Abstract: The inland navigation sector makes a significant contribution to the growth of the global economy as well as to climate change due to pollutants emitted by diesel engines. NOx emissions are very high in port areas where, due to traffic, the ships run at idling regimes. Selective catalytic reduction (SCR) represents one of the most suitable technologies, in terms of cost effectiveness, but does not perform well if the temperature during vessel operation is lower than 180°C. Microwave technology can support preheating of the ceramic core of SCR in order to increase the temperature towards the optimal interval for the best NOx reduction. Research has focused on coupling a magnetron head to a SCR device in order to evaluate to what extent the technology can meet the requirements of Stage V of the European Directive related to NOx emissions. Measurements of NOx emitted have been performed on engines with 603.5 kW nominal power and 1500 rpm that operate at a lower engine speed (700–1200 rpm) and output power (58–418 kW). The values recorded for emissions using microwave heating of ceramic core of SCR have decreased by 89% for a constant load of engine and idling engine speed.

Keywords: NOx emissions reduction; sustainability of retrofitted inland ships; microwave technology; selective catalytic reduction

1. Introduction

Water transport plays an important role in goods transport systems when speed is not of the essence. It is invaluable for the transport of consignments of heavy weight or large dimensions, and provides direct connections via rivers, lakes, or canals between seaports and inland ports. Means of water transport (motor cargo vessels, pushed convoys) use inland waterways (navigable rivers, artificial canals, and other inland waters) for their movement. The importance of water transport is conditioned by historical developments and geographical and economic conditions [1]. As a result of global warming, this mode of transport has also taken various measures to reduce the share of greenhouse gases in the atmosphere on motor cargo vessels or pushers. Compared to inland waterway transport, maritime transport reacted to these changes earlier. In 1997, the International Maritime Organization adopted MARPOL Annex VI. The basic goal of this regulation was...
the reduction of Sulfur oxides, nitrogen oxides, and carbon oxides from the exhaust gases of seagoing vessels. Not only shipyards but also refinery companies that produce fuels have had to adapt to these changes. Shipyards and refinery companies are looking for new types of fuels, such as hydrogen and liquefied natural gas (LNG), or new propulsion systems.

Strategies that can be used to reduce NOx and SOx emissions were introduced in the study by Seddiek and Elgohary [2]. The strategies included: applying reduction technologies onboard, the use of alternative fuels, and following fuel-saving strategies. According to Galieriková and Sosedová [3], road transport represents the most polluting mode of transport, responsible for a growth in external costs, such as congestion, accidents, noise, and pollution. The study recommends reducing high levels of emissions by splitting a larger road freight volume between water and rail transport.

Van Dingenen et al. [4] provide a comprehensive analysis of air pollutant emission scenarios for the Danube region. Their pollutant emission scenarios are analyzed with the global reduced-form air quality model TM5-FASST, which provides pollutant concentrations and their associated impacts on human health and agricultural crop production losses. Pecho et al. [5] analyze the current pollution status of the water transport sector. Their study provides an overview of current standards dealing with the limits of pollutants such as NOx, SOx, carbon dioxide, greenhouse gases (GHG), and particulate matter (PM), including systems to ensure compliance with the limits. The matter of finding solutions for green and efficient inland ships was elaborated by Chirica et al. [6]. Their paper presents the principles of the design-for-retrofitting methodology developed for inland ships. The technologies involved aim at improving the efficiency of emissions aftertreatment and meeting Stage V requirements (for a Romanian fleet). This step could ensure a reduction in greenhouse gas emissions and facilitate voyage planning. An investigation of the effects of ship maneuvering motions on NOx formation was performed by Trodden and Harotunian [7]. In this paper, an emission factor was developed using a numerical engine model coupled with chemical kinetics computations. The same model, coupled to a ship maneuvering simulator, was then used to compare formations during maneuvering operations. Tarasenko et al. [8] dealt with building a common model for managing energy efficiency and the environmental performance of a self-propelled river towing and traction fleet. Their analysis investigated the energy efficiency indicators established for international maritime shipping, as well as the peculiarities of their use in inland navigation. A study by Anghelută et al. [9] was based on the idea of reducing the environmental impact of inland waterway vessels by using state-of-the-art technologies to treat exhaust gases. Their paper has an analysis of the feasibility of retrofitting existing ships so as to comply with Stage V, the latest emission norms of the European Commission. In Tudor et al. [10], seasonal measurements were performed, using high-precision mobile equipment, in order to quantify the NO, NO2, NOx, SO2, CO, and PM emissions from ship traffic on the Danube. The results showed significant increases in emissions in the diurnal range, and the statistical analysis of the data showed good correlations between the power developed by ship engines and nitric gases. It has also been observed that the emission peaks can be attributed to the maximum power developed by the ships’ engines.

