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List of abbreviations and symbols

DF – diesel fuel;

SSU – the state standard of Ukraine;

CP – coefficient of performance;

UN – United Nations;

SICE – ship internal combustion engine;

m/s – motor ship;

FW – FuelWell (device, which decrease fuel consumption and toxic exhaust gases).

Introduction

In recent decades, due to the significant growth in transport volumes, the problems of the transport impact on the environmental have been exacerbated. About 70% of harmful emissions comes from road transport, 15% of emissions are attributed to the river and sea fleet, while other 15% are emissions from industrial enterprises, railways, volcanic activity.

In the EU's countries the pollutant emission from the exhaust gases of automotive diesel engines is carried out in accordance with UNECE Regulation № 49, which is based on the requirements of the Geneva Agreement of 1958. Over the past years, these rules have been repeatedly subjected to significant adjustments, both in the list of normalized harmful substances, and in the strengthening of their norms. Thus, at the Euro-5 stage, which has been on operation since 2008, in comparison with Euro-3 (2000 year of introduction) the emission reduction requirements are: for oxides of nitrogen (NOx) – in 2,5 times, for carbon monoxide (CO) - in 1,4 times, for hydrocarbon (CH) - in 1,4 times, for disperse particles (DP), including soot - in 5 times. According to Euro-5 the maximum allowable NOx emissions are limited to 2 g/(kW-hour).

The power plants of the ships pollute the exhaust gases first of all the atmosphere, from where the toxic substances partially or almost completely fall into the waters of the sea, ocean, rivers. At the present, the vast majority of vessels of the domestic (and world) fleet are equipped with the diesel engines..

Recently, restrictions on the content of harmful substances in exhaust gases of ship internal combustion engine (SICE) have been introduced in accordance with the requirements of the sixth Marpol annex and the United Nations Paris Conference on the UNEP Program on December 12, 2016. Simultaneously with the strengthening of nitrogen oxide NOx emissions requirements, for all modes of transport and industrial enterprises under parity arrangements, carbon dioxide (CO_2) reduction are also introduced..

The Legislature for the standardization of the environmental performance of the SICE is the International Maritime Organization (IMO). The technical standards of IMO Tier – 2 developed by it and it force since January 1, 2011 apply only to emissions of nitrogen oxides. From 2016, it is proposed to introduce a new IMO's standard Tier - 3, in which the maximum permissible content of NOx in exhaust gases will be reduced by almost 4 times. Thus, from 2016 ship engines will have to provide the same NOx emissions figures as automotive diesel engines[1].

[1] http://www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/nitrogen-oxides-(nox)-%E2%80%93-regulation-13.aspx

The reduction of harmful emissions from the diesel SICE's exhaust gases is a complex problem related to the efficient use of fuel. Directly related to it is the amount of carbon dioxide that is found in the atmosphere, and determines the ecological state of the planet associated with the greenhouse effect. Carbon dioxide is a product of complete combustion, so the only way to decrease it is to reduce fuel consumption.

Thus, the solution to this problem is aimed at finding a compromise between emissions and fuel consumption.

At present, a situation has arisen where the development of modern SICEs and their competiveness are determined mainly by the availability of funds that will reduce the emissions of harmful substances to the level of relevant environmental requirements. At present, situation has arisen where the development of modern ICEs and their competiveness are determined mainly by the availability of funds that will reduce the emissions of harmful substances to the level of relevant environmental requirements. These requirements can be achieved by different methods.

Among all the various methods deserve special attention, especially those that are aimed at selective catalytic regeneration. One such means of reducing the negative environmental impact of internal combustion engines is the use of special devices to reduce harmful emissions to the atmosphere and fuel economy, in particular FuelWell. Such devices are used in the fuel system of a vehicle and are used for pre-treatment of fuel supplied to the engine.

Apart from the environmental impact, FuelWell also has a fuel economy effect, which can range from 5 to 30 %[2] of traditional combustion.

In this works the results of measurements of the exhaust gas composition of ship internal combustion engine, which is used as a power plant of the «Captain Zhidkov» ship, owned by PJSC «Ukrainian Danube Shipping Company» (Izmail, Odessa region) equipped with FuelWell, are given.

[2] According to producers

1 Normative base

During performing the work the following normative documents were used:

- SSU 24585-81 Marine engines, diesel locomotive and industrial. Harmful emissions with the toxic exhaust gases. Norms and methods for measuring.
- SSU 24028-80: Marine, diesel locomotive and industrial engines. Smoke of the exhaust gases. Norms and methods for measuring.
- SSU 7688:2015 Diesel Euro fuel. Specifications.
- SSU 10448-80 Marine, diesel locomotive and industrial engines. Acceptance. Methods of measuring.
- SSU 4276:2004 «Standard's system in the field of environmental protection and rational use of resources. Atmosphere. Standards and methods for measuring the smoke of exhaust gases of cars with diesel engines and gas dischargers».
- SSU 4277:2004 «Standard's system in the field of environmental protection and rational use of resources. Atmosphere. Standards and methods for measuring the content of carbon monoxide and hydrocarbons in the exhaust gases of cars with engines operating on gasoline or gas fuels».
- SSU 4276:2004 Norms and methods of measuring the smoke of exhaust gases of cars and diesel engines or gas dischips.
- SSU 2501-94 Gas analyzers for transport emissions monitoring. General technical requirements and tests methods.
- SSU 17.2.1.02-76 «Protection of Nature. Atmosphere. Terms and definitions engine's emissions, cars, tractors, self-propelled agricultural and road construction machinery».
- SSU 17.2.2.01-84 «Protection of Nature. Atmosphere. Diesel engines for automobiles. Smoke of exhaust gases. Standards and methods of measurements».
- SSU 17.2.2.02-98 «Protection of Nature. Atmosphere. Norms and methods for determining the smokiness of exhaust gases of diesel engines, tractors and self-propelled agricultural machinery».

