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Considerations regarding reducing Danube navigation emissions

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Abstract. Some results of the concept working out are proposed to improve ecological parameters in the inland Danube navigation by increasing energy efficiency of the already owned fleet at the basis of possible methods, which also were proposed during GRENDEL (Green and Efficient Danube Fleet) Project, finished in November, 2020. It has been a pilot project directed to coordinate the Danube fleet modernization according to the European Green Deal conception. The results, introduced during GRENDEL Final Event show an active interest of all participants to the main objectives of the project, and both to the prolongation of investigations in this sphere. Obviously, the main interest is concentrated around issues of harmful emissions of ship main engines decreasing as soon as preparing Danube inland vessels for using technologies of zero emission. However, very expensive practical realization, Danube market falling, pandemic limitations, points of wasteland in Danube countries economics – these all factors make impossible to use modern findings and solutions in sphere of the Danube fleet modernization for today's shipowners. Nowadays shipowners are using to feel financial deficits even for current operational maintenance. The best way to rich zero emission fast is implementation of governmental regulatory and financial support planes, which unfortunately are too far from developing and realization. The only result could be reached by shipping companies is to find the ways to improve energy efficiency for existing fleet. It will also lead to better ecological parameters.
Keywords: energy efficiency, emissions, existing fleet, inland vessels, diesel engine, top dead center, ship engines performance.

1. Introduction

For over 20 years, research has been carried out to reduce emissions from inland waterway transport. To date, the overall result can be characterized by the following positions:

- in the regulatory level – limit levels for emissions of marine engines have been established, Stage V [4];

- projects of innovative vessels for the Danube have been developed, differing in the optimal hull shape and power plant, allowing to achieve or as close as possible to achieving zero emissions;
- a number of modernization projects have been developed for the existing fleet of self-propelled cargo ships and pushers;
- an understanding has been reached that the work of the existing fleet will not stop;
- low investment opportunities of Danube shipowners and fleet operators will not contribute to the widespread introduction of expensive innovative vessels and modernization projects.

In the context of the latter of these factors, active work is underway to find options for government incentives and support of the shipping business on the way to achieving environmental friendliness and zero emissions. Without effective measures in this direction, innovative projects will not be able to become implemented and massively replace existing ships, which, although morally and technically outdated, but still are successfully operating and making a profit.

2. Analyses of the Literature Data and the Problem Statement

There are many different developments and projects aimed at reducing harmful emissions to the atmosphere from marine engines. The main areas of research include increasing useful thrust by reducing drag resistance, using water-fuel emulsions, cleaning exhaust gases before being released into the atmosphere. Basically, modern developments in the field of fleet modernization are based on the use of exhaust gas cleaning systems, first of all SCR catalysts and DPF – diesel particulate filter [2, 3, 6]. As noted above, these developments involve large-scale and costly design changes.

However, it is often enough to have reliable information and analytical algorithms to perform a correct analysis and obtain reliable information about the current state of the propulsion complex and its components. In particular, it is known that for the correct assessment of power and technical diagnostics that improve the economic and environmental performance of transport diesel engines, the problem of correct processing of experimental data for monitoring the working process of ship engines - analytical synchronization - is urgent [7, 8].

3. Aims

Realizing the importance of obtaining a solution to the complex task of improving environmental friendliness and maintaining the presence of the existing fleet on the market, the Danube Institute of the National University "Odessa Maritime Academy", with the assistance of the Ukrainian Danube Shipping Company, initiated research on the operating modes of vessels in the Danube shipping. The purpose of these studies is to obtain reliable results on the current and achievable indicators of energy efficiency and environmental friendliness of the Danube fleet.

4. Observations and research

Making analyses from the positions of the intensity (density) of both passengers and goods transportation, the Danube transport system can be roughly represented as follows:

- Upper Danube (sections of Germany, Austria, Slovakia and partly Hungary);
- Middle Danube (sections of Hungary, Croatia and Serbia);
- Lower Danube (sections of Serbia, Romania, Bulgaria, Republic of Moldova and Ukraine).

