Comparative analysis of selected design variants of propulsion system for an inland waterways ship

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ABSTRACT

In this paper are presented design assumptions and technical conditions as well as selected design versions of propulsion system for an inland waterways ship, and also a preliminary comparative analysis of two solutions. In the first version this is a combustion-electric system fitted with frequency converter and in the other – combustion-hydraulic one with hydrostatic reduction gear.

Keywords : ship propulsion systems, combustion-electric driving system, combustion-hydraulic driving system

INTRODUCTION

Today several kinds of propulsion systems are applied on board inland waterways ships, out of which the following can be enumerated :

- ❖ conventional one fitted with a combustion engine, toothed gear and fixed or controllable pitch propeller, free or ducted in a fixed or pivotable Kort's nozzle
- ❖ combustion-electric one fitted with an electric transmission and frequency converter making it possible to steplessly control rotational speed of the propeller which may be fixed one
- ❖ combustion-hydraulic one fitted with a hydrostatic transmission and fixed propeller
- ❖ propulsion system fitted with two azimuthal propellers (rotatable thrusters) driven by combustion engines through a toothed, electric or hydrostatic transmission
- ❖ propulsion system fitted with cycloidal (Voith- Schneider) propellers
- ❖ propulsion system fitted with water jet propellers.

Construction of inland waterways ships and their propulsion systems decisively depend on depth of waterways in which a given ship is to sail, as well as on dimensions of sluices existing in the waterways, and also on other conditions including ecological ones.

Below are presented basic design assumptions and selected design concepts of propulsion system for an inland waterways passenger ship intended for sailing on a shipping route of the minimum water depth of 1.2 m.

BASIC DESIGN ASSUMPTIONS AND CHOICE OF PROPULSION SYSTEM

The to-be-designed propulsion system is intended for the passenger ship of the following technical parameters :

★ overall length	L	= 56 m		
★ overall breadth	B	= 9 m		
★ draught	d	= 1 m		
★ ship displacement	∇	= 440 t	for	d = 1m
★ assumed ship speed	V	= 14 km/h	at	d = 1m
★ required power output	P	= 300 kW		

The required very small draught of the ship is an important limitation in searching for a suitable propulsion system. Certainly it cannot be a propulsion system using cycloidal propellers which are located under the ship's hull. Ships driven by water jets fairly well operate in shallow waters. However such drive is unfavourable from the ecological point of view. A large water stream sucked out from under ship's bottom and thrown overboard with a great velocity destroys bottom and side structures of the waterway and biological live existing there. In this case the factor has been deemed so important that it was decided to exclude the water jet propulsion system from further considerations.

Hence only the systems fitted with screw propellers have been taken into account. As the propeller is assumed to operate in non-cavitating range, its appropriate diameter should be greater than 1.4 m. In the case of two propellers used e.g. in Schottel rotatable thrusters the diameter of each of them might be a little smaller, equal to about 1.35 m.

Due to the small draught of the ship the above mentioned values of propeller diameter are not acceptable. Therefore it was deemed necessary to apply a double-propeller propulsion system. This way it would be possible to decrease the diameter of the propellers to such an extent as to decrease its value to 0.83 – – 0.85 m in the case of placing them in Kort's nozzles, being still large enough to transfer the assumed power. The outer diameter of the nozzles would then exceed a little the draught of 1 m, but if ship's hull form is suitably corected it will not be a problem. Such solution has many advantages. The double-propeller propulsion system provides higher ship's manoeuvrability and reliability. Location of the propellers inside the nozzles significantly lowers risk of catching the propeller's blade on the bottom that usually results in a failure and necessity of replacement of the propeller. Ducting the propellers also lowers unfavourable influence of screw race on the waterway bottom structure.

An additional improvement of reliability of the system and its simplification can be obtain by applying the fixed-pitch propeller. However it requires to provide the system with capability of changing magnitude and direction of rotational speed of the propeller shaft, that can be realized in the simplest way by a hydrostatic or electric transmission included in the propulsion system.

Further advantages can be achieved by replacing the fixed nozzle with pivotable one, and even better by using a rotatable thruster. This makes it possible to resign from applying the traditional rudder and in consequence to significantly decrease gabarites and weight of the device and simultaneously to improve ship's manoeuvrability.

Taking into account the above presented factors one decided to elaborate conceptual design projects of two solutions of the propulsion system fitted with rotatable thrusters, the most technically justified in the opinion of these authors, namely :

- combustion-electric one fitted with typical asynchronous squirrel-cage electric motors and frequency converters making stepless control of rotational speed of fixed propeller possible
- combustion-hydraulic one fitted with hydrostatic transmission.