2 Terms

2.1 Characteristics of the vehicle and the internal combustion engine

The exhaust gas's measurement was carried out on the ship's internal combustion engine on the motor ship «Captain Zhidkov» (Fig. 2.1). The main technical characteristics of the m/s are given on the table 2.1.

M/s «Captain Zhidkov» was built in 1980 by the Austrian company Osterreichische Schiffswerften Linz-Korneuburg under the project MO44, such as «Captain Antipov».

Fig. 2.1 – The look of the m/s «Captain Zhidkov»

The table 2.1 – The main technical characteristics of m/s «Captain Zhidkov»

№	Denomination	Meaning
	General information	
1	Type	"Captain Antipov"
2	Case class	Register of Shipping of Ukraine: (dry cargo + pusher)
3	Registration №	2-031028. Prescribed - Izmail
3	Length	95,16 m
5	Width	11,03 m
6	Height of the board	3,20 m

7	Maximum sediment	2,73 m
8	Fixed point	6,50 m
9	Deadweight	1900 t
10	Volume of cargo hold	2109 m^3
11	Capacity of the power plant	2100 hp (2 x 772 kW)
12	Speed without a caravan	19 km/hour

2.2 Methotodoly and tools of instrumental measurements

During the performers of measurements with the help of a gas analyzer, the measurement of the composition of the exhaust gases of the main (left) SICE, in particular the content of such substances:

- O_2
- CO_2
- CO
- NO
- NO_2
- NO_x
- SO_2

Some of the above components are poisonous and toxic.

Measurements of the exhaust gas composition of the SICE was carried out in accordance with the current normative documents (SSU 24585-81, SSU 24028-80, SSU 10448-80).

These documents contain requirements for measuring instruments used for measuring the content of carbon monoxide, hydrocarbons, and the smoke of exhaust gases of marine diesel aggregates.

Measurement of hazardous substances in exhaust gases was carried out during the loading of the loaded vessel upstream of the Danube river at the distance of 10 km, within the limits of the city of Izmail.

Measurements were made for different frequencies (low and high) rotation of the engine shaft. Measurements were made for frequencies within the limits 120…300 r/min.

During the measurement, the marine diesel engine was used to power the fuel of the brand 10ppm Euro-5 standard. According to the supplier of fuel, this diesel fuel belongs to the hight quality of the standard Euro-5 with a sulfur content of no more than 10 ppm. The main technical characteristics of diesel fuel correspond to SSU 7688:2015 Diesel Euro fuel. Specifications.

The measurements of the exhaust gases of the SICE was carries out according to the program presented on the table 2.2.

All measurements were made for two modes of operation of the SICE:

- Mode 1 – with the FuelWell;

- Mode 2 – without the FuelWell.

According to the measurement program, the vessel was moving upstream. At a distance of about 5 km, the measurements were made with the FuelWell. Then the device was switched off and made repeated measurements.

Before starting the measurements, the engine was warmed up to the temperature regulated coolant temperature.

The results of each measurement were stored in the memory of the meter.

The table 2.2 – Program of measuring works

№ of measuring	SICE mode operation	Rotational speed, r/min	SICE average composition of exhaust gases, % or ppm
1	With the FuelWell	300	
2		280	
3		260	
4		250	
5		120	
6	Without the FuelWell	120	
7		250	
8		260	
9		280	
10		300	

The performed measurements were carried out with the use of measuring devices, both portable and regular, installed on the vessel.

To determine the composition of the exhaust gases the portable gas analyzer Testo 350 (Reg. № 02283438) with measuring sensors of O_2, CO, NO, NO_2, SO_2, H_2S was used.

The «Testo» gas analyzer that was used on the measurement process meets the approved type, which is registered in the State Register of Measuring Instruments under number У971-08 and has a corresponded certificate.

The gas analyzer was used to control the metrological characteristics of the production, which was carried out by the Metrological Service of «Testo» (accredited by the National Metrology Service of Germany), as well as by the State Enterprise «Ukrmetertеststandard».

A standard ship tachometer installed on board the vessel was used to control the number of SICE shafts rotations.

2.3 Measurement conditions

The main parameters and conditions for measuring work are given on the table 2.3.

The table 2.3 – The main parameters and conditions for measuring work

№	Denomination	Meaning	Note
1	Date of measurement	29.07.2017	
2	Time of measurement	From 2 pm to 4 pm	
3	Environmental temperature	+25…+28 ^{0}C	
4	Marine type	M/s «Captain Shidkov»	
5	Fuel type	Ship diesel fuel 10ppm Euro-5 standard	
6	Distance move	10 km	Under pressure

3 Results of measurements

According to the results of the measurements, the composition of the exhaust gases of the SICE, in particular the content of CO and NOx was determined.

3.1 The results of the measurements of the exhaust gas content of the ship internal combustion engine

During the measurement of the exhaust gas content of the SICE, a number of indicators were obtained, the values of which were averaged. All received results were systematized depending on:

- SICE shaft rotation speed (in the range from 120 r/min. to 300 r/min.);
- SICE operation mode (with and without the FuelWell).

In addition to the exhaust gas SICE also recorded their temperature, which was on average 250…255^{0}C.

The measurements of all components of exhaust gases (except O_2 and CO_2) carried out in millions of shares, which is a unit of measurement of concentration and other relative quantities, is similar in content per cent or ppm, and represents one million pounds (1 ppm = 0,0001 %). Affected by abbreviations ppm. Oxygen and carbon monoxide content is measured in %.

Except ppm the results of measurement can measure in % and in mg/m^3.

