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Chapter 6. Innovative technology of compact marine jet scrubbers

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Streszczenie. W rozdziale przedstawiono wyniki badań przeprowadzonych nad innowacyjnym układem oczyszczania spalin wykorzystującym technologię strumieniową, przeznaczonym do okrętowych silników wysokoprężnych o mocy 0,25 MW i 1,0 MW. Prace w zakresie rozpoznania zjawisk występujących w skruberze strumienicowym wykonano dla modelowej siłowni o mocy 40 kW. Prace obejmowały budowę i uruchomienie specjalnych stanowisk badawczych oraz wykonanie pomiarów emisji dla szerokiego spektrum stanów pracy. Odrębne zadanie badawcze dotyczyło efektywności odsiarczania spalin w zależności od parametrów pracy skrubera strumieniowego. Zidentyfikowano dominującą rolę stosunku ciśnień w skruberze oraz wyznaczono jego krytyczną wartość progową. Na podstawie kompleksowej serii badań eksperymentalnych sformułowano uogólnioną korelację opisującą efektywność skrubera, stanowiącą krajowe odniesienie do doboru optymalnych warunków pracy układu skrubera.

Abstract. The chapter presents the outcomes of investigations carried out on a novel exhaust flue gas cleaning system employing jet-ejector technology, intended for 0.25 MW and 1.0 MW marine diesel engines. Preliminary development research have been carried out at the test unit of 40 kW power. The research included the construction and commissioning of dedicated test stands and the execution of emission measurements for a broad spectrum of operating states. A separate research task addressed the desulphurisation efficiency of exhaust gases in relation to the operating parameters of the jet scrubber. A dominant role of the scrubber pressure ratio was identified, along with the determination of its critical threshold value. Based on a comprehensive series of experimental tests, a generalised correlation was formulated to describe the scrubbing efficiency, providing a domestic reference for selecting optimal operating conditions of scrubber systems.

Słowa kluczowe: skruber strumienicowy, odsiarczanie gazów spalinowych, sprawność skrubera

Keywords: jet ejector scrubber, desulphurisation of flue gases, scrubbing efficiency.

Introduction

Marine diesel engines used on marine vessels are responsible for considerable emissions of airborne pollutants, adversely affecting both atmospheric conditions and marine ecosystems. Key emission components include sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter [1, 2, 3]. Consequently, emissions from large-scale maritime operations are now classified as a major and steadily intensifying environmental challenge.

In response to these concerns, since 2013 the International Maritime Organization (IMO) has mandated that ships carry Ship Energy Efficiency Management Plans (SEEMPs), outlining guidelines for improving onboard operational energy efficiency [4]. IMO projections require that all newly constructed vessels achieve a 30% enhancement in energy efficiency by 2025 compared to ships built in 2014 [5]. Despite these targets, heavy fuel oil (HFO) continued to dominate maritime energy use – constituting 79% of the sector's consumption in 2018. Parallel to these measures, rigorous fuel monitoring and reporting requirements have become part of the global emission reduction framework.

The regulatory milestone commonly known as "IMO 2020" significantly restricted sulphur content in marine fuels. Outside Emission Control Areas (ECAs), allowable sulphur levels were reduced from 3.5% to 0.50% (by mass), becoming enforceable under revised provisions of MARPOL Annex VI [6]. This step was expected to reduce sulphur dioxide (SO_2) emissions by up to 85%. Under the amended regulations, compliance may be achieved either by using low-sulphur fuel oils or by equipping vessels with exhaust gas cleaning systems. Fuel blending – mixing low- and high-sulphur fuels – remains an additional pathway to conformity.

A common compliance measure adopted by shipowners is the installation of exhaust gas cleaning units, broadly referred to as scrubbers.

IMO recognises scrubbers as an acceptable alternative to low-sulphur fuels. These systems are available in two principal variants: wet and dry [7]. Wet scrubbers exploit the solubility of SOx in water and operate in three configurations: open-loop (using seawater), closed-loop (using recirculated alkaline-enhanced fresh water), and hybrid systems capable of switching between both modes. Dry scrubbers use solid sorbents to bind sulphur oxides. Owing to their proven performance, wet systems remain the preferred technology for maritime installations.

Between 2012 and 2018, global maritime emissions rose from 977 to 1,076 million tonnes CO_2-equivalent – an increase of 9.6%. These figures encompass emissions from international, domestic, and fishing operations. During the same period, the share of maritime transport in global anthropogenic emissions grew from 2.76% to 2.89%. Long-term forecasts suggest that emissions may reach 130% of the 2008 level by 2050 (IMO, 2020). In parallel, SEEMP plans have been mandated since 2013 [14], and IMO benchmarks continue to push for improved vessel performance [5]. Despite these interventions, HFO remains the dominant fuel option for global shipping. The timeline of tightening sulphur limits is presented in Table 1.

TABLE 1. Time schedule of sulphur limit reductions in MARPOL Annex VI (2005)

	sulphur limits in marine fuel, %	
Year	**Inside ECA-SO_x**	**Outside ECA-SO_x**
2008	1.5	4.5
2010	1.0	4.5
2012	1.0	3.5
2015	0.1	3.5
2020	0.1	0.5
2025	0.1	0.5

A significant decline in SOx emissions causes not only environmental improvements but also to health benefits for populations living near ports and coastlines. Semi-dry flue-gas desulphurisation systems, which reduce SO_2 emissions while moderating water usage, comply well with Annex VI requirements and provide an alternative to low-sulphur fuels. The IMO introduced a comparative indicator – the sulphur fuel equivalent allowing emission evaluation based on a reference relationship:

$$ER = \frac{\mathrm{SO}\left[\mathrm{ppm,dry}\right]}{\mathrm{CO}\left[\%\mathrm{v/v,dry}\right]} \tag{1}$$

The above formula is commonly applied for assessment of operation of the scrubbers in marine engines. There should be noted that basing on limits of sulphur content in marine fuel at the level of 0.1%, the limiting level of emission ratio is ER = 4.3 according to the actual MARPOL legislation measures.