COMBUSTION-ELECTRIC PROPULSION SYSTEM

The elaborated combustion-electric main propulsion system of the ship in question is presented in Fig.1 and 2 in two versions differing to each other mainly by size of electric motors and way of their positioning.

Three electric generating sets were applied; each of them consisted of a four-stroke combustion engine driving a three-phase synchronous generator.

The total power output of the generating sets fully covers power demand for propelling and steering the ship. The output of the third generating set suffices to cover the assumed power demand of other consumers. So produced energy is delivered to the main switchboard. From here its main part goes to the frequency converters and next to the three-phase asynchronous electric motors driving the fixed screw propellers through the toothed intersecting-axis gear.

In the first version of the system in question, shown in two axonometric projections in Fig.1, have been applied the electric motors in vertical position, that made it possible to obtain a modular construction of rotatable thruster, more compact and having relatively small gabarites. The drive is transmitted from the motors to the propeller shaft through the one-stage toothed gear placed inside the pod (electric podded propulsor) of rotatable thruster under water. Its reduction ratio is small because of a limited size of the pod, that makes it necessary to use a four-pole medium-speed electric motor.

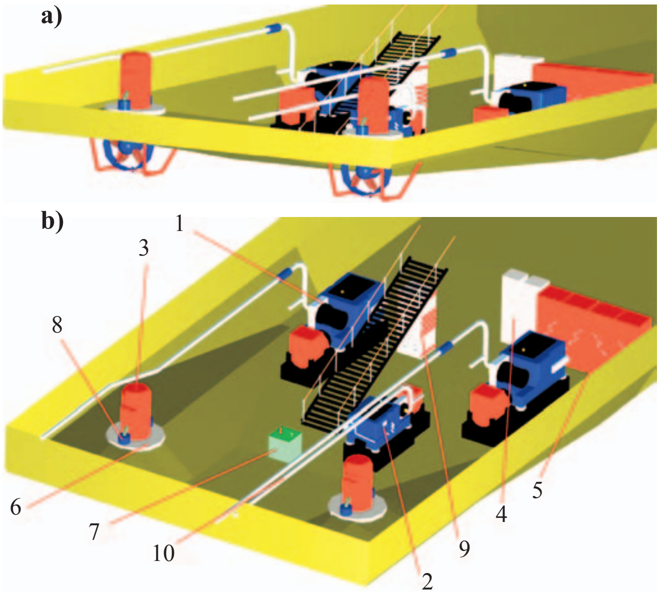

Fig. 1. *View of an example arrangement of the main components of the combustion-electric propulsion system fitted with the electric motors in vertical position .*

Notation *: 1 – electric generating set, 2 – auxiliary electric generating set, 3 – electric three-phase asynchronous cage motor driving the propeller, 4 – frequency converter, 5 – main switchboard, 6 – rotatable thruster, 7 – hydraulic unit for supplying hydraulic motors, 8 – hydraulic motor fitted with planetary gear to drive the mechanism rotating the column of rotatable thruster, 9 – central „outboard water – fresh water" cooler, 10 – exhaust piping with silencers .*

The ship steering functions are realized by rotating the column of rotatable thruster by an arbitrary angle around the vertical axis. To this end were used two hydraulic motors of a constant absorbing capacity, driving the column through toothed gears. The motors are fed from a constant capacity pump placed in the oil tank system.

A drawback of the solution is that the upper surface of the electric motor sticks out a little over the first deck of the ship (not shown in the figure). Another unfavourable feature is that the mass centre of electric motors is located high and shifted aft.

In the second version shown in Fig.2. the electric motors were placed in horizontal position. In consequence it was necessary to use a two-stage reduction gear of „Z" type. This way

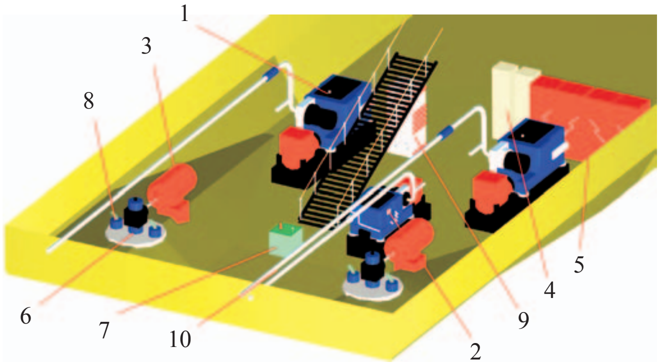

Fig. 2. *View of an example arrangement of the main components of the combustion-electric propulsion system fitted with the electric motors in horizontal position .*