In order to move the measurement results from ppm in mg/m^3 it is necessary to use the

molecular weight of the chemical element. Conversion is done under normal conditions (20ºC and 1 atm, 760 mm rt. st).

The results of the measurement of the exhaust gas composition of the SICE are given on the tables 3.1 (ppm), 3.2 (%) and 3.3 mg/m^3.

Comparison of exhaust combustion with and without the FuelWell is shown on Figures 3.1 – 3.6.

The table 3.1 – Results of the measurement of the exhaust gas content of the SICE (ppm)

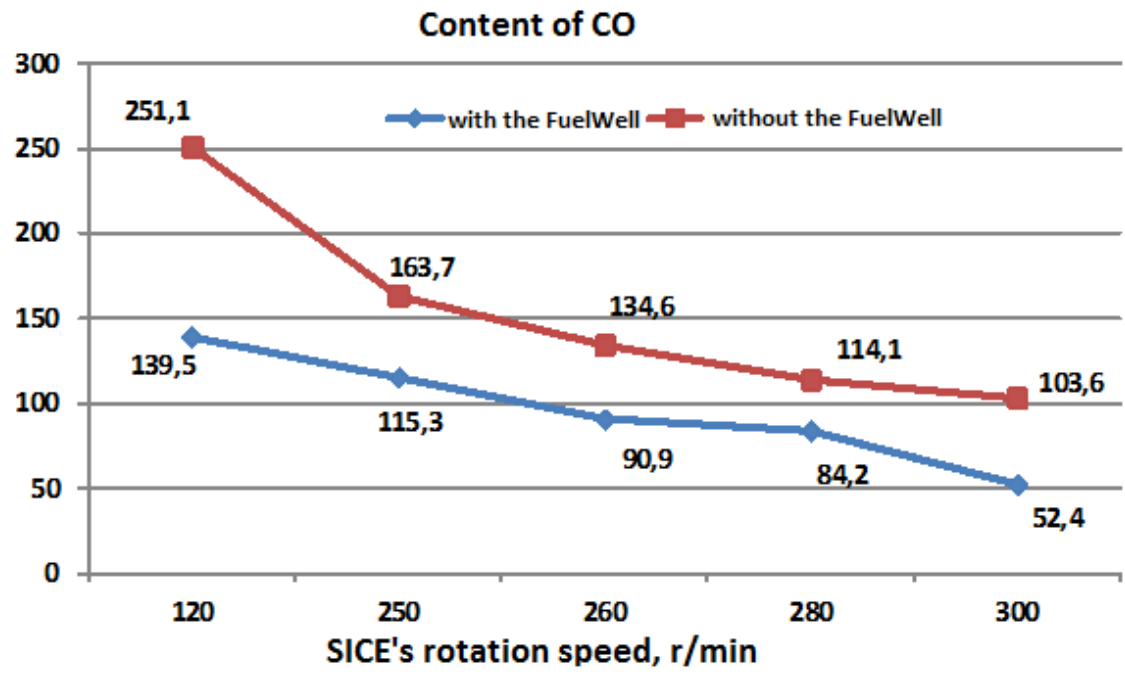
№	Mode	Rotation speed, r/min	SICE average composition of exhaust gases							Exhaust gas temperature, ^{0}C	Note
			O_2, %	CO, ppm	NOx, ppm	NO, ppm	NO_2, mg/m^3	SO_2, mg/m^3	CO_2, %		
1	With the FuelWell	300	12,87	52,4	1398,8	1342	258	0	5,85	271,8	
2		280	12,3	84,2	1353,8	1300	228	0	6,14	292,6	
3		260	11,82	90,9	1137,2	1087	202	0	6,18	321,0	
4		250	12,64	115,3	963,8	852,9	200	0	6,02	267,8	
5		120	18,33	139,5	502,7	478,1	185	0	5,95	190,1	
6	Without the FuelWell	120	18,24	251,1	545,2	470	238	0	6,14	163,8	
7		250	12,75	163,7	1293,5	1244	268	0	6,12	273,3	
8		260	11,61	134,6	1561,8	1541,4	371	0	6,52	297,7	
9		280	12,61	114,1	1593,3	1644,0	736	0	6,38	273,3	
10		300	18,48	103,6	1893,5	1713,0	738	0	5,95	198,5	

The table 3.2 – Results of the measurement of the SICE exhaust gas composition (%)