Besides the NOx emissions reported on nominal operating regimes of inland ships’ engines, the cold start effect makes a significant contribution to pollutant emissions that can affect the environment and therefore drive climate change. This is why the academic and research communities have focused on determining to what extent the cold start effect influences the total NOx emissions from transport systems. Yuanwang et al. [11] studied the cold start effect of diesel engines in a low temperature range (−25.5 °C to −16 °C) in order to establish how comprehensive, efficient preheating of diesel engine reduces the cold start effect. Thuy et al. [12] reported that changes in the injection strategy have significant effects on NOx and PM reduction during the cold start of an engine. They found that, for a 1500 rpm engine speed and 25% load, during the first minute of engine start, the NOx emissions were approximately 1.5 times higher than those recorded for an engine at nominal operating temperature. Miqdam et al. also studied the effect of the injection
timing and coolant temperatures of a diesel engine in order to establish to what extent the cold start temperature influences the HC and CO emissions [13,14]. They concluded that, during a cold start (−10 °C to 0 °C), the levels of combustion noise, HC, CO, and smoke opacity are extremely high, but the injection timings have a significant influence on the starting ability and emissions.

The current technologies for the reduction of NOx emissions from diesel engines are focused on the selective catalytic reduction process. The aftertreatment system is introduced for both automotive and naval industries. Therefore, the research community has focused on the influence of the gas temperature on NOx reduction by selective catalytic reduction systems (SCR). Colombo et al. [15] studied the mathematical modelling of the cold start effect over zeolite SCR catalysts for exhaust gas aftertreatment. They concluded that the consumption of NOx increases in the 150–400 °C temperature range, and the subsequent decrease is related to the approach to thermodynamic equilibrium conditions. Yong et al. studied the influence of SCR on emissions reduction during cold start using the energy method [16]. They reported a significant amount of NOx emissions during the SCR heat-up period. It was reported that it takes about 200 s for the SCR to reach the light-off temperature. They identified two ways to shorten the cold-start time, reducing the thermal inertia of the system or introducing an additional heat source. They concluded that, by using thermal inertia reduction, the SCR light-off time could be reduced from 232 s to 170 s. On the other hand, they reported that a heating time of up to 200 s can be achieved if an electrical heating system with 520 kJ is implemented in the aftertreatment system. The cold start effect and methods for reducing the NOx emissions were also studied by Arumugam et al. [17]. They reported that, for an engine of 199 kW at 4000 rpm, spikes in NOx emissions were observed at a −7 °C intake air temperature. The levels of NOx decreased by 17% for a 5 °C intake air temperature, but there was also an increase of NOx of about 2% at 15 °C due to the warmer in-cylinder conditions. Jie et al. [18] studied the emissions characteristics of a nonroad diesel engine equipped with an integrated Diesel Oxidation Catalyst (DOC), Catalytic Diesel Particulate Filter (CDPF), and Selective Catalytic Reduction (SCR) aftertreatment system. They reported that, when using SCR, the NOx reduction efficiency was 90% and the ammonia slip was 14 ppm on average. These results were obtained under steady operations and a transient cycle. However, the results presented a significant decrease in SCR performance down to 57.7% due to lack of reaction time in the transient cycle. A NOx emissions analysis was performed for Euro-6 light-duty diesel vehicles by Hyung and colleagues [19]. Based on their study in South Korea, the transport sector accounts for 35% of total NOx emissions. According to their reports, for a 210 °C temperature of SCR and low vehicle speed, the NOx emissions were reduced to nearly 0 g/kWh. Jun et al. [20–22] studied the influence of a direct mix of anhydrous ethanol with diesel fuel on the improvement of the NOx smoke trade-off relationship. They reported that the presence of ethanol contributes to the reduction of NOx. Also, they reported that a blend of fuels simultaneously reduces NOx emissions, hydrocarbons, and smoke. Other studies by the same authors found the effective reduction of NOx when the diesel engine had a B30 blend fuel with a 10% EGR rate.