While many shipowners resort to low-sulphur fuels, equipping vessels with cleaning systems or applying blending strategies remain equally valid options. Additives improving fuel properties, including lubrication, may also support compliance. Paper [15] provides a cost analysis indicating that the implementation of Annex VI poses significant financial challenges for the shipping sector, potentially increasing freight rates.

Scrubber systems remain one of the most frequently adopted mitigation strategies. Wet scrubbing systems are further divided into open, closed, and hybrid loops depending on the method of water utilisation [7]. Dry scrubbers, relying on solid sorbents, eliminate the need for liquids. Among these solutions, wet scrubbers dominate due to their established desulphurisation efficiency. However, the installation of such systems is often hindered by engineering constraints. The need for sufficient residence time between gas and liquid requires tall structural designs, causing difficulties in vessel integration – such as limited space, complex exhaust routing, and potential effects on vessel stability and centre of gravity. Retrofitting typically involves substantial modifications, high cost, and extended installation times. Consequently, the search for more compact and easier-to-implement technologies continues.

One such alternative is the two-phase jet scrubber using low-pressure liquid-gas ejectors proposed in [8].

The presented research provides experimental results obtained from a prototype jet scrubber developed for flue gas treatment in 40 kW, 0.25 MW, and 1 MW marine diesel engines. All measurements were conducted by an accredited external laboratory.

Technical solution of jet-ejector scrubbers

Traditional marine scrubbers are designed primarily for SOx reduction from ship exhaust streams generated by main propulsion engines, auxiliary power units, and sometimes marine boilers. However, these systems present substantial practical limitations. Their considerable height and diameter – necessary to ensure sufficient gas-liquid contact – complicates installation, particularly in relation to space constraints, exhaust routing, and vessel stability. Retrofitting often requires extensive modifications and entails high operational downtime. This motivates the search for more compact, modular, and simpler alternatives.

Among the promising options are low-pressure liquid-gas ejector scrubbers featuring two-phase flow operation, as demonstrated by Butrymowicz et al. [8]. A schematic representation of such a configuration is shown in Fig. 1. The schematic illustrates the main ejector components: the motive nozzle, suction chamber, and the mixing section, together with the static pressure distribution along the scrubber. The volumetric entrainment ratio χ, defined as the volume flow rate of entrained gas divided by the volume flow rate of the motive liquid, may reach several tens under certain operating conditions.

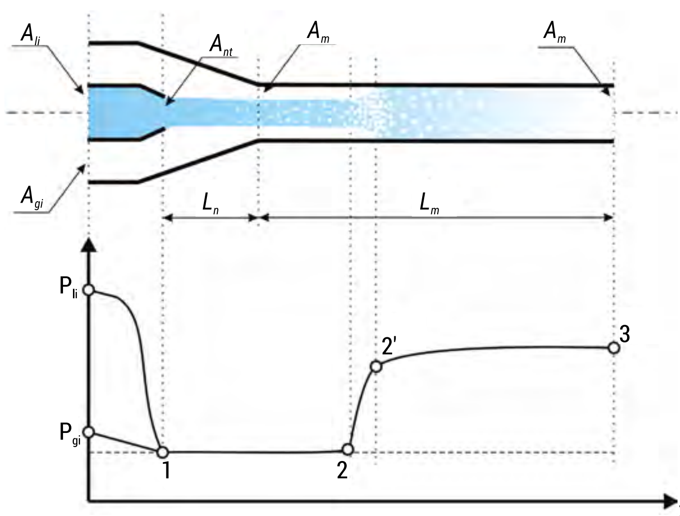

FIGURE 1. Schematic of liquid-gas ejector scrubber with static pressure profile along the scrubber

The motive liquid enters the ejector at pressure p_{li} through cross-section A_{li}. Inside the nozzle, the liquid accelerates and expands, discharging through A_{nt}. Flue gas is drawn into the suction chamber through area A_{gi}, entering the mixing chamber of cross-section A_m. At the mixing chamber inlet, an annular flow pattern normally forms. Further downstream, the liquid destabilises and breaks up, creating a liquid-gas foam region. Within this region, a mixing wave, analogous to a two-phase shock, develops, beyond which a quasi-uniform mixture flows at higher static pressure. Reverse mixture motion as foam flow pattern may appear in the initial part of the mixing chamber, forming recirculation zones that enhance momentum and mass transfer. The internal flow structure is complex due to the presence of the mixing shock wave and the evolving two-phase pattern. While this wave shares certain features with classical gas-dynamic shocks, such as rise in pressure and reduction in velocity, several differences exist. The process is essentially isothermal, slip velocity is present upstream, and the mixing wave has a finite spatial extent.

Although previous research has evaluated various ejector-based configurations, many are unsuitable for direct use in maritime systems [8]. Furthermore, the influence of geometric characteristics on jet-ejector scrubber hydrodynamics remains insufficiently studied. In particular, the length of the cylindrical mixing chamber – critical when shock-induced mixing occurs – has not been comprehensively discussed in the literature, where conical designs are more common.