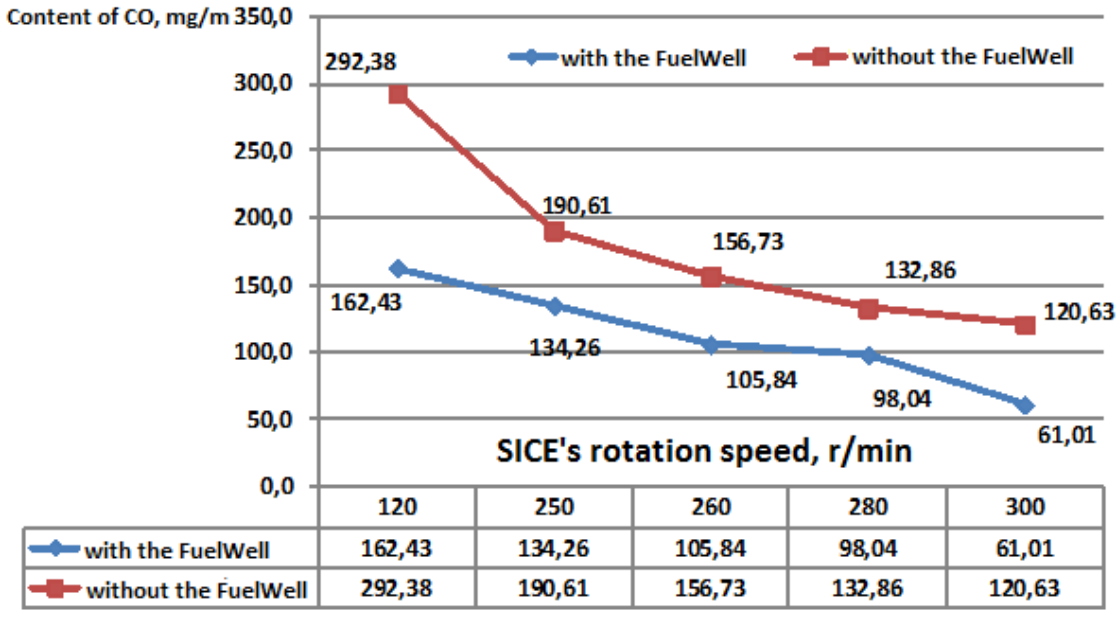
№	Mode	Rotation speed, r/min	SICE average composition of exhaust gases							Exhaust gas temperature, ^{0}C	Note
			O_2, %	CO, %	NOx, %	NO, %	NO_2, mg/m^3	SO_2, mg/m^3	CO_2, %		
1	With the FuelWell	300	12,87	0,00524	0,1399	0,1342	258	0	5,85	271,8	
2		280	12,3	0,00842	0,1354	0,13	228	0	6,14	292,6	
3		260	11,82	0,00909	0,1137	0,1087	202	0	6,18	321	
4		250	12,64	0,01153	0,0964	0,0853	200	0	6,02	267,8	
5		120	18,33	0,01395	0,0503	0,0478	185	0	5,95	190,1	
6	Without the FuelWell	120	18,24	0,02511	0,0525	0,047	238	0	6,14	163,8	
7		250	12,75	0,01637	0,1294	0,1244	268	0	6,12	273,3	
8		260	11,61	0,01346	0,1562	0,1541	371	0	6,52	297,7	
9		280	12,61	0,01141	0,1593	0,1644	736	0	6,38	273,3	
10		300	18,48	0,01036	0,1894	0,1713	738	0	5,95	198,5	

The table 3.3 – Results of the measurement of the SICE exhaust gas composition (mg/m^3)

№	Mode	Rotation speed, r/min	SICE average composition of exhaust gases				Exhaust gas temperature, ^{0}C	Note
			CO, mg/m^3	NO, mg/m^3	NO_2, mg/m^3	SO_2, mg/m^3		
			Molecular weight, g/mol					
			28,01	*30,01*	*46,01*	*64,06*		
1	With the FuelWell	300	61,01	1674,20	258	0	271,8	
2		280	98,04	1621,81	228	0	292,6	
3		260	105,84	1356,08	202	0	321	
4		250	134,26	1064,03	200	0	267,8	
5		120	162,43	596,45	185	0	190,1	
6	Without the FuelWell	120	292,38	586,35	238	0	163,8	
7		250	190,61	1551,94	268	0	273,3	
8		260	156,73	1922,96	371	0	297,7	
9		280	132,86	2050,96	736	0	273,3	
10		300	120,63	2137,04	738	0	198,5	



a)



b)

Fig. 3.1 – The content of carbon monoxide (CO) in the SICE exhaust gases in ppm (a) and mg/m^3 (b)