Notation *: 1 – electric generating set, 2 – auxiliary electric generating set, 3 – electric three-phase asynchronous cage motor driving the propeller, 4 – frequency converter, 5 – main switchboard, 6 – rotatable thruster, 7 – hydraulic unit for supplying hydraulic motors, 8 – hydraulic motor fitted with planetary gear to drive the mechanism rotating the column of rotatable thruster, 9 – central „outboard water – fresh water" cooler, 10 – exhaust piping with silencers .*

the total reduction ratio could be greater resulting in possible application of two-pole electric motors of twice higher rotational speed, smaller and somewhat lighter. However it should be stressed that such solution is sometimes characterized by significant displacements of motor's shaft axis against rotatable thruster, caused by ship's hull deformations in heavy weather conditions. In order to eliminate the unfavourable influence of the deformations on operation of the toothed gear a flexible connection of the motor shaft and gear shaft by means of a Cardan coupling, was provided for.

Though such solution makes the construction more complex and of greater gabarites, it does not lower weight of the construction but only provides more favourable location of its centre of gravity.

COMBUSTION-HYDRAULIC PROPULSION SYSTEM

Fig.3 shows the propulsion system fitted with hydrostatic transmission, described in detail in [1]. To simplify the drawing the oil piping and other auxiliary devices of power plant have been omitted. The system is composed of two identical, mutually independent sub-systems; each of them is driven by the high-speed combustion engine (2). The engine directly drives : the main oil pump of variable capacity (4) and through the mechanical gear (3), the oil pump of constant capacity (not shown in the figure) for driving the rotation mechanism of the rotatable thruster, as well as the three-phase synchronous electric generator (5).

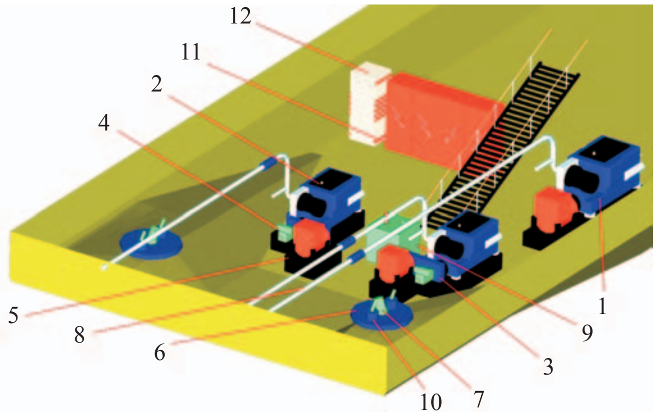

Fig. 3. *View of an example arrangement of the main components of the combustion-hydraulic propulsion system .*

Notation *: 1- electric generating set, 2 – combustion engine, 3 – mechanical gear, 4 – the main pump unit to drive the propeller, 5 – electric generator, 6 – rotatable thruster, 7 – hydraulic motor driving the propeller, 8 – exhaust piping with silencers, 9 – hydraulic oil supplying unit, 10 – hydraulic motors to rotate the rotatable thruster around vertical axis, 11 – electric switchboard, 12 – central „outboard water – – fresh water" cooler .*

The main oil pump (4) feeds the hydraulic motor of constant absorbing capacity (7). The motor drives, through the toothed bevel gear, the fixed propeller located within pivotable nozzle of the rotatable thruster (6). In this case the application of a fixed propeller was justified by making it possible to steplessly control speed and direction of rotation of the hydraulic motor. This is realized by changing the capacity of the pump (4) and oil pumping direction. The control system of the variable capacity pump is fed from a small pump installed at the main pump.

The system was provided with one large oil tank (9) and one central „outboard water – fresh water" cooler (12) that made it possible to reduce space of the ship power plant as well as a number of its auxiliary devices. The electric generating set (1) was applied to satisfy electric energy demand of other consumers.

COMPARATIVE ANALYSIS OF THE SYSTEMS

Final choice of the most favourable system is not an easy task as it must take into account a broad range of various factors including first of all: manoeuvrability, reliability, initial and operational costs, as well as area and space occupied by the system, its mass, location of its centre of gravity etc.

In Tab. 1-3 and diagrams (Fig.4,5) are presented some important data concerning the features and costs of the considered propulsion systems, which are supposed to make decision--taking easier.

As it follows from the given data both variants of combustion-electric system are very similar. However some rather important differences between them dealing with constructional problems not clearly indicated in the tables, do exist. The horizontal position of electric motors, as compared with vertical one, results in the necessity of application of the second stage of the bevel gear, additional shaft and couplings between the gear and motor, that makes the construction more complicated and real initial cost of rotatable thruster greater. Moreover the area occupied by the motor increases, however in that region it probably would not be used for other purposes.