Novelty of the paper is related with application of a two-phase ejector with cylindrical mixing chamber as a new type of exhaust gas cleaning device. Such application of jet scrubber for flue gas cleaning was proposed for the first time in paper [8]. Therefore, the first part of the researchfocused on the geometry of the scrubber and the determination of its required operating parameters. For this purpose, a model of a two-phase liquid-gas ejector was developed, and supplementary investigations were carried out in the field of hydrodynamics of a two-phase system using glass ejector. The aspects of the required geometry of the motive nozzle were considered. These studies focused on the identification of the flow structures with mixing shock wave that appears in the mixing section. The developed model of a two-phase liquid-gas ejector is beyond the scope of this paper and is not discussed there.

FIGURE 2. The CAD model of the tested jet-ejector scrubber for 40 kW engine

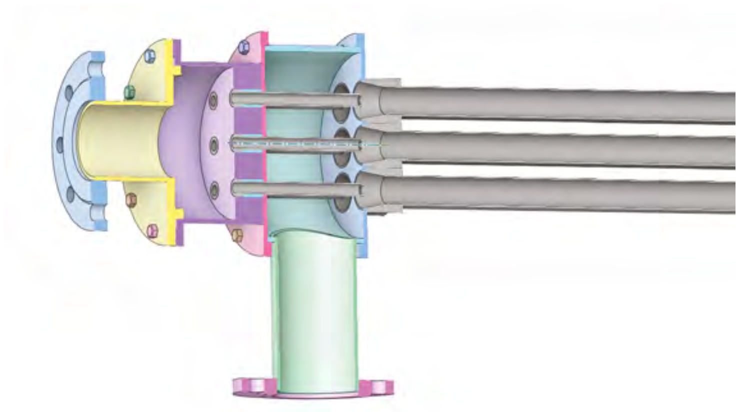

FIGURE 3. Cross-section of CAD model of the jet ejector scrubber designed for application for 250 kW diesel engine

Based on the results obtained from the experimental studies supported by modelling, a reactor dedicated for initial implementation in a 40 kW engine was proposed, see Fig. 2. The jetejector scrubber dedicated for the marine 250 kW unit is presented in Fig. 3. In the last case the proposed jet ejector scrubber has the form of a battery made up of nine sections consisting of the motive nozzle and the cylindrical mixing chamber. Three cases of the geometry of the tested jet ejector scrubbers were investigated with ratios of diameter of the liquid motive nozzle to diameter of the mixing chamber 0.067; 0.100, and 0.133. Sharp-edged orifice motive nozzles were applied for all of the individual scrubber section. The mixing section length to diameter ratio of 25 was applied.

Scrubbing Efficiency Assessment for 40 kW Unit

The laboratory testing stand (see Fig. 4) is located at Bialystok University of Technology. The testing stand is equipped with Lombardini LDW 2204 MG diesel engine of 40 kW maximum power. The feed pump is used to supply the jet reactor with sea water at designed pressure. The motive liquid stream parameters are determined using mass flow meter, pressure transducers, and temperature sensors. The mass flow rate of water supplied to the jet ejector scrubber is regulated by changing the rotational speed of the pump. In the tested jet ejector scrubber the motive stream entrains the exhaust gases. Mixing of the sea water with entrained gas occurs in the mixing chamber. Inside the jet ejector scrubber the sulphur compounds are absorbed by water mostly within mixing shock wave that is formed in the mixing chamber. Once the mixing process is completed, the two-phase mixture is directed to phase separator. The water stream leaving the jet reactor is directed outside the vessel while cleaned gas is released to the atmosphere. The testing stand was equipped with a recovery heat exchanger in which the exhaust gases optionally may be cooled. Motivation of the application of this heat exchanger comes from the potential application of discussed jet ejector scrubbers in flue gases exhaust system for heat recovery that covers the waste heat loop section. The potential condensation of water vapour from exhaust gas due to cooling process was also taken into consideration as it has significant effect on sulphur dioxide reduction process. Therefore, the experimental investigations were performed for the system in which the recovery heat exchanger was used as well as without using discussed heat exchanger. Mass flow rate of exhaust gas, its pressure and temperature at the inlet and outlet of the heat exchanger were measured. View of the laboratory testing stand is showed in Fig. 5.