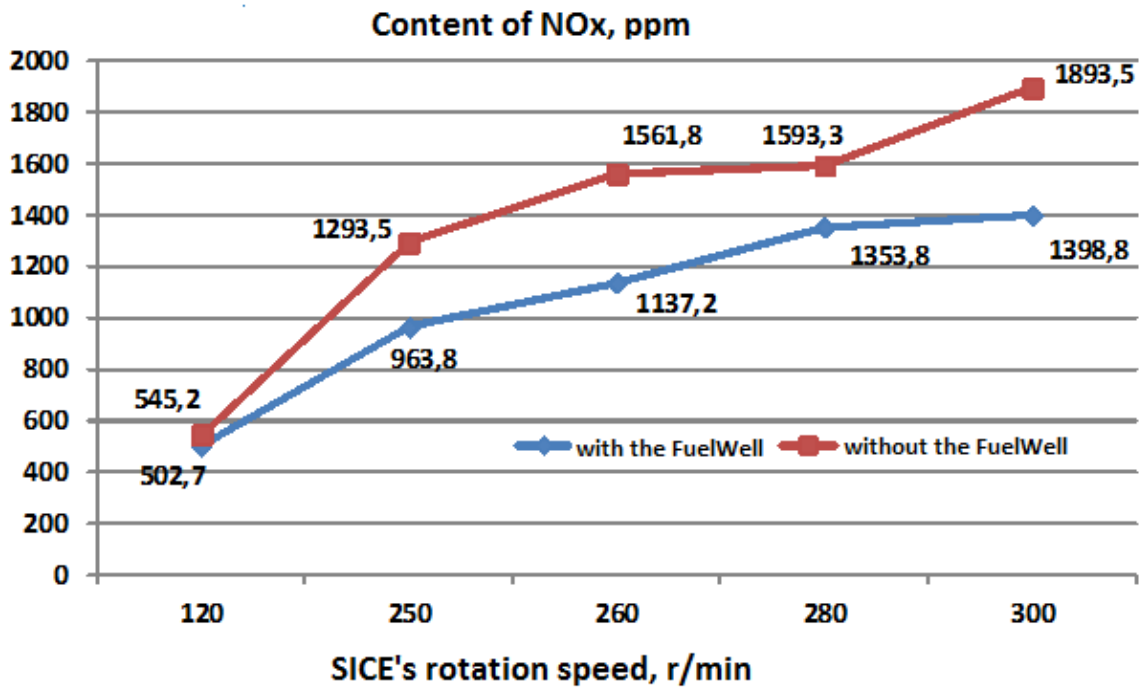
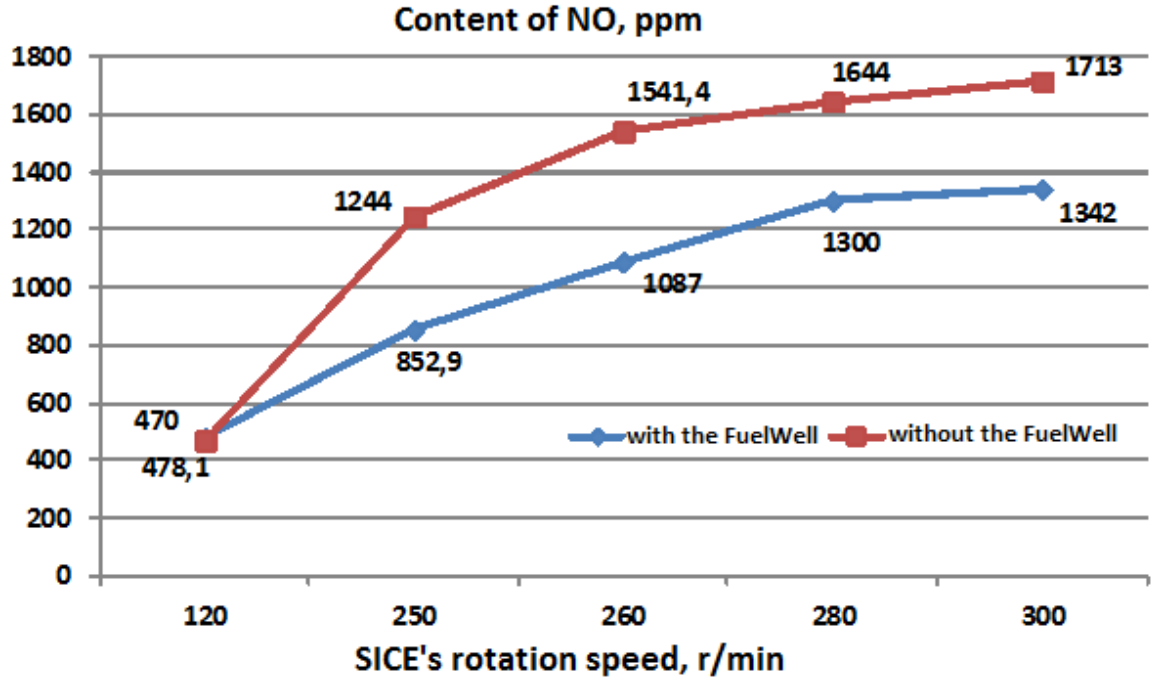
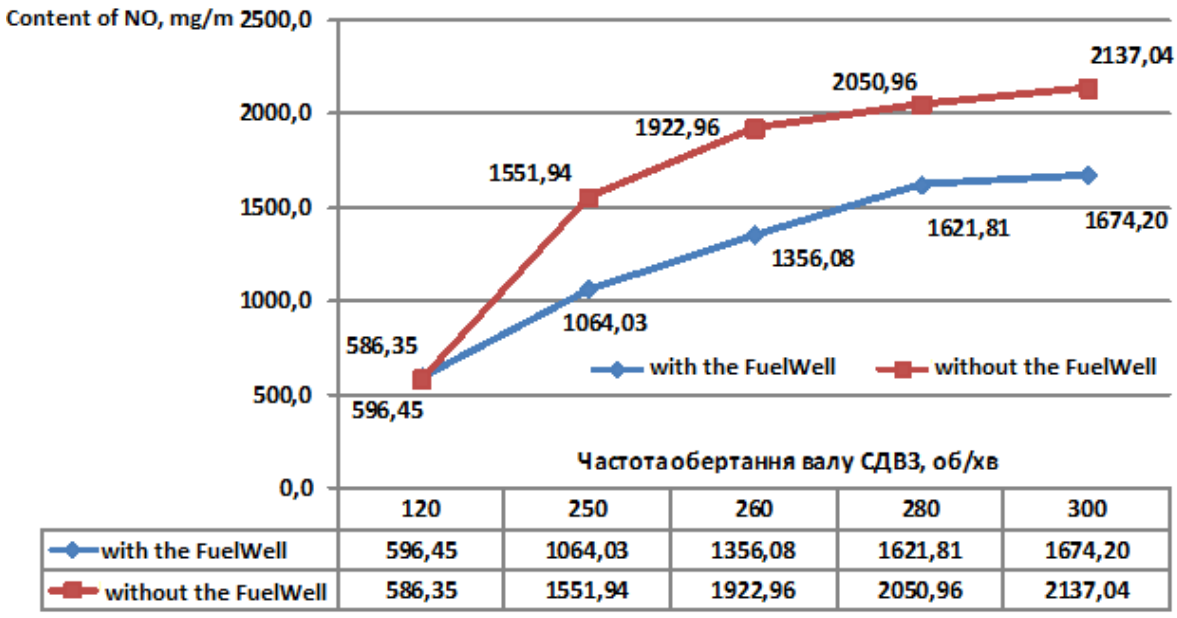