Microwave heating is a technology that can be applied for fast heating or sintering for different applications such as medical implants [23–26], as well as the microwave joining of metals and polymers, or 3D printing [27]. In this field, previously published research [28–30] has focused on microwave heating of the ceramic core of selective catalytic reduction systems (SCR) or direct microwave heating of the exhaust pipe of a SCR device. In both cases, mathematical models for the gas temperature were developed, simulated, and experimentally validated by heating the ceramic core of the SCR and the exhaust pipes (see Figure 1).
The main conclusion reached is related to the performance of the microwave heating/preheating process over time. According to Figure 1a, the gas temperature during microwave preheating reached 250 °C after 2.5 min. The temperature evolution can be expressed as a logarithmic function, according to Equation (1):

\[ T = a \ln t - b, \] (1)

where \( a \) and \( b \) represent parameters that can be determined analytically and depend on the microwave-injected power, matching the load impedance between the microwave generator and the cordierite material, and the material properties (thermal expansion coefficient, specific heat, density and thermal conductivity); \( T (°C) \) = temperature of ceramic core, and \( t (min) \) = microwave heating time.

The second study related to the microwave preheating of the exhaust pipe showed that it did not exceed 100 °C after 2.5 min. These results led to the decision to develop a MW-SCR (microwave selective catalytic reduction) aftertreatment device for old naval engines in order to reduce NOx emissions.

This research aims to contribute to the sustainability of inland waterway transport systems by focusing on retrofitting the old fleet through introducing new preheating/heating technologies in the form of an SCR system activated by microwave technology, before the treatment and reduction of NOx emissions. The objective is to increase the SCR temperature to 250–350 °C in a very short time, less than 2 min, in order to obtain the NOx reduction from the very beginning of the engine’s functioning.

2. Materials and Methods
2.1. Experimental Research on NOx Measurement

The measurement and calculation of NOx emissions was performed on the pusher convoy in Drobeta Turnu Severin (Romania) port, on km 926 of the Lower Danube. The literature provides different experimental procedures for measuring the NOx emissions from diesel engines [32–35]. In this research, the pusher engine was set to constant load and engine speeds of 700, 800, 900, 1000, 1100, and 1200 rpm. The technical characteristics of the engines of the pusher are presented in Tables 1 and 2.

![Figure 1. Temperature of exhaust gases during microwave heating with an injected power of 1200 W: (a) the ceramic core (cordierite); (b) the exhaust pipe before SCR [31].](image-url)
Table 1. Technical specifications of pusher.

| Manufacturer                  | Type                  | No. of Main/Auxiliary Engines |
|-------------------------------|-----------------------|-------------------------------|
| “23 August Plant,” Bucharest, Romania | Main Engine: MDB20 Db | 2/2                           |
|                               | Auxiliary Engine: D120–75 kW |                              |

Table 2. Technical specifications of main engines.

| Engine Data          | Units | Characteristics             |
|----------------------|-------|----------------------------|
| Power                | kW/hbp | 603.5/802/engine           |
| Speed                | rpm   | Max. 1500                  |
| Number of cylinders  | -     | 12                         |
| Displacement         | m³    | 59.21                      |
| Bore × Distance      | mm    | 175 × 205                  |
| Compression ratio    | -     | 1:16                       |
| Effective avg. pressure | kgf/cm² | 13.7 @ 1500 rpm          |
| consumption          | g/hbp/h | 170 + 5                  |
| Transmission ratio   | -     | 1:3                        |