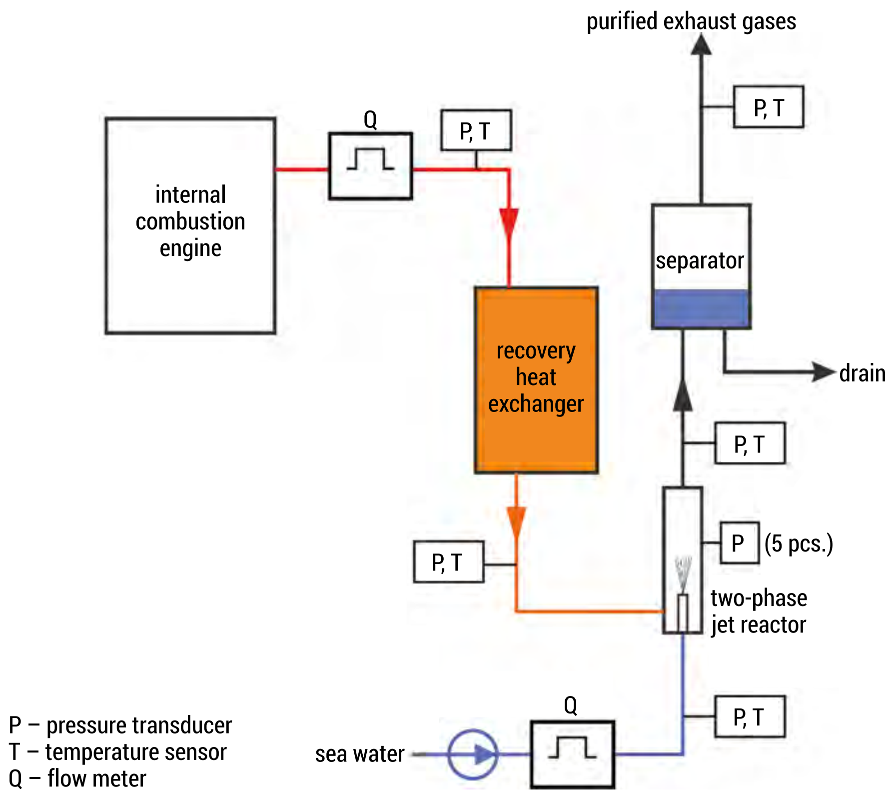

FIGURE 4. Schematic of laboratory testing stand for 40 kW engine equipped with the tested jet ejector scrubber; the measurement sensors locations are indicated

The measurement system based on National Instruments data acquisition system and LabVIEW software has been applied for the tested prototype system. In the test procedure, at least 100 readings (one reading per second) gathered at the steady-state conditions were taken and averaged to produce a single experimental point. Pressure and temperatures changes in the characteristic locations in the tested systems were observed and when no significant changes of pressure and temperature were observed, measured operation parameters were taken as the steady-state conditions.

Concerning the pressure transducers applied in the tests, their measurement accuracy was 0.25% of the full range. First-class K-type thermocouples were applied for the experiments. All of the thermocouples applied in the tested system were calibrated before the experimental investigations to achieve the total accuracy of temperature measurement ±0.2 K. Flow rate was measured with use of the Coriolis mass flow meters of the measurement accuracy 0.15% of the measured value. The flue gas composition was measured with use of AFRISO RGT-03 gas analyser, and the composition of cold flue gas emanating from the separator was measured with use of gas chromatograph INFICON 3000 Micro GC. Locations of the measurement transducers and sensors are shown in Fig. 4, the ranges of the measured parameters are presented in Table 2.

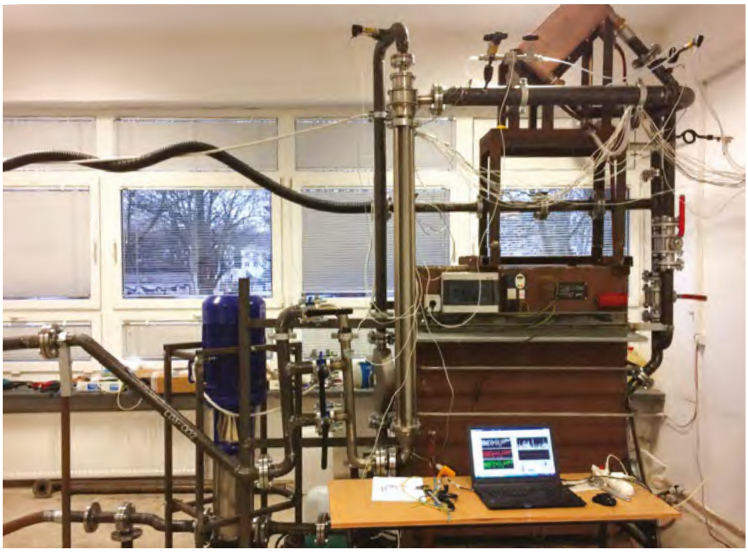

FIGURE 5. Photograph of the laboratory testing stand of 40 kW power

TABLE 2. Details of the measurement system components

Description	Range	Unit
exhaust gas flow rate	0–8.51	m^3/min
pressure of exhaust gas at the heat exchanger inlet	0–6	bar abs.
pressure of exhaust gas at the heat exchanger outlet	0–6	bar abs.
pressure of water at the scrubber inlet	0–16	bar abs.
pressure of water at the scrubber outlet	0–10	bar abs.
mass flow rate of water at the scrubber inlet	0–30	kg/h
temperature of exhaust gas at the heat exchanger inlet	0–500	°C
temperature of exhaust gas at the heat exchanger outlet	0–500	°C
temperature of water at the scrubber inlet	−10÷150	°C

Description	Range	Unit
temperature of water at the scrubber outlet	−10÷150	°C
pressure at various locations along the mixing section	0–6	bar abs.
rotational speed of the pump motor	0–100	%

TABLE 3. Operating parameters of the tested jet ejector scrubber for 40 kW marine unit