Accordingly, the operational (monthly) analysis of the transport market is carried out by sections and in the cross-border (country / country) section using a special method, in which, in addition to the official statistics of the Danube member countries of the Danube Comission, the control data of the main points are also assessed:

- Upper Danube: waterworks Kelheim, Jochenstein and Gabchikovo;
- Middle Danube: Mohacs checkpoint.

Based on the analysis of observations of the Danube transport market carried out and published by the Danube Commission (Tables 1 and 2), pusher vessels working with heavy-duty trains were identified as the target group [10].

Table 1. Transportation of goods through the observation point Mohacs.

Year	Goods transported, mln tons		%
	Total	Pushed caravans	
2014	5,40	4,051	75,00
2015	6,28	5,13	81,69
2016	5,85	4,62	78,97
2017	5,748	4,483	77,99
2018	4,523	3,558	78,66
2019	5,582	4,44	79,54

Table 2. Transportation of goods through the observation point Gabchikovo.

Year	Goods transported, mln tons		%
	Total	Pushed caravans	
2014	5,40	2,74	50,72
2015	4,59	2,41	52,51
2016	5,33	2,99	56,10
2017	5,495	3,227	58,73
2018	4,486	2,612	58,23
2019	5,836	3,469	59,44

This choice of the target focus group of pusher vessels is due to a significant advantage in regularly performed transport work compared to other types of vessels, according to observations of two key observation points - Mohacs (1450 km of the Danube River, Hungary) and Gabchikovo (1820 km of the Danube River, Slovakia).

In the period 1990 - 2003, the Ukrainian Danube Shipping Company conducted research to find rational modes of movement in various navigational conditions [1]. The thrust of the propulsive complex was determined with different convoy compositions at the same depths with the "Znamenka" pusher (series "Zaporozhye"). Main engines SBV6M628 from Deutz, Germany, cylinder diameter 240 mm, piston stroke 280 mm, 2 × 910 kW at n = 1000 min^{-1}. Also, the hourly fuel consumption in kg/hour, and the speed in km/h, were determined.

The test results mathematically confirm the fundamentally known fact that the shape composition of the caravan and its mass significantly affect fuel consumption at the same depth under the keel. Even a simple rearrangement of a barge in the convoy of the same mass (Shapes 1 and 4, Fig. 1) causes a significant change in the hourly fuel consumption for a given power (at a speed of 10 km/hour, the difference in fuel consumption was about 27 kg/hour, Fig. 2).

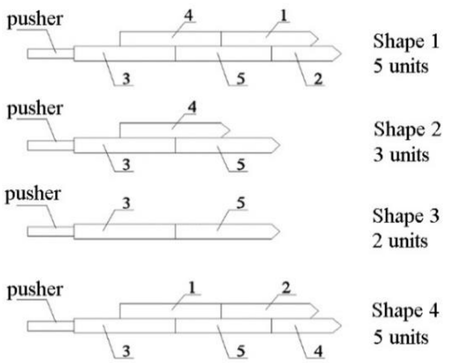


Figure 1. Schemes for compiling caravan's shapes. Barges: 1 – draught 2,0 m, cargo 895,2 tons; 2 – draught 2,0 m, cargo 888,2 tons; 3 – draught 2,3 m, cargo 1409,3 tons; 4 – draught 2,0 m, cargo 1159,7 tons; 5 – draught 2,3 m, cargo 1409,3 tons