Measurements were performed using equipment provided by MAHA Maschinenbau Haldenwang GmbH (Germany, Haldenwang, 2006) and the exhausted gas was analyzed using MGT 5-LON Gas Analyzer with MDO 2-LON Opacimeter. The equipment was placed near the funnels of the ship (the funnel diameter was 300 mm). The data were recorded in real time using a laptop connected to the equipment. The instantaneous exhaust gas mass flow rate on wet basis was calculated using Equation (2) [36]:

\[
G_{\text{exhaustGMW}} = G_F \cdot \left(1 + \lambda \cdot \frac{A}{F}\right),
\]

where \(G_{\text{exhaustGMW}}\) (kg/h) = exhaust gas mass flow rate on wet basis, \(G_F\) (kg/h) = fuel mass flow rate, \(\lambda\) = air to fuel ratio, measured using a MGT 5-LON Gas Analyzer and \(A/F = 14.5\) —the stoichiometric air to fuel ratio representing the air quantity for a complete combustion of 1 kg diesel fuel with \(H/C = 1.8\). The emission mass flow rates for the working conditions were calculated using Equation (3):

\[
\text{NOx}_{\text{mass}} = C_{\text{NOx}} \cdot \rho_{\text{NOx}} \cdot G_{\text{exhaustGMW}} \cdot 10^{-6},
\]

where \(\text{NOx}_{\text{mass}}\) (kg/h) = instant flow rate of \(\text{NOx}\), \(C_{\text{NOx}} = 0.63\) (considering equal parts of \(\text{NO}, \text{NO}_2, \text{NO}_3, \text{and N}_2\text{O}_3\) in the gas mixture), representing the concentration of \(\text{NOx}\), with \(\rho_{\text{NOx}} = 1.91\) kg/m³ representing the density of \(\text{NOx}\).

The specific emissions were calculated according to the European directive, in g/kWh, using Equation (4):

\[
\text{NOx}_{\text{specific emissions}} = \frac{\text{NOx}_{\text{mass}}}{P} \cdot 10^3,
\]

where \(\text{NOx}_{\text{specific emissions}}\) (g/kWh) = specific emissions of \(\text{NOx}\) and \(P = \) engine power at speed recorded during experimental measurements (values calculated and presented in Table 3).
Table 3. Specific emissions of NOx for different engine speeds.

| Engine Speed (rpm) | $P_n$ (kW) | $P_r$ (kW) | NOx (g/kWh) |
|--------------------|------------|------------|-------------|
| 700                | 603.5      | 58         | 69.57       |
| 800                | 603.5      | 87         | 44.20       |
| 900                | 603.5      | 161        | 23.45       |
| 100                | 603.5      | 241        | 13.18       |
| 1100               | 603.5      | 327        | 12.57       |
| 1200               | 603.5      | 418        | 13.60       |

where: $P_n$ (kW) represents the nominal power of diesel engine and $P_r$ (kW) represents the output power of the diesel engine during the measurements. The measurements were performed for a cold engine (simulating the idle operating regime of engines in port areas), with the temperature at the moment of measurement being 50 °C. The evolution of NOx emissions without an aftertreatment system is presented in Figure 2.

The results show that increasing the power output of the diesel engine will lead to a significant reduction in NOx emissions. However, even with a reduction of about 80% from the emissions during an idling operation regime, the NOx emissions are 750% higher than the limits imposed by the Stage V regulations for propulsion engines (IWP) and auxiliary engines (IWA) for engine power higher than 300 kW. Moreover, considering the idling operating regime (700 rpm), the NOx emissions are 3865% higher than the current regulations enforced for 2020. Therefore, old inland waterway vessels make a major contribution to global warming and the inland waterway transport system is of low sustainability in the global economy.

2.2. Developing a New MW-SCR Aftertreatment System

According to the results presented above, the old inland vessels that execute maneuvers in port area are subject to higher emissions due to the idling operating regime and no aftertreatment system being installed on board the ship.

The MW-SCR aftertreatment system (Figure 3) consists of a commercial SCR-based cordierite material as the ceramic core and a rectangular waveguide type WR340 connected to the reaction chamber. The reactor has a parallelepiped shape, made from aluminum in order to better reflect the microwaves from walls to the SCR ceramic core. This design will ensure uniform interaction of microwaves with cordierite and therefore a uniform conversion of high-frequency electromagnetic waves into heat.
The reflection of microwaves from the ceramic core towards the microwave generator is minimized by using a matching load autotuner Tristan 6000 W from Muegge GmbH (Germany, Reichelsheim, 2008) with three stub tuners driven by step motors. In order to obtain a resonant circuit, the length of the three stub tuners can be determined based on the Smith Chart diagram, representing a nomogram for solving problems with transmission lines and matching circuits in radio frequency engineering (see Figure 4) [37–39].