parameter	unit	without heat exchanger			with heat exchanger		
motive nozzle to mixing chamber diameter ratio	–	0.067	0.10	0.133	0.067	0.10	0.133
ea water mass flow rate	kg/h	2 874	9 113	11 994	3 307	9 341	12 034
motive pressure	MPa	1.53	1.451	1.453	1.512	1.502	1.457
outlet pressure	MPa	0.119	0.153	0.173	0.121	0.158	0.173
ea water temperature inlet	°C	21.9	11.5	9.2	21.9	18.4	13.8
ea water temperature outlet	°C	25.1	14.2	10.6	22.8	18.9	14.4
flue gas flow rate	Nm^3/min	1.78	1.51	1.49	1.43	1.22	1.19
flue gas pressure inlet	MPa	0.193	0.144	0.162	0.195	0.15	0.162
flue gas pressure outlet	MPa	0.118	0.146	0.161	0.119	0.15	0.161
flue gas temperature inlet	°C	203.7	227.6	224.9	230.7	206.8	220.5
flue gas temperature outlet	°C	152.3	173.5	167.7	34.4	33.2	36.6
entrained gas flow rate	Nm^3/min	0.08	0.5	0.74	0.06	0.45	0.66
pH of inlet water	–	7.98	7.98	7.84	8.01	7.91	7.92
pH of outlet water	–	7.75	7.12	7.83	7.01	6.84	6.86
flue gas inlet O_2	%	11.0	10.7	10.8	11.0	10.7	10.8
flue gas inlet CO/H_2	ppm	155	149	145	155	149	145
flue gas inlet CO	ppm	325	298	299	325	298	299
flue gas inlet CO_2	%	7.5	7.9	7.7	7.5	7.9	7.7
flue gas inlet NO	ppm	545	545	541	545	545	541
flue gas inlet NOx	ppm	562	559	557	562	559	557
SO_2 at the scrubber inlet	ppm	46.3	40	44	46.3	40	44
SO_2 at the scrubber outlet	ppm	0	0	0	0	0	0

The chemical composition of water used in the jet scrubber and the chemical composition of the condensate that condenses from the flue gas were performed. The exhaust gas composition was measured with a dedicated exhaust gas analyzer AFRISO RGT-03 and INFICON 3000 Micro GC gas chromatograph. The main parameters such as pressure, temperature, and mass flow rates as well as the composition of exhaust gas and sludge water were measured for the tested scrubbers for three types of sulphurised fuel supplied by Marine Projects Ltd. shipyards with mass sulphur content of 0.35%. The operating parameters of the tested jet ejector scrubbers are presented in Table 3. The provided results confirmed effective operation of the tested jet scrubber device and total reduction of sulphur dioxide content.

It should be noted that exhaust systems without after treatment process do not usually have a system for filtering particulate pollutants from the exhaust gas and particulates, especially TOC. New regulations on exhaust gases including particulates are expected to be introduced in the coming years. In addition to cleaning of sulphur compounds without additional filters, the system tested affects the amount of TOC extracted from the flue gas. The highest quantitative reduction was found for TOC (total organic carbon in the dust phase) with reduction result 46.2%. In the dust phase, TOC appears as unburned fuel in the form of soot. The exhaust gas cleaning system significantly reduces the emission of metals that are introduced with the fuel into the engine.

Scrubbing Efficiency Assessment for 0.25 MW Unit

The diagram presented in Fig. 6 illustrates the principal process loops and instrumentation installed on a 0.25 MW marine diesel engine test stand [16]. The seawater-cooled engine drives an electric generator whose output is absorbed by controllable electrical heaters. Exhaust gas can be directed either to the atmosphere or through the jet scrubber. The motive seawater is supplied by a dedicated pump.

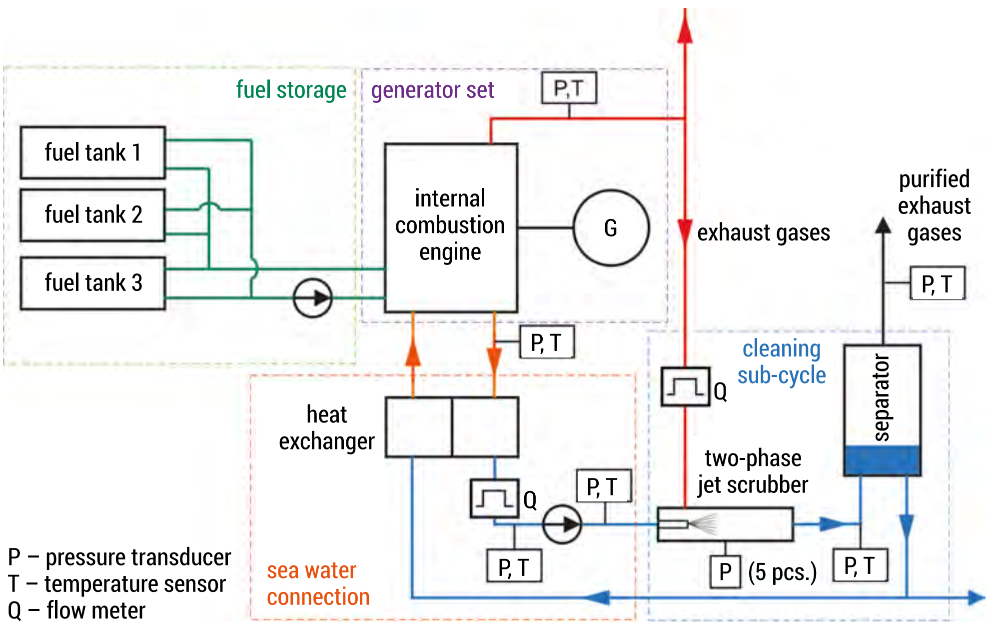

FIGURE 6. Schematic of the marine testing stand of maximum power 250 kW

The two-phase discharge from the scrubber flows to a liquid-gas separator. Cleaned gas is vented overboard, while sludge water is removed separately. Sampling valves allow the analysis of the separated wastewater.

TABLE 4. Details of the measurement system components

Description	Range	Unit
exhaust gas flow rate	0–8.51	m^3/min
exhaust gas pressure	0–6 (inlet/outlet)	bar abs.
exhaust gas temperature	0–500 (inlet/outlet)	°C
water pressure	0–16 (inlet) 0–10 (outlet)	bar abs.
water flow rate	0–30	kg/h
water temperature	–10÷150 (inlet/outlet)	°C
rotational speed of the pump	0–100	%
pressure along ejector	0–6	bar abs.