Fig. 3.2 – The content of nitrogen oxides (NOx) in the SICE exhaust gases



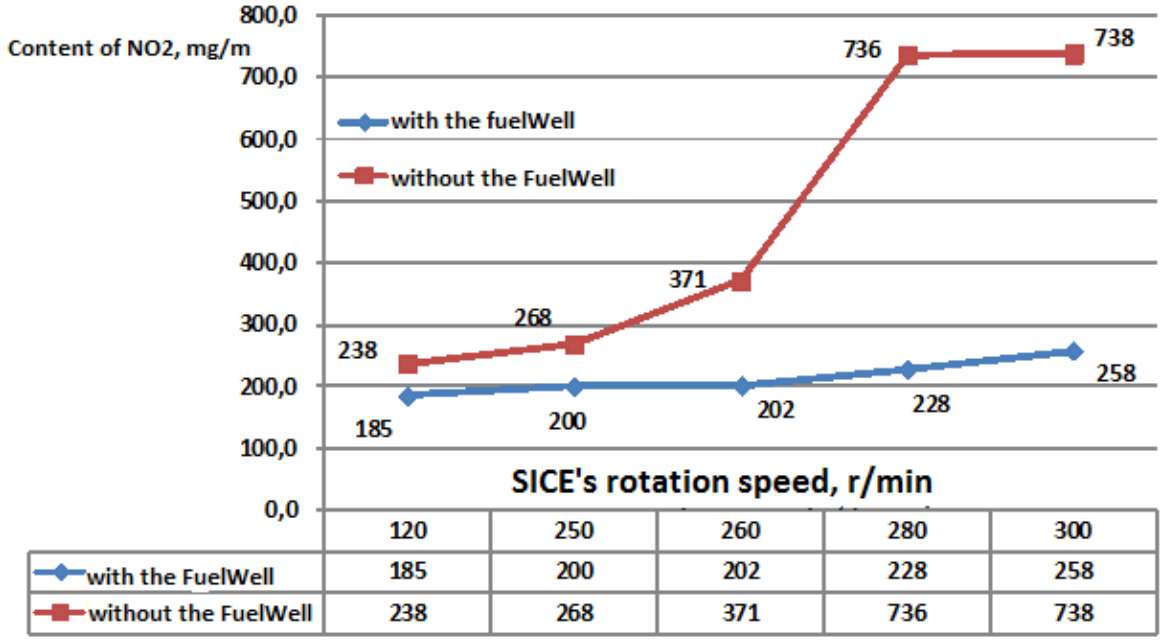
a)



	120	250	260	280	300
with the FuelWell	596,45	1064,03	1356,08	1621,81	1674,20
without the FuelWell	586,35	1551,94	1922,96	2050,96	2137,04

b)

Fig. 3.3 – The content of nitrogen oxide (NO) in the SICE exhaust gases ppm (a) and mg/m^3 (b)



	120	250	260	280	300
with the FuelWell	185	200	202	228	258
without the FuelWell	238	268	371	736	738