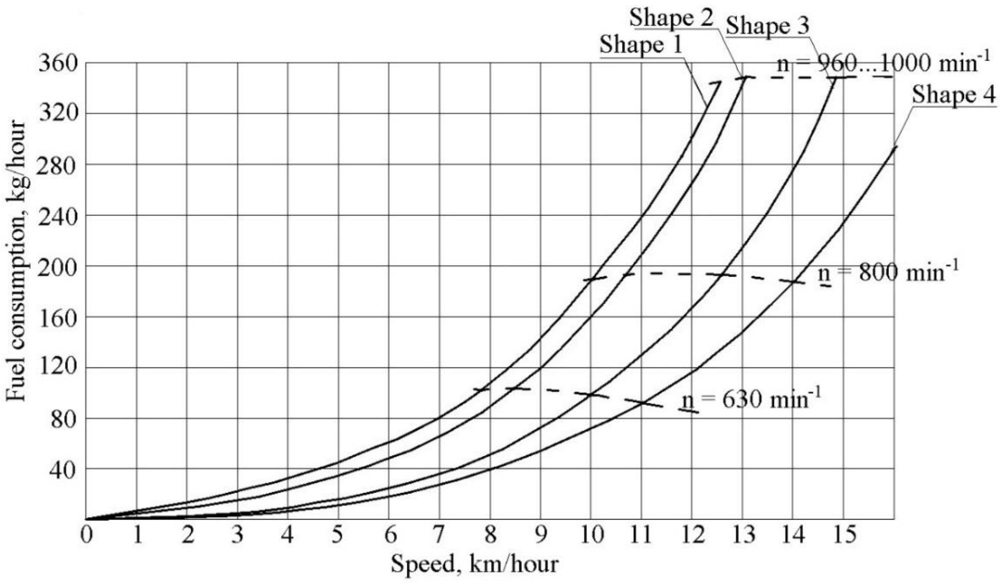


Figure 2. Graphs of hourly fuel consumption on speed for various convoys configurations

For a preliminary assessment of the energy efficiency index according to the principles applied by the International Maritime Organization for sea-going vessels, the test results of the m/v "Znamenka" with caravans of loaded non-self-propelled units were taken at four different options (EEIs 1 to 4 match Shapes 1 to 4 accordingly) for compiling a convoy (Fig. 3) in the operating speed range [1].

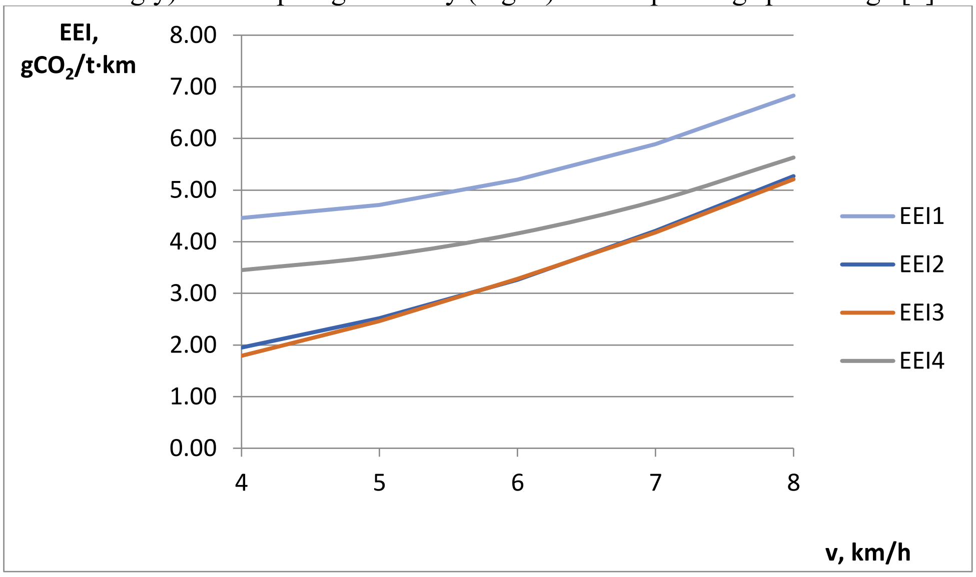


Figure 3. Indices of energy efficiency of m/v "Znamenka" for various forms of convoy composition, based on the test results

Another aspect – diagnostics and subsequent improvement of the characteristics of the engine's working process is one of the options for solving the efficiency of the power plant. Thus, during the voyage on the m/v "Boris Makarov" (owner - the Ukrainian Danube Shipping Company), diagnostic work was carried out to indicate the main and auxiliary engines using the DEPAS D4.0H system (development and implementation in cooperation with Odessa National Maritime University).

The basic diagnostic parameter found in all workflow monitoring systems is cylinder gas pressure. In most cases, this value is determined using special pressure sensors installed on the indicator valve. In some systems, stationary built-in pressure sensors are used with a large motor resource, designed for the entire period of engine operation. In addition to measuring the pressure of gases in the cylinder, the DEPAS D4.0H system uses the current method of vibroacoustic analysis [7].Using the VS-20 vibration sensor, the geometric and actual phases of the fuel supply are recorded, as well as the nature of the movement of the nozzle needle, which is especially important for determining the technical condition of both the nozzle itself and the high-pressure fuel equipment as a whole.