The vertical position of the electric motor is, in the solution, a disadvantage resulting from a too-large height of the motor fixed on the rotatable thruster, not fitting under the deck. However its importance may be effectively reduced by a suitable arrangement of shipboard equipment in that region.

A greater number of even more important differences can be revealed by comparing both systems to each other : combustion-electric and combustion-hydraulic one.

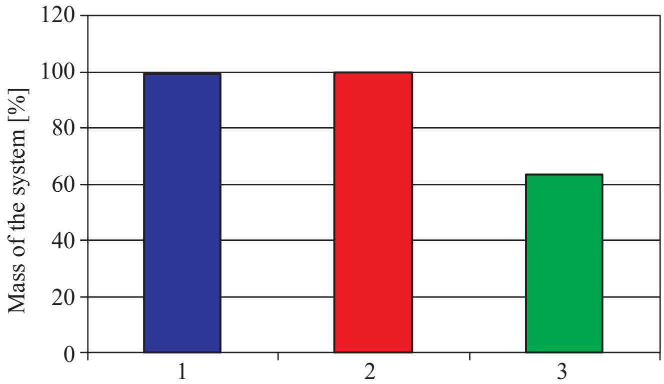

Fig. 4. *Comparison of mass of the presented propulsion systems :*
1 – combustion-electric one with electric motors in vertical position,
2 – combustion-electric one with electric motors in horizontal position,
3 – combustion-hydraulic one .

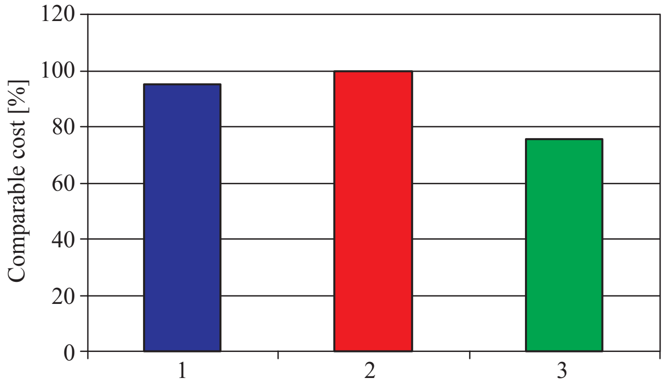

Fig. 5. *Comparison of initial costs of the presented propulsion systems :*
1 – combustion-electric one with electric motors in vertical position,
2 – combustion-electric one with electric motors in horizontal position,
3 – combustion-hydraulic one .

Tab. 1. *Parameters and prices (costs) of the units of the combustion-electric propulsion system with electric motors located in vertical position .*

Name of unit	Gabarites	Number	Mass : of one unit / total [kg]	Volume [m^3] / area [m^2]	Gross price (cost) : of one unit / total [EURO]
Electric generating set of 240 kW output : **IVECO GE 8210SRM45**	2737x1150x1371	2	2820 / 5640	8.63 / 6.30	57050 / 114100
Electric generating set of 112 kW output : **IVECO GE 8361SRM32**	2309x720x1280	1	1950 / 1950	2.13 / 1.66	37100 / 37100
Electric motor of 200 kW power : **EMIT SVgm 315 mL4**	1210x600x800	2	1120 / 2240	1.16 / 0.96 not accounted for in calculations *	6500 / 13000
Frequency converter : **Danfoss VLT**	370x420x1600	2	200 / 400	0.50 / 0.31	18000 / 36000
Hydraulic oil tank unit	500x500x700	1	300 / 300	0.15 / 0.25	
Rotatable thruster		2	910 / 1820		54000 / 108000
Total			/12350	11.41 / 8.52	/~308200

Tab. 2. *Parameters and prices (costs) of the units of the combustion-electric propulsion system with electric motors located in horizontal position .*

Name of unit	Gabarites	Number	Mass : of one unit / total [kg]	Volume [m^3] / area [m^2]	Gross price (cost) : of one unit / total [EURO]
Electric generating set of 240 kW output : **IVECO GE 8210SRM45**	2737x1150x1371	2	2820 / 5640	8.63 / 6.30	57050 / 114100
Electric generating set of 112 kW output : **IVECO GE 8361SRM32**	2309x720x1280	1	1950 / 1950	2.13 / 1.66	37100 / 37100
Electric motor of 200 kW power : **EMIT Sgm 315 mL2**	1200x1000x615	2	1100 / 2200	1.48 / 2.4 not accounted for in calculations *	18000 / 36000
Frequency converter : **Danfoss VLT**	370x420x1600	2	200 / 400	0.50 / 0.31	5200 / 10400
Hydraulic oil tank unit	500x500x800	1	300 / 300	0.20 / 0.25	
Rotatable thruster		2	980 / 1960		60000 / 120000
Total			/12450	11.41 / 8.52	/~317600