Fig. 3.4 – Nitrogen dioxide content (NO_2) in the SICE exhaust gases

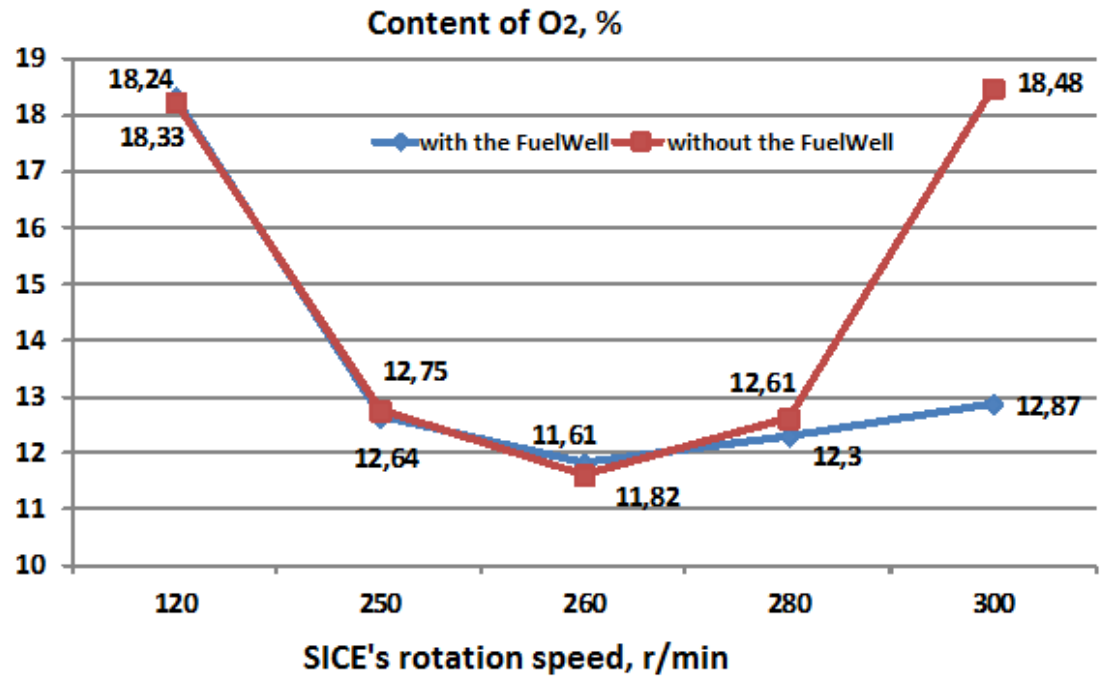


Fig. 3.5 – Oxygen content (O_2) in the SICE exhaust gases

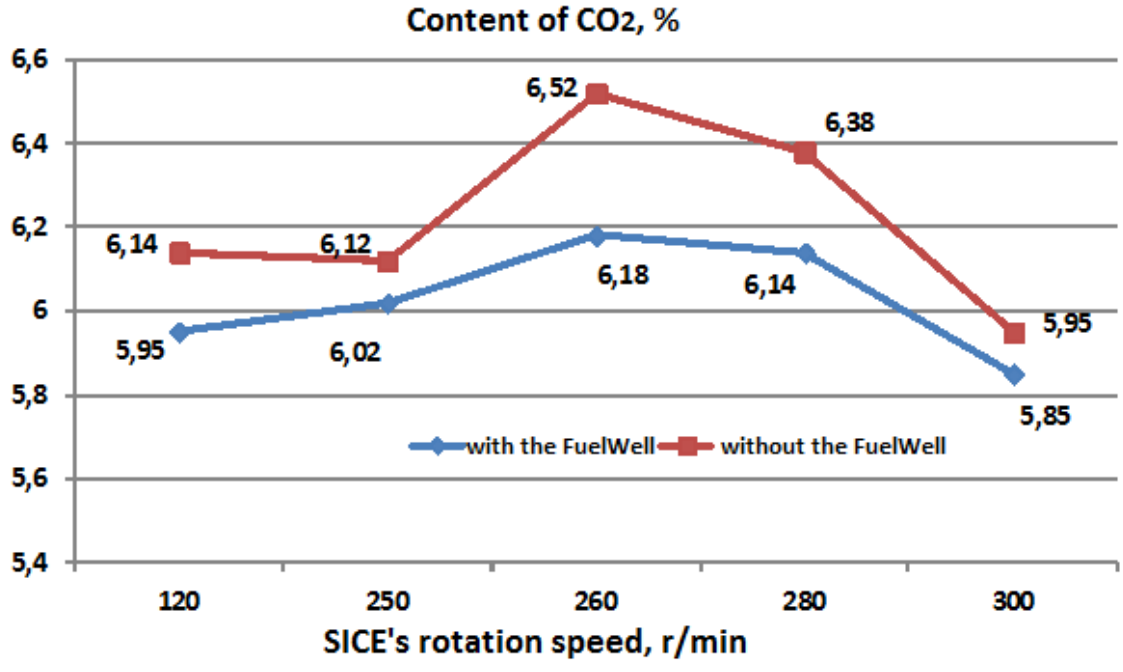


Fig. 3.6 – Carbon dioxide content (CO_2) in the SICE exhaust gases

3.2. Analysis of the measurement results of the exhaust gas composition of the marine internal combustion engine

The main environmental performance of marine engines of internal combustion is the content of exhaust gases of nitrogen oxides (NOx) тand carbon monoxide (CO).

During the measurement of the exhaust gas content of the SICE, the values of NOx and CO content in the exhaust gases were determined using and without the FuelWell.

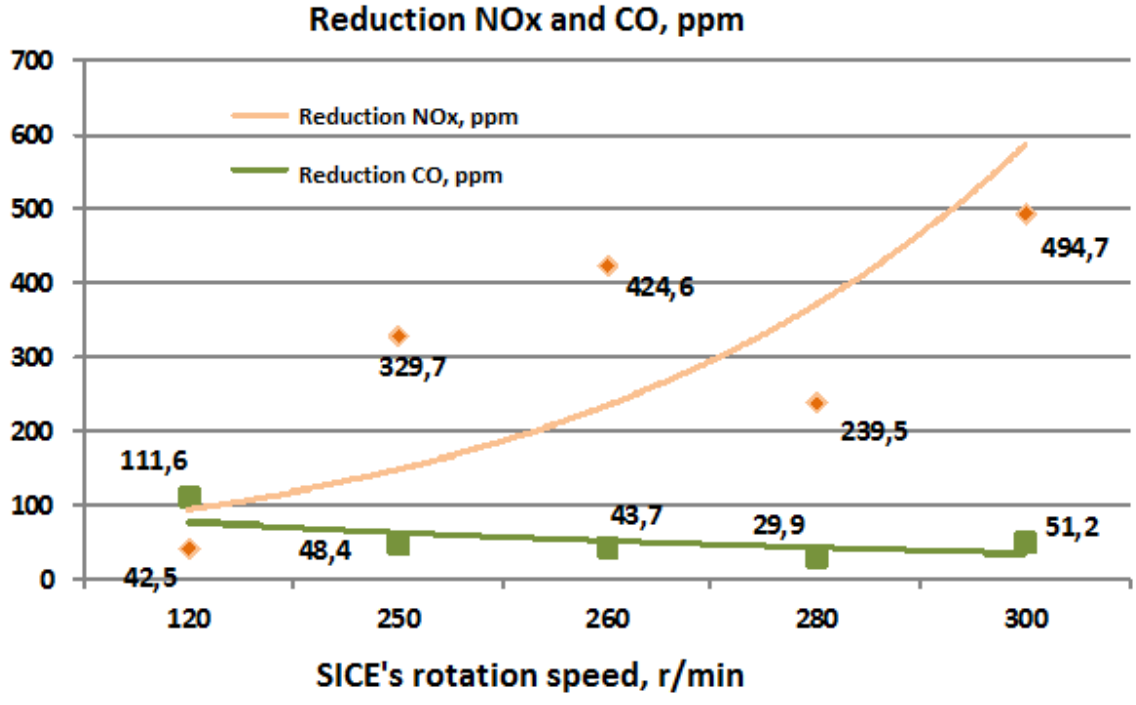
As shown on Figures 3.1 and 3.2, using the FuelWell in fuel's system of the SICE allows to reduce NOx and CO content in the exhaust gases. In particular, an average content of CO is reduced in 1,6 times (in 36 %), a NOx – in 1,3 times (in 20 %).

In addition, the carbon monoxide content in the exhaust gases increases at low speeds of the SICE shafts. Increasing the SICE shafts rotation speed causes an increase in the temperature inside the engine cylinders and, accordingly, provokes the intensification of the formation of nitrogen oxides and increases the NOx content in the exhaust gases.