The use of a vibration sensor in the system is illustrated in Figure 2. The phases of fuel injection (the beginning corresponding to the “needle up” and the ending corresponding to the “needle down” landing) coincide with the leading edges of the vibration impulses on the lower vibration diagram. Analysis of vibration diagrams makes it possible to evaluate the fuel supply phases using a contact vibration sensor, without preparing the nozzle and without introducing special sensors into the high pressure system. In addition, the shape of the vibration impulses reflects the technical condition of the injector and the entire high-pressure fuel equipment as a whole. In normal technical condition, the injector generates two pulses (at the beginning and at the end of the injection) with clearly defined leading edges (Fig. 4).

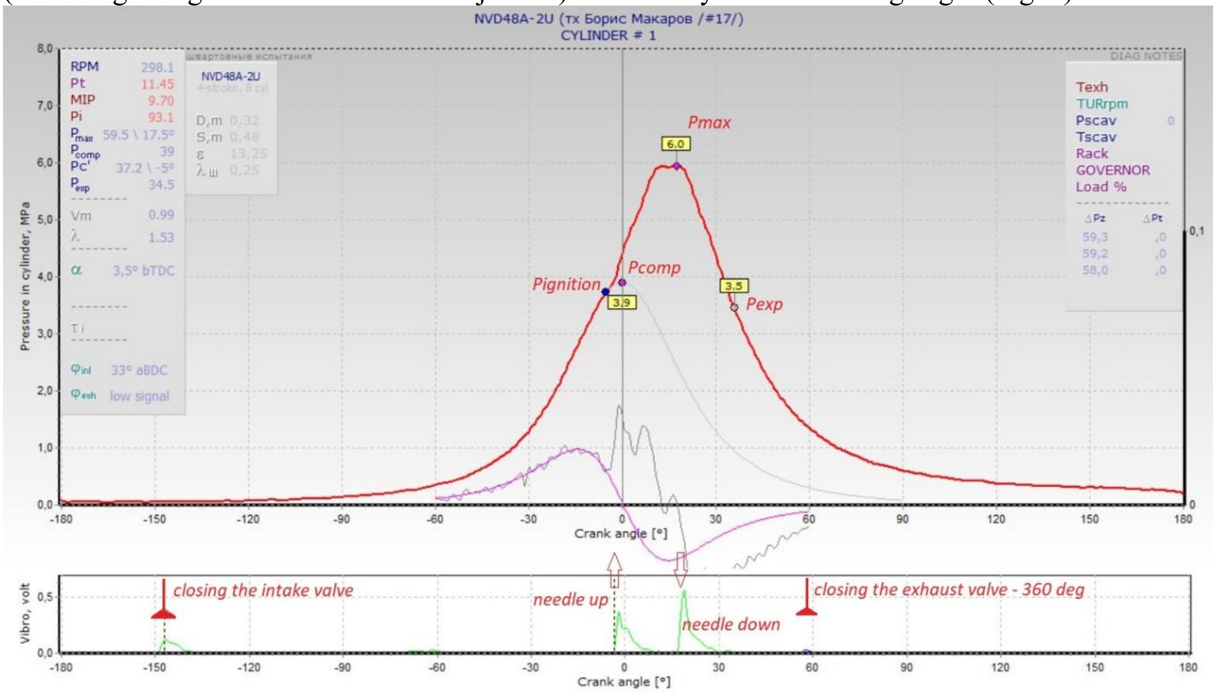


Figure 4. Indicator diagram and vibration diagram of the DEPAS D4.0H system, based on the test results m/v "Boris Makarov"

In the case of installing a vibration sensor on the end of the injector, the phase distance from the leading edge to the top dead center (TDC) characterizes the actual advance angle of fuel injection. When the vibration sensor is installed on the plug, opposite the shut-off window of the high-pressure fuel pump, the phase distance from the leading edge of the vibration pulse to TDC characterizes the geometric angle of the start of the fuel injection (the angle determined by the "meniscus").