The exhaust loop is equipped with flow meters, thermocouples, pressure sensors, and gas sampling ports upstream and downstream of the scrubber. The details of the measurement system components are provided in Table 4. The seawater loop includes analogous instrumentation. Data acquisition was performed with a National Instruments system using LabVIEW. Each steady-state test point averaged at least 100 consecutive one-second measurements. Pressure sensors offered ±0.25% full-scale accuracy, temperature was measured with K-type thermocouples (±0.2 K), and Coriolis meters (±0.15%) measured flow rates. Hot exhaust gas composition (CO, CO_2, NO_2, SO_2, O_2) was analysed by TESMO Ltd. using a SIEMENS ULTRAMAT 23 NDIR analyser under accredited procedures. Cold gas analysis was carried out with an INFICON 3000 Micro GC chromatograph.

The experimental research conditions as well as obtained results of the tested scrubbers operation are presented in Table 5. For all of the operation conditions motive water pressure 1.0 MPa has been applied in tests.

The sulphur dioxide emission reduction can be evaluated on the basis of emissions ratio (ER) assessment and was adopted as a measure of scrubber performance:

$$\eta_{ER} = 1 - \frac{ER}{ER_{ref}}, \tag{2}$$

where 'ref' denotes reference conditions without scrubbing of flue gases. The analysis is based on 1549 measurement points of the jet scrubber operations.

TABLE 5. Tests conditio s and results of tested scrubbers operation for 0.25 MW unit

gas	unit	idle operation		engine load 50 kW		engine load 100 kW		engine load 200 kW	
		reference value no cleaning	scrubber operation	reference value no cleaning	scrubber operation	reference value no cleaning	scrubber operation	reference value no cleaning	scrubber operation
		jet scrubber L/D=25, fuel type SON120 with sulphur content 1.0624%							
CO	ppm	495	507	368	379	543	548	1070	1057
NO_2	ppm	157	173	487	511	657	685	885	905
SO_2	ppm	72	0	187	0	334	0	309	0
O_2	%	17.8	17.6	13.7	13.3	10.1	9	6.4	6.2
CO_2	%	25	26	5.2	5.4	7.8	8.4	10.5	10.3
SO_2/CO_2	–	28.8	0	36.0	0	42.8	0	29.4	0
		jet scrubber L/D=125, fuel type SON120 with sulphur content 1.0624%							
CO	ppm	522	529	388	393	482	489	794	828
NO_2	ppm	153	191	462	495	653	691	901	919
SO_2	ppm	80	0	185	0	317	0	437	0
O_2	%	17.9	17.5	13.9	13.3	10.2	9.2	7.5	6.9
CO_2	%	24	26	5.1	5.4	7.7	8.3	9.6	9.8
SO_2/CO_2	–	33.2	0	36.3	0	41.0	0	45.3	0
		jet scrubber L/D=25, fuel type CON120 with sulphur content 1.4750%							
CO	ppm	647	618	407	429	475	619	>1100	>1100
NO_2	ppm	172	204	477	505	656	694	907	892
SO_2	ppm	169	0	320	0	490	0	701	2
O_2	%	17.1	17.0	14.0	13.4	10.2	9.2	6.5	5.7
CO_2	%	29	3.0	5.1	5.3	7.7	8.4	10.5	10.9
SO_2/CO_2	–	57.7	0	63.1	0	63.4	0	66.8	0.2

Fig. 2 provides with relationship of the experimental values of the desulphurisation efficiency, η_{ER}, as a function of the compression ratio produced by the jet scrubber, π_d. Back pressure was adopted as a parameter describing the changes of static pressure during scrubbing process:

$$\pi_d = \frac{p_t - p_a}{p_{gi} - p_a}, \tag{3}$$

where: p_a – pressure at the separator at the scrubber discharge line; p_t – outlet pressure from the scrubber mixing chamber; p_{gi} – exhaust flue gas pressure at the inlet to the scrubber suction chamber.

The obtained experimental results allow for development of correlation for desulphurisation efficiency given by equation:

$$\eta_{ER} = 1 - 0.000266 b^{-0.0611} \chi_n^{0.7922} \pi_n^{-0.3089} \pi_d^{-0.6239}, \quad (4)$$

where: b is the geometric module defined as ratio of the motive nozzle throat to the mixing chamber cross section surface areas, π_n is the ratio or pressure at motive nozzle outlet to the inlet pressure, and χ is volumetric entrainment ratio. The determination coefficient for the developed efficiency correlation is $R^2 = 0.909$.

The comparison between measured results and the proposed correlation presented in Fig. 7 indicates a strong agreement for $\pi d > 0.96$, where the efficiency remains close to 1.0. For lower compression ratios ($\pi_d \approx 0.92$), a noticeable spread of experimental data is observed, which suggests increased process variability in this range. The model captures the general trend but does not fully account for the dispersion of results. At $\pi_d \approx 0.90$, the efficiency of the scrubber operations in terms of the emission ratio decreases sharply. Therefore, the compression ratio $\pi d \approx 0.90$ is assessed as the limiting threshold for the jet scrubber operations.