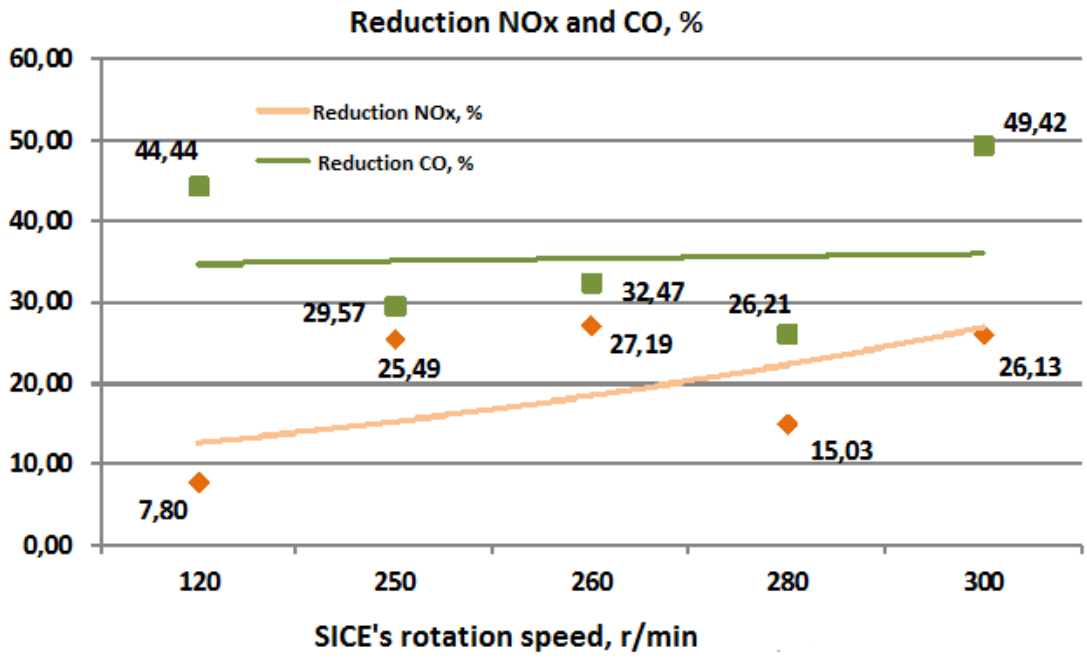
Increasing the rotation of the SICE shaft leads to a greater reduction in the NOx and CO content in the exhaust gases.

The dependence of the reduction (on the application of FuelWell) of the NOx and CO content in the exhaust gases from the number of revolutions of the SICE shaft in absolute (ppm) and relative (%) units is shown on Figures. 3.7.

The use of FuelWell leads to more efficient combustion of fuel in SICE and a reduction in the content of carbon monoxide and nitrogen oxide.



a)



b)

Fig. 3.7 – Dependence of the reduction of NOx and CO content in the exhaust gases from the number of SICE shaft revolutions in absolute units, (a) and relative units, % (b)

Conclusion

One of the means to reduce the negative environmental impact of ship internal combustion engines is the use of FuelWell – special device, which reduce harmful emissions to the atmosphere and fuel economy. The use of such devices allows not only to reduce the content of harmful substances in exhaust gases, but also to reduce fuel consumption.

In order to measure the composition of the exhaust gases of the ship internal combustion engine, on July 29, 2017 the river transport was tested, the diesel engine of which was equipped with a device for reducing harmful emissions into the atmosphere and fuel economy – FuelWell.

The measurement of the exhaust gas was carried out on the motor ship «Captain Zhidkov» (Izmail, PJSC «Ukrainian Danube Shipping Company»), manufactured under the project MO44 (Austria), «Captain Antipov» type and successfully equipped with two major SICEs with a total capacity of 2100 hp (2 x 772 kW). At the time of the measurement of the exhaust, the main left diesel engine of the ship was equipped with the FuelWell.

During the measurement to feed the ship engine the diesel fuel (DF) of the mark 10ppm EURO-5 standard.

In order to evaluate the results, the test were conducted in two modes of operation of the SICE:

- Mode 1: with the FuelWell;
- Mode 2: without the FuelWell.

Measurements of exhaust gas were carried out in each mode of the SRWS using a portable gas analyzer. Measurements were made at different engine rotational speeds - from 120 r/min. up to 300 r/min.

During the measurement of the composition of the exhaust gases, the content of the following elements was recorded

- oxygen (O_2);
- carbon dioxide (CO_2);
- nitrogen oxides (NOx: NO, NO_2);
- carbon monoxide (CO);
- sulfur oxide (SO_2).

According to the results of the measurement of the exhaust gas of the SICE and the comparison of the results for two modes of operation of the engine (with and without the FuelWell) we can draw the following conclusions.

The amount of NOx of the SICE exhaust gases equipped with the FuelWell device was about 500 ppm at an engine speed of 120 r/min. and about 1400 ppm at an engine speed 300 r/min.

NOx content of the SICE exhaust gases, which worked without the FuelWell, was about 550 ppm at an engine speed 120 r/min. and about 1900 ppm at an engine speed of 300 r/min.

Thus, using the FuelWell allows to reduce NOx content of the exhaust gases of the SICE on average in 15…25 %.

CO content in the equipped with FuelWell SICE was about 0,014 % at an engine speed 120 r/min. and about 0,0052 % at an engine speed 300 r/min.

CO content of the SICE exhaust gases, which worked without the FuelWell was about 0,025 % at an engine speed 120 r/min. and about 0,010% at an engine speed 300 r/min.

Thus, using the FuelWell allows to significantly reduce the CO content of the SICE exhaust gases on average in 40…50 %.

An average content of CO_2 in the SICE exhaust gases equipped with the was about 6 %. An average CO_2 content in the SICE exhaust gases, which worked without the FuelWell was about 6,3 %.

Using the FuelWell caused a slight (на 3-5 %) decrease in the CO_2 content of the exhaust gases.

Calculated-analytical method specific indicators, using the appropriate conversion methods, will allow comparative analyses of the received emission factors of pollutants with the

requirements of international organizations, in particular MARPOL and IMO.