Tab. 3. *Parameters and prices (costs) of the units of the combustion-hydraulic propulsion system with hydrostatic transmission .*

Name of unit	Gabarites	Number	Mass : of one unit / total [kg]	Volume [m^3] / area [m^2]	Gross price (cost) : of one unit / total [EURO]
Combustion engine of 220 kW output : **IVECO CURSOR 300**	1770x935x1030	2	900 / 1800	3.41 / 3.31	24500 / 49000
Electric generating set of 220 kW output : **IVECO GE8210SRM36**	2975x1110x1940	1	2520 /2520	6.41 / 3.30	47160 / 47160
Hydraulic pump of 252 kW maximum output : **Rexroth A4VSG 180**	350x300x220	2	114 / 228	0.05 / 0.21	12000 / 24000
Hydraulic motor of 220 kW maximum output : **Rexroth A2FM 250**	224x280x250	2	73 / 146	0.03 / 0.13 not accounted for in calculations *	5368 / 10736
Electric generator of 40 kW output : **Leroy – Somer 42.2VL8**	615x450x450	2	165 / 330	0.25 / 0.55	3000 / 6000
Hydraulic oil tank unit	1000x1000x1300	1	1050 / 1050	1.23/ 1	
Rotatable thruster		2	900 / 1800		54000 / 108000
Total			/ 7874	11.31 / 8.37	/~244900

* This unit does not occupy any useful space of the power plant

As far as the broadly understood ship's manoeuvrability is concerned the propulsion system with hydrostatic transmission shows more advantages out of which the following are most important :

- better protection of the propulsion system against overloading that results in much higher reliability and durability of its units especially the bevel gear
- more accurately and faster realized manoeuvers that mainly results from many times smaller inertia moments of the hydraulic motors as compared with those of electric ones.

Successive advantages of the combustion-hydraulic system are its smaller weight and gabarites. They first of all result from several times smaller mass of the hydraulic motors and space occupied by them against those of the electric motors of the same power. As results from the data included in the tables the masses differ to each other almost fifteen times. Another source of the merits is the application of the high-speed combustion engines for driving the hydraulic pumps, having rotational speed much higher than that of the electric generating sets used in the combustion-electric propulsion system. The features are especially favourable in the case of small vessels especially those intended for sailing in shallow waters.

Another important advantage of the system fitted with hydrostatic transmission is its smaller initial cost amounting to less than 77% of that of the remaining systems in question.

An important drawback of the considered system is its higher operational costs. They mainly result from a lower efficiency of the system. From the so far performed analyses it results that the efficiency of the combustion-electric system is by about 5% higher than that of the combustion-hydraulic system, at rated values of their operational parameters. For this reason in the combustion-hydraulic system a somewhat higher total power output of combustion engines has been provided for. The need of periodical change of oil and filtering cartridges additionally rises operational costs.

FINAL REMARKS

All the three presented design variants of the ship propulsion systems satisfy the assumptions enumerated in *Introduction* and each of them could be applied to the designed ship. To choose the most favourable one out them is not an easy task. However these authors are convinced that the above presented analysis of basic features and costs of each of the systems certainly may help the principal designer of the ship in making a proper choice.

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Conference

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On 20-22 May 2005, under this slogan, Faculty of Mechanical Engineering, Gdańsk University of Technology, organized the international symposium which was a continuation of meetings of the Faculty's staff and representatives of German partnership scientific research centres.

25 years ago such meetings have started from the contact with Hochschule in Bremen and in the course of time the number of German participants has increased.

As Poland entered the European Union, the following program assumptions were announced for the Symposium of 2005 :

- *presentation of advances and latest achievements in mechanical engineering as to enable common applications for European grants*
- *experience and information transfer in the field of implementation of European curricula in academic education at technical universities*
- *discussing problems of industrial implementation of research results*
- *establishing new personal contacts and strengthening existing friendly relations between scientists.*

and also scientific workers from France and Great Britain took part in the Symposium.

The Symposium program contained presentation and discussion of 53 papers out of which 29 were submitted by the organizers, 8 by scientific workers from Stralsund University, and the rest by representatives of other scientific centres : 8 German, 2 French, and 1 British, as well as 2 Polish ones (Częstochowa University of Technology and Institute of Fluid Flow Machinery, Gdańsk).