The operating parameters of the gas distribution mechanism during engine operation are not determined by any of the known diagnostic systems. In this case, the use of vibroacoustic analysis methods in D4.0H systems makes it possible to determine the valve timing by vibration impulses when closing the “closing the intake valve” and “closing the exhaust valve” and to evaluate their technical condition by the form of vibration diagrams Fig. 4, 5. The system also provides for the output of summary indicator diagrams and vibration diagrams of the main diesel engines, Fig. 6, 7.

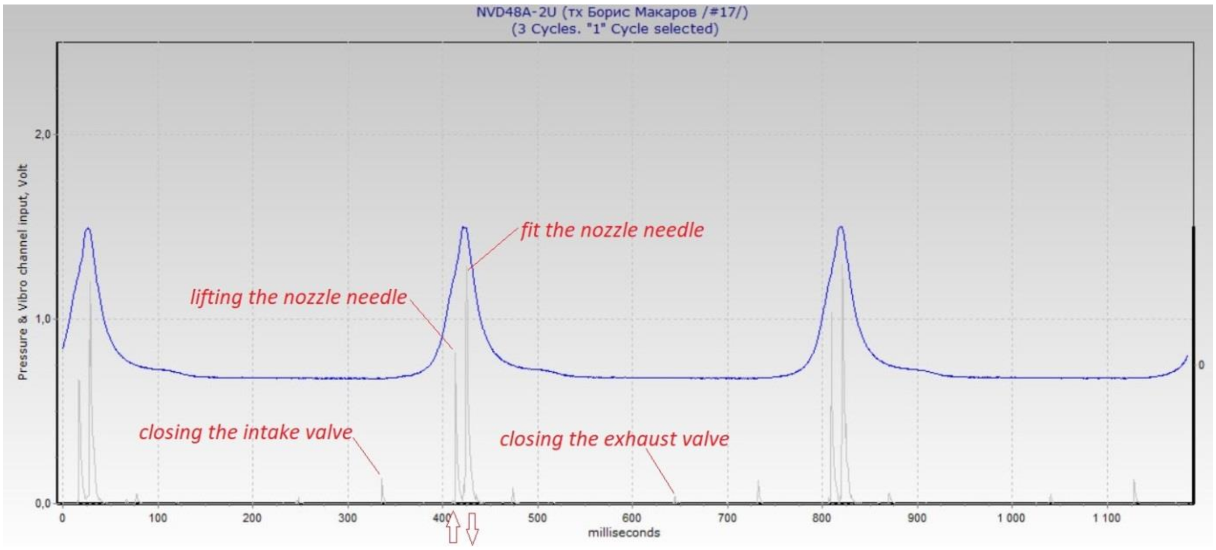
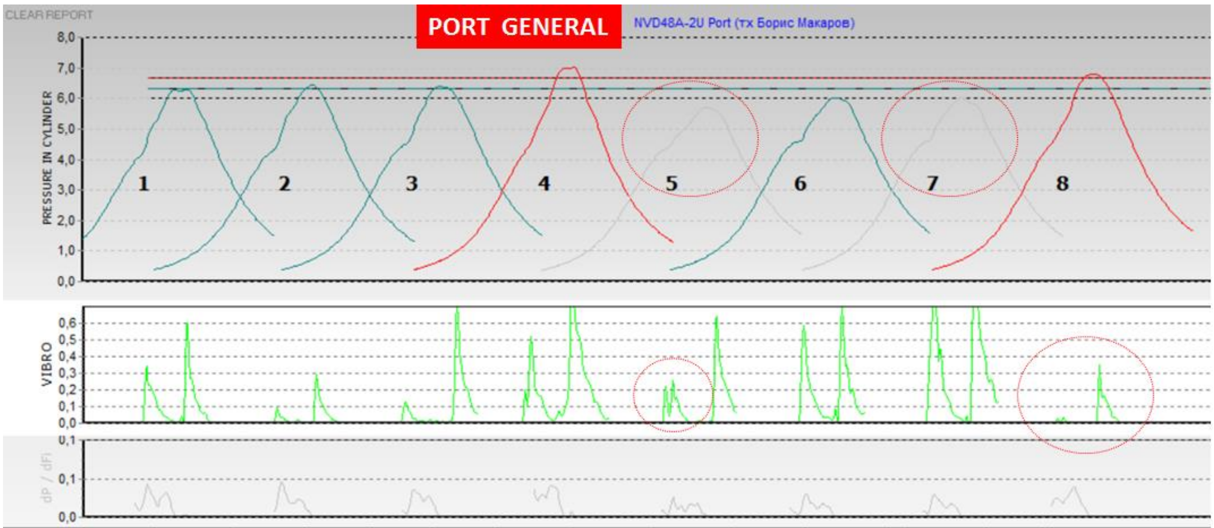
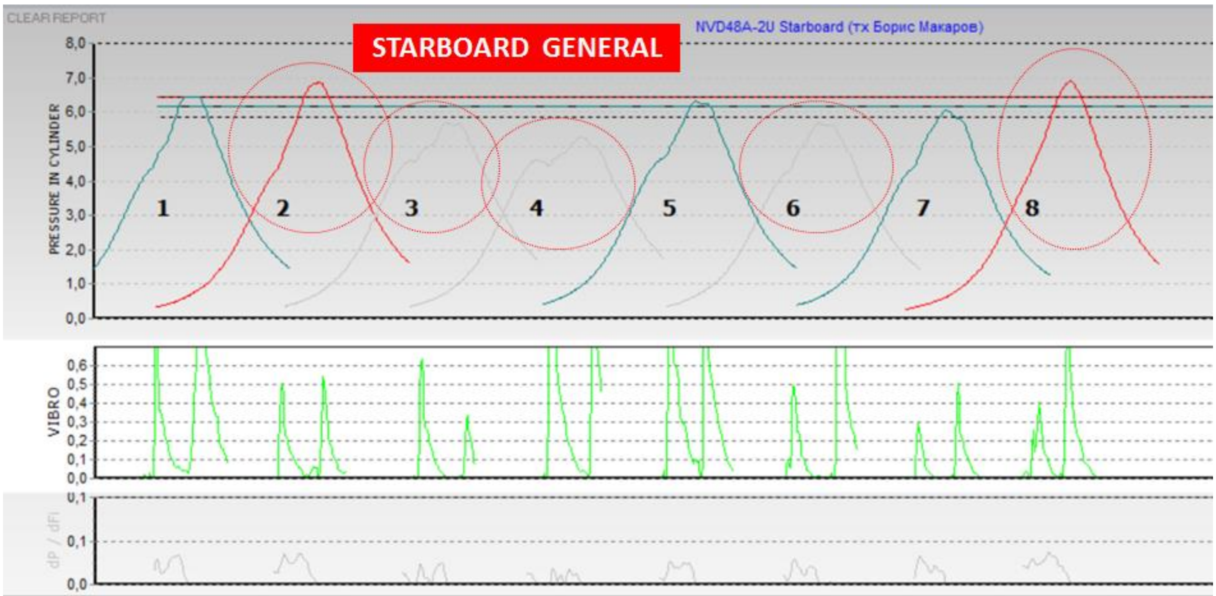


