surface area equal to 160 m^2 it is possible to achieve the ca 15-20% savings in the fuel consumption, and for the kite of double the surface area operating at the height up to 420 m provided for the bulk carrier of 25,000 DWT, even up to 35% [12].

The kite is an attractive propulsion appliance because the force with which is acts on the ship generates directly the towing power without any additional energy losses resulting from its conversion. While assuming the average value of the Diesel engine powered ship propulsion efficiency, defined according to [7] as the ratio of the towing power to the power carried to the tail-end, equal to ca 0.5, then the equivalent engine power output for the transfer of the same speed to the ship must be twice as big as the kite power output. Pursuant to [3] the kite of surface area 320 m^2 can "replace" 20 MW of the main engine power output.

The precise determination of the kite towing force is a complex issue on account of its movements with the variable speed and the dependence on many construction parameters. A good approximate of the measurement values is provided in the model presented in [1].

The force exerted by the wind on the kite surface can be determined from the relation (2) for the wind power through the relation:

$$N = \vec{F}\,\vec{v} = \frac{1}{2}\rho v^3 S_w \tag{3}$$

where:

$\vec{F}$ – wind force vector,
$\vec{v}$ – wind velocity vector,
S_w – kite usable surface area swept over by the wind.

The kite usable area S_w, in the result of its movements, is swept over in a variable manner by the wind, ie the same fragment of its surface is swept over every certain specific time. For this reason the wind utilisation coefficient is introduced ε_k and thus the kite usable power P_k can be presented by the following relation:

$$P_k = \varepsilon_k N = \varepsilon_k \frac{1}{2}\rho v^3 S_w = \frac{1}{2}\rho v^3 S_k \tag{4}$$

where:
S_k – conventional surface area where the wind acts on the kite.

The surface S_k for the kite doing the figures of eight in the air is equal approximately to the surface of the path covered by the kite so to the product of the kite way along the figure eight and the width of the kite. Practically the value S_k depends inter alia on such parameters as the surface, shape coefficients, positioning angle towards the wind direction, the shape of the "eight" and kite speed in the movements along the "eight". Knowing power P_k from the relation (5) there can be determined force F_k acting on the kite and whose vector is parallel to the wind velocity vector:

$$P_k = F_k v = \varepsilon_k N = \varepsilon_k \vec{F}\vec{v} = \varepsilon_k F v = \frac{1}{2}\rho v^3 S_k\,, \tag{5}$$

therefore

$$F_k = \varepsilon_k F v = \frac{1}{2}\rho v^2 S_k\,. \tag{6}$$

In fact for the ship what is important is the value of the force in the rope perpendicular to the surface S_k. and the towing force. The force in the rope F_L can be presented in the form of the relation (7)

$$F_L = F_k \cos\alpha\cos\beta = \frac{1}{2}\rho v^2 S_k \cos\alpha\cos\beta \tag{7}$$

where:
α – angle between the rope and wind direction in the horizontal plane,
β – angle between the rope and wind direction in the vertical plane.

Since the surface S_k depends on many parameters and can be determined only experimentally, then it is stated as follows

$$F_L = v^p A\cos\alpha\cos\beta \tag{8}$$

where:
p, a – experimentally established constants.

Eventually the towing force is determined from the relation:

$$F_h = F_L \cos\alpha_A \cos\beta_H \tag{9}$$

where:

α_A – instantaneous angle between the rope and the ship's motion direction in the vertical plane,
β_H – instantaneous angle between the rope and the ship's motion direction in the horizontal plane.

Thus in case of the towing force of relatively minor value eg 20 kN reached by the kite of the surface area 80 m^2 and the ship's speed of 14 knots (7.2 m/s) there is 144 kW towing power generated. Assuming the efficiency of the motor ship's propulsion system equal to η_n=0,5, this corresponds to the saved main engine power equal to 288 kW. For example for the B186 containership built in Stocznia Szczecińska with the engine developing the contractual power of 12,180 kW and the specific fuel consumption of 0.171 kg/kWh, the application of the kite under such assumptions would produce the savings of ca 50 kg/h of the fuel.

4. Summary

The two methods of the utilisation of the wind blowing at different heights above the water surface offer some insight into the benefits possible to be achieved and resulting from the application of the wind energy on the motor ships. From the considerations made it results that the turbines with the horizontal axis and dimensions of the rotor diameter exceeding 15 m would provide the notable and measurable benefits in the amount of the fuel saved by the generating sets during the ship's stay. Therefore such arrangements could be taken into account on large ships, eg tankers. Also another location of the turbines could be considered as well as the application of another number of the turbines, eg 4 turbines – in the fore and aft and at the superstructure sides, offering the undisturbed operation and larger total power.

Also the application of the towing kite as the propulsion appliance is beneficial as it utilises the strong and permanent winds blowing at the significant heights above the water level and supports the main propulsion. In this case in relation to the kite surface area and the meteorological conditions it is possible to reduce considerably the main engine power output in comparison to the ship driven by the engine alone and to achieve the limitation of the fuel consumption.

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