Figure 3. Schematic of experimental MW-SCR device.

Figure 4. Three stub tuner model for matching load impedance.

Lengths $d_1$, $d_2$, and $d_3$ can be calculated based on Equation (5):

$$d_i = \frac{\lambda}{2\pi} \cdot \tan^{-1}(B_i; Z_0),$$

(5)

where $d$ (mm) represents the final length of each stub tuner, $\lambda$ (mm) represents the wavelength, $B$ is the stub susceptance, and $Z_0$ is the air impedance.

The source of microwaves is a MW-Generator Set (6000 W, 2450 MHz) continuous-wave containing magnetron head type MH6000S-251BF from Muegge GmbH (Germany, 2020). The microwave generator is driven by a MW-Power Source Supply (6000 W,
2450 MHz, 3 × 400 V), continuous wave type MX6000D-154KL, both manufactured by Muegge GmbH (Germany, 2020).

The measurement unit consists of NOx sensors connected to a MGT 5-LON Gas Analyzer with MDO 2-LON Opacimeter, and temperature sensors (type K, range: 0–1300 °C) connected to PCI 2064 DMM 7 1/2 Digital Multimeter from Signametrics (Keysight Technologies, Santa Rosa, CA, USA, 2008). Both acquisition cards transmitted the data to the computer. The process computer is based on Intel 10th generation being connected to the Tristan tuner through a RS232 serial port and USB 2.0 to MGT 5 equipment. The microwave power source was driven manually from a process computer through the UTP connection and web interface.

3. Results and Discussion

Temperature of SCR Core

Microwave heating is an unstable process and if the reflection of the microwaves is too high, it leads to low rates of conversion into heat. For the initial process parameters, the temperature evolution is presented in Figure 5. The process parameters for microwave heating of the cordierite core of the SCR have been established as 1200 W microwave injected power and a heating time of 1 min before starting the main engine of the inland ship. The time limit has been set in order to evaluate the performance of the MW-SCR system, meaning that, after 1 min, the temperature should reach the minimal value for activation of the reducing NOx process. These parameters have been considered for a cold engine in order to avoid the cold start effect.

![Figure 5. Evolution of SCR core temperature.](image-url)

The temperature was recorded until it reached the value required by the SCR for the reduction of NOx emissions. In case of exceeding the total time for heating (longer than 1 min), optimization of the heating process must be performed through calculation of the positions of three stub screw in order to obtain the best microwave power transfer from the generator to the ceramic core. For the experimental program, the initial position of stub screws was established as 0 (no tuning of matching load impedance). According to Figure 5, the required temperature for SCR activation is reached after 50 s for 250 °C and after 75 s for 350 °C.
The total time for the microwave heating of the SCR core has to be improved by tuning the process. The resonant circuit has been obtained by computing the parameters from Equation (5). The computation for cordierite led to the following values: $d_1 = 0$ mm, $d_2 = 21.53$ mm, and $d_3 = 22.98$ mm. By restarting the experimental procedure with these values introduced in the heating process, the reflected power was decreased and the rate of conversion of microwaves into heat was increased. Figure ??a presents the balance of powers as a result of matching the load impedance to the microwave generator. The graph was obtained using Homer software [39] (Slovak Republic, S-TEAM Export, Bratislava, 2009) and presents $P_{\text{inc}}$ (W), the total power injected by the microwave generator; $P_{\text{refl}}$ (W), the power reflected from the cordierite ceramic core towards the microwave generator; and $P_{\text{abs}}$ (W), the absorbed microwave power that has been converted into heat. The caption “Power vs. Points” represents the point of measurement where the three powers have been recorded [33]. Figure ??b presents the evolution of the temperature in the ceramic core after the optimization of heating in the microwave field. The target value of 350 °C was obtained after 63 s, which is considered acceptable for a MW-SCR system. Using these parameters, the measurement of NOx emissions was performed for different engine speeds (700, 800, 900, 1000, 1100, and 1200 rpm). The temperature of the engine before microwave heating was 50 °C, corresponding to the cold start conditions. The microwave injected power was set to increase from 0 to 1200 W in order to avoid the thermal runaway [40] of the cordierite material.