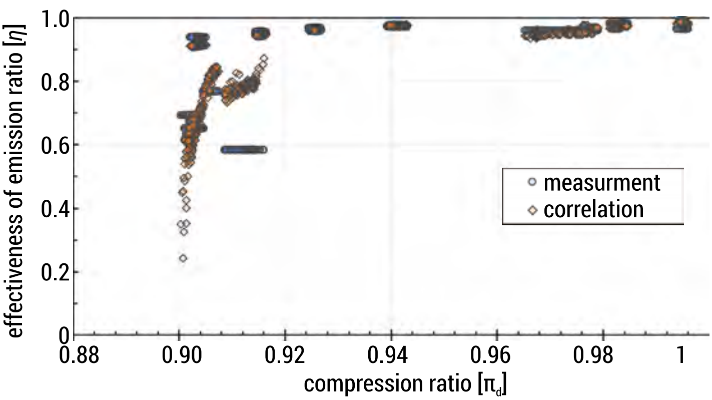

FIGURE 7. Relationship between scrubber efficiency η_{ER} and compression ratio π_d

The results indicate good overall agreement, with the correlation closely matching experimental values, particularly for η_{ER} above 0.90. The proposed relationship in eq. (4) is a basis for rational operation of the scrubbing system as limiting level according to the legislation measures is ER = 4.0, and in most of the cases of conventional marine scrubbers operation assumed level is app. ER = 2.5. Therefore, the provided relationship is a basis for rational usage of water flow rate and motive pressure in order to produce required emission ratio level for the jet scrubber.

Scrubbing Assessment for 1 MW Unit

Experiments for the 1 MW marine engine were conducted at the Marine Projects shipyard in Gdansk with multi-jet ejector scrubber presented in Fig. 8.

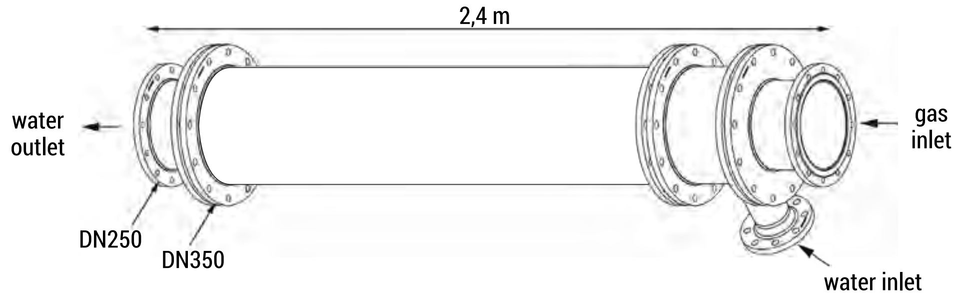

FIGURE 8. Geometry of the tested multi-jet scrubber applied for marine unit of 1 MW power

Tests covered the entire load range from idle to 1000 kW. Measurements of SO_2, NOx, O_2, CO_2, and particulate matter were performed using accredited reference methods. In the case of sulphur dioxide, concentrations decreased from over 2500 mg/m^3 to below 25 mg/m^3, yielding efficiencies above 99%.

The obtained data provide a foundation for refining the scrubber geometry and scaling the technology to larger propulsion systems. The study marks an important step towards widespread adoption of jet-ejector scrubbing as an alternative to conventional systems meeting MARPOL Annex VI requirements. Additional benefits included noticeable reductions in NOx emissions and particulate concentrations. The system demonstrated compactness, low energy demand, and operational simplicity.

The installation shown in Fig. 9 constitutes an integrated exhaust gas and water-treatment system for marine applications. It comprises of: a SCR reactor, a DPF filter, air compression units, heat exchangers, several process pumps, a water treatment section, sedimentation and circulation tanks, reagent storage, and sludge removal systems. The layout forms a closed loop ensuring the reduction of gaseous and particulate pollutants while simultaneously managing process wastewater.

Measurements – conducted by TESMO Ltd., accredited by the Polish Centre for Accreditation – included SO_2, NOx, O_2, CO_2 and PM concentrations upstream and downstream of the system at loads of 750 and 1000 kW as well as idle. PM measurements were performed with WHATMAN 19×90 glass-fibre filters, weighed before and after sampling. Measurement ports were installed following PN-EN 15259:2011 [9]. PM concentration was determined according to the Polish Regulation of 7 September 2021 [10] and PN-Z-04030-7:1994 [11]. Gaseous pollutants were recorded automatically under the standards PN-ISO 10396:2001 [12] and PN-EN 14789:2006 [13]. HORIBA PG 250 and PG 350 analysers, calibrated with reference gas mixtures (Air Liquide cylinders DH5L2, DLN1G), were used.