Figure 5. Vibration diagrams of the main NVD48A-2U diesel engines of m/v "Boris Makarov" using the DEPAS D4.0H system



CYLINDER	rpm	Pmax	Pcomp	MIP	Pi	Pt	Vm	Lmd	Alf inj	Fi inl	Fi exh	dltPmax	dltPc
1	292	63	41,8	10,21	96,1	11,9	1	1,51	3,1°	33,9°	low		
2	302	64,4	43,5	10,29	99,9	12,1	1,24	1,48	low	low	low		
3	302	64	45,0	11,31	110,0	12,7	1,3	1,42	3,1°	low	low		
4	303	70,3	45,1	10,07	98,2	12,5	1,25	1,56	7,5°	38°	54°		
5	301	57	43,7	10,87	105,3	12,1	0,74	1,31	3,1°	low	low		
6	302	60,3	45,8	10,84	105,6	12,5	0,9	1,32	-0,1°	low	55,6°		
7	304	60,1	46,0	10,60	103,7	12,4	0,96	1,31	1,1°	30,9°	49,9°		
8	304	67,9	45,9	12,16	119,1	13,4	1,15	1,48	low	low	low		

Figure 6. Summary indicator diagrams and vibration diagrams of the port main NVD48A-2U diesel engine of m/v "Boris Makarov" 10/01/2020, based on the test results



CYLINDER	rpm	Pmax	Pcomp	MIP	Pi	Pt	Vm	Lmd	Alf inj	Fi inl	Fi exh	dltPmax	dltPc
1	303	64,5	44,2	11,28	110,0	12,7	1,26	1,46	2,8°	37,2°	low		
2	304	68,6	44,0	11,35	111,0	12,8	1,23	1,56	3,6°	36,4°	low		
3	304	57	45,7	11,37	111,2	12,5	0,76	1,25	-2,7°	low	low		
4	305	52,6	45,9	11,17	109,6	12,2	0,5	1,15	-4,2°	36,7°	61,7°		
5	303	63	46,6	10,82	105,7	12,7	1,09	1,35	1,4°	39,6°	low		
6	303	56,8	42,7	10,13	98,7	11,8	0,98	1,33	2,8°	25,2°	low		
7	303	60,5	44,0	9,49	92,7	11,8	1,09	1,38	1,7°	low	low		
8	304	69	45,0	9,10	89,0	12,0	1,39	1,53	9,6°	low	low		

Figure 7. Summary indicator diagrams and vibration diagrams of the starboard main NVD48A-2U diesel engine of m/v "Boris Makarov" 10/01/2020, based on the test results

5. The Results

An operational voyage, during which measurements and tests were carried out, were held in October, 2020. The conditions of the voyage were as complex as possible for the operation of the main engines.

The main dimensions and characteristics of the m/v "Boris Makarov":

- Vessel's type – self-propelled, pusher
- Length overall – 38,5 m
- Breadth – 11,03 m
- Height – 3,20 m
- Depth moulded – 2,1 m
- Power plant – 2×852 kW
- Velocity without convoy – 19 km/h
- Crew – 7 persons.

Two 8NVD48A-2U diesel engines manufactured by SKL (Germany) are installed as main engines. Diesels are four-stroke, in-line, reversible, trunk, single-acting, with gas turbine charging and automated remote control. Main characteristics:

- rated power – 852 kW
- rotation speed – 375 min^{-1}
- number of cylinders – 8
- cylinder diameter – 320 mm
- piston stroke – 480 mm
- average effective pressure – 0.9 MPa

- specific effective fuel consumption – 220 g / kWh (max 230 g / kWh)
- average consumption of lubricating oil (total) – 1500 g / h.