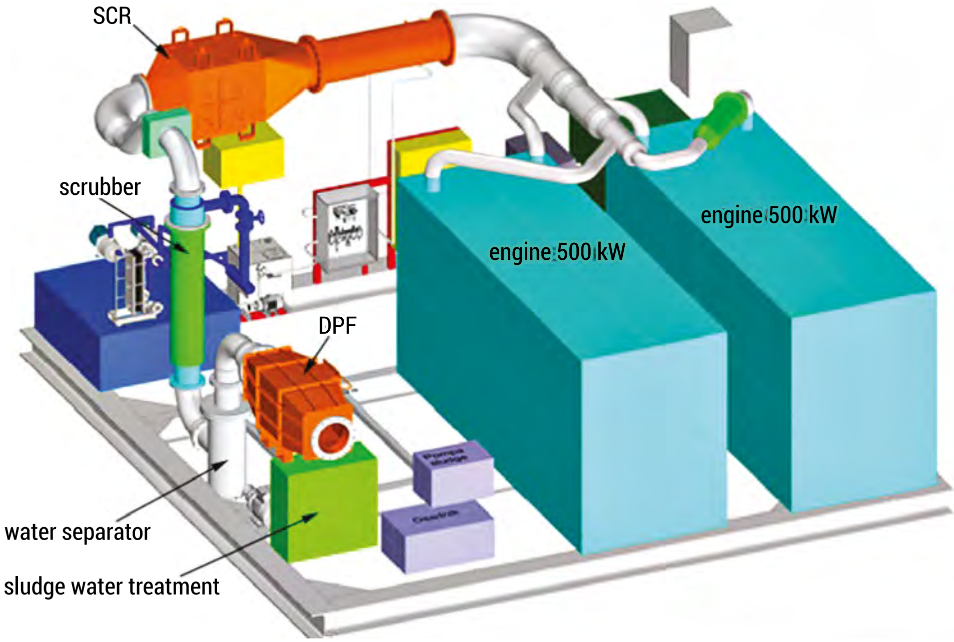

FIGURE 9. Schematic of tested flue gases cleaning system for 1.0 MW diesel engine unit

FIGURE 10. Photograph of the tested flue gases cleaning system fitted with multi-jet scrubber

Measurement uncertainties (expanded, k = 2) were:

- PM (gravimetric): ±11.1%,
- SO_2 (NDIR): ±3.41%,
- NOx (CLD): ±6.3%,
- O_2 (paramagnetic): ±3.6%,
- CO_2 (NDIR): ±3.8%.

Equipment used included:
- EMIOTEST 2598 dust meter,
- HORIBA PG-250A,
- HORIBA PG-350E,
- RADWAG AS 82/220.R2 scale.

TABLE 6. Results of measurements for 1.0 MW diesel engine for various fuel sulphur concentrations and various engine loads.

Exhaust gases at the inlet to system					Exhaust gases at the outlet of the system				
O_2	CO_2	SO_2	NO_x	PM	O_2	CO_2	SO_2	NO_x	PM
%	%	mg/m^3_U	mg/m^3_U	mg/m^3_U	%	%	mg/m^3_U	mg/m^3_U	mg/m^3_U
750 kW load									
8.13	10.27	6.30	1383	45.02	8.27	9.29	3.98	30.3	31.93
750 kW load									
9.82	8.96	1340.02	1075	40.86	9.90	7.92	15.84	28.4	28.58
1000 kW load									
7.90	10.42	2562.59	1976	–	7.92	9.45	22.97	6.7	–

The experimental research results for the 1 MW system are summarised in Table 6. DPF-based PM removal efficiency was assessed at the primary load of 750 kW. At 1000 kW, the emission ratio was ER = 0.91; at 750 kW, ER = 0.75. MARPOL imposes a limiting value of ER = 4.0, hence reductions were significantly greater than required. The pump feeding the jet scrubber consumed approximately 0.55% of engine rated power – comparable to conventional wet scrubbers.

Sludge water treatment

The presented paper provides validated results of an innovative approach for scrubbing process. However, another open issue that has been addressed in the research is the aspect of sludge water treatment process. In this case also an innovative approach has been proposed. This technology is based on utilisation of the partial vaporisation process using waste heat from marine diesel engine. Due to legislation measures and technical standards, the system operates under saturation temperature app. 80°C which requires pressure lower than atmospheric pressure.

The thermal treatment of sludge water significantly reduces the amount of sludge waste and improves the sludge water cleaning process. Evaporative unit applied in the system is shown in Fig. 11. Detailed investigations of the sludge water treatment process are out of the scope of the present paper.

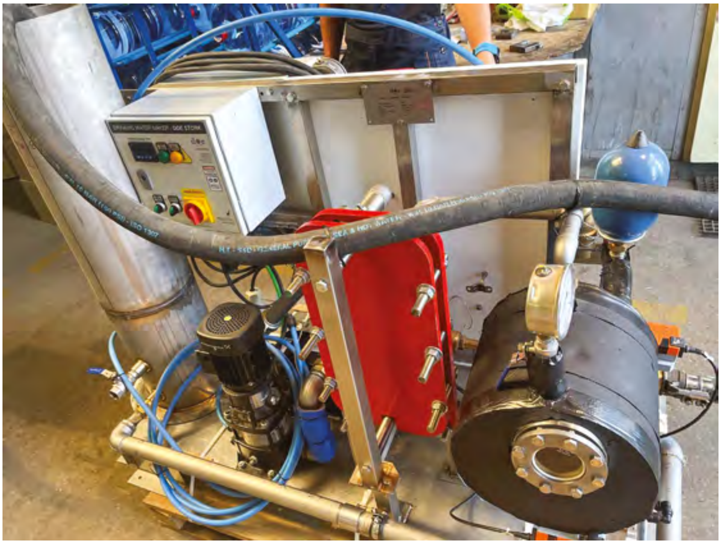

FIGURE 11. Photograph of an evaporative water treatment system for a 40 kW power plant at Marine Projects Ltd.

Conclusions

The investigations confirmed the high performance of the prototype jet scrubber for a 1 MW marine diesel engine. SO_2 levels dropped from above 2500 mg/m^3 to under 25 mg/m^3, corresponding to efficiency exceeding 99%. Noticeable reductions were also achieved for NOx and particulate matter. The system demonstrated low auxiliary power consumption – only 0.55% of engine output – and proved compact and operationally straightforward. A generalised empirical correlation was proposed to estimate emission ratio reduction as a function of principal operating parameters. Based on systematic testing, the limiting compression ratio for multi-jet scrubbers was established. The developed correlation enables rational operation of the scrubbing system with respect to energy use and emission-reduction targets.

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