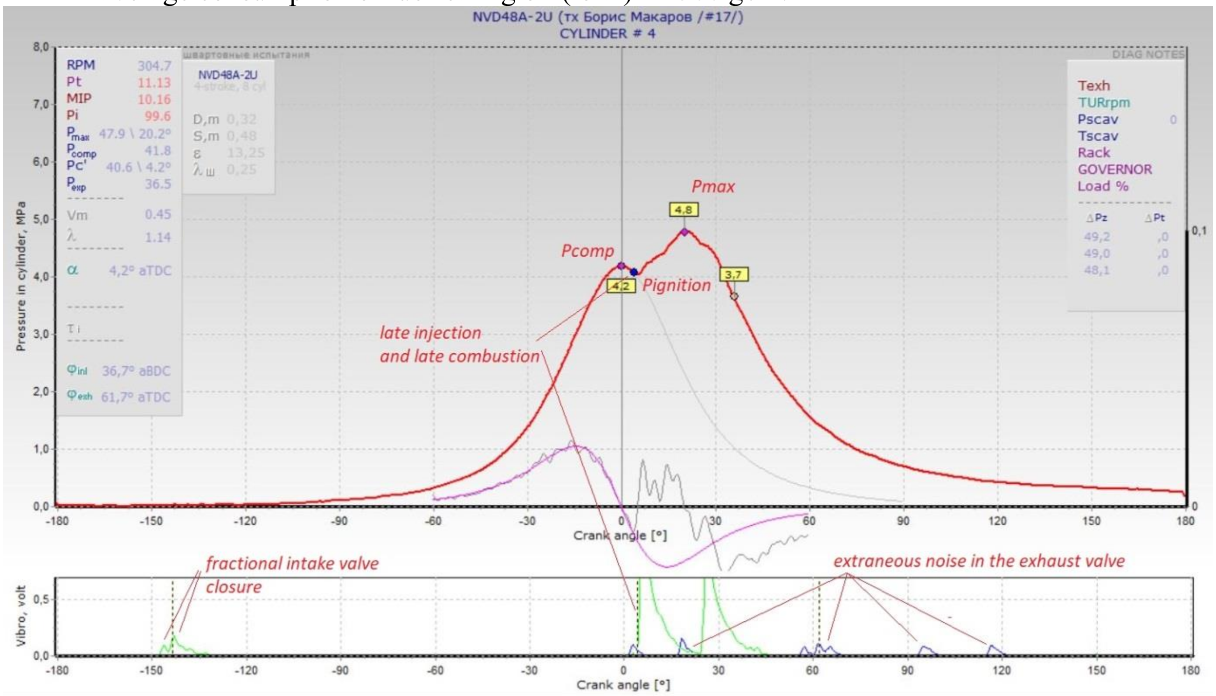


Figure 8. Indicator diagrams and vibration diagrams cylinder №4 of the main NVD48A-2U diesel engine of m/v "Boris Makarov" 10/01/2020, based on the test results

Table 3. Port main NVD48A-2U engine indication results of m/v "Boris Makarov" 10/01/2020.

Diesel 8NVD48A-2U PORT	Diesel engine was indicated with crankshaft rotation speed: n ~ 300 min^{-1}. Exhaust gases in cylinder temperatures,° C: 1 2 3 4 5 6 7 8 310° 360° 355° 330° 320° 360° 360° 340° -- Cyl.1. - Cyl.2. - Cyl.3. – Cyl.4. cycle feed increased for 2-3 points, valves revision Cyl.5. injector defect Cyl.6. Late injection angle, intake valves revision Cyl.7. Late injection angle, check shim state and injection angle / plunger pair Cyl.8. injector revision

Table 4. Starboard main NVD48A-2U engine indication results of m/v "Boris Makarov" 10/01/2020.

Diesel 8NVD48A-2U STARBOARD	Diesel engine was indicated with crankshaft rotation speed: n ~ 300 min^{-1}. Exhaust gases in cylinder temperatures,° C: 1 2 3 4 5 6 7 8 400° 350° 350° 380° 380° 370° 300° 300° --- Cyl.1. – Cyl.2. cycle feed increased for 2 points Cyl.3. Late injection angle, injector – OK, check shim angle / FPHP plunger pair revision Cyl.4. Late injection angle, injector – OK, reduced injection angle - injection pump plunger pair revision, exhaust valve revision Cyl.5. exhaust valve revision Cyl.6. – cycle feed decreased for 2-3 points, intake valve revision Cyl.7. – Cyl.8. injector revision

6. Conclusions

The range of changes in the values of the energy efficiency index is 25 ... 60%, depending on the speed and the train form. Subject to the choice of a rational speed and the shape of trains, the potential for increasing energy efficiency in the inland Danube shipping is 20 ... 55%, which will also lead to an improvement in the environmental performance of pushers. At the same time, it is undoubtedly attractive that there is no need for capital investments on the part of shipowners to modernize the fleet (except for the usual operating and operating costs), to maintain the established principles of long-arm operation with heavy caravans on the market and at the same time achieve the best indicators of energy efficiency and environmental friendliness.

Experience with the *DEPAS D4.0H* system shows that constant monitoring of the technical condition of the main and auxiliary engines, the timely elimination of defects in the fuel equipment and its adjustment together with the adjustment of the gas distribution mechanism gives good results:

- uniform distribution of loads over the cylinders and exhaust gas temperatures is maintained;
- the total heat stress of the parts of the cylinder-piston group decreases, overheating of individual cylinders and the forced decrease in engine power are eliminated;
- emergency situations are prevented, in particular, such as fires in subpiston ones (one of the main causes of ignition in subpiston ones is poor-quality fuel atomization, its mixing into the cylinder oil and, consequently, a decrease in the oil flash point);
- timely elimination of defects and adjustment of the main engine and diesel generator makes it possible to withstand the passport operation modes, the planned speed of the vessel and have a reserve of engine power.

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