Figure 7 presents graphs of NOx emissions when microwave heating is applied to a SCR core for engine speeds from 700 to 1200 rpm.

Figure 7 presents the NOx emissions recorded for constant load and different engines speeds when a microwave heating is applied to a SCR core. For a low operating regime of engines (700 rpm) and microwave power up to 300 W, NOx reduction was not possible due to the insufficient temperature in the SCR core. By increasing the engine speed to 800 rpm and the microwave power to 400 W, the NOx emissions were reduced from 44.24 g/kWh to 7.65 g/kWh due to the temperature reached, 211 °C. Starting at 900 rpm, even with a constant load, the operating regime is very close to the nominal regime of a naval engine. The initial value recorded on the exhauster was 23.45 g/kWh, but for 500 W microwave power, the temperature reached 244 °C and the NOx emissions decreased to 8.74 g/kWh. For a nominal operating regime, 1000 rpm, the reduction of NOx occurs later due to the high speed of the engine and the reduction process proved to be unstable. It can be observed that, for 689 W injected power, the ceramic core suffered a cooling process. That can be explained by the errors that occurred in matching load impedance computation. The process became stable after 751 W microwave injected power and the average NOx emissions were recorded at 2.62 g/kWh. This model of MW-SCR functioning provides low NOx emissions, similar but higher than the limits imposed by Stage V of the European Directive. Similar results were obtained for 1100 rpm and 400 W microwave injected power. The level of NOx, recorded at the exhaust system, was 3.25 g/kWh and the reduction process presented high stability. However, for 327 W injected power, the level of NOx decreased to 2.14 g/kWh, but the process was unstable. The best results were obtained for 1200 rpm engine speed, when the level of NOx emissions was recorded at 3.15 g/kWh, the lowest values of the experimental procedure. Even for these values, the NOx emissions were higher than the limitations of 1.8 g/kWh stipulated by Stage V of the European Directive [41–44].
of matching the load impedance to the microwave generator. The graph was obtained using Homer software [39] (Slovak Republic, S-TEAM Export, Bratislava, 2009) and presents $P_{\text{inc}}$ (W), the total power injected by the microwave generator; $P_{\text{refl}}$ (W), the power reflected from the cordierite ceramic core towards the microwave generator; and $P_{\text{abs}}$ (W), the absorbed microwave power that has been converted into heat. The caption "Power vs. Points" represents the point of measurement where the three powers have been recorded [33]. Figure 6b presents the evolution of the temperature in the ceramic core after the optimization of heating in the microwave field. The target value of 350 °C was obtained after 63 s, which is considered acceptable for a MW-SCR system. Using these parameters, the measurement of NOx emissions was performed for different engine speeds (700, 800, 900, 1000, 1100, and 1200 rpm). The temperature of the engine before microwave heating was 50 °C, corresponding to the cold start conditions. The microwave injected power was set to increase from 0 to 1200 W in order to avoid the thermal runaway [40] of the cordierite material.

Figure 6. Three stub tuners model for matching load impedance: (a) Balance of powers, (b) optimized heating process.
Figure 7 presents graphs of NOx emissions when microwave heating is applied to a SCR core for engine speeds from 700 to 1200 rpm.

(a) 

(b)

Figure 7. Cont.
Figure 7. Cont.
Figure 7. NOx emissions recorded after MW-SCR aftertreatment system: (a) 700 rpm, (b) 800 rpm, (c) 900 rpm, (d) 1000 rpm, (e) 1100 rpm, (f) 1200 rpm.

Figure 7 presents the NOx emissions recorded for constant load and different engine speeds when a microwave heating is applied to the SCR core. For a low operating regime, the best results were obtained for the 1100 rpm engine speed.

Figure 8 presents a comparative analysis of the NOx emissions for different operating regimes of naval engines. The best results were obtained for the 1100 rpm engine speed.
when the level of NOx emissions was 2.14 g/kWh. However, even for these values, the NOx emissions were 19% higher than the limits established by Stage V of the European Directive.

Figure 8 also provides information related to correlations between engine output power and NOx emissions when the MW-SCR system is activated. The graph shows that, for the idling regime and low power of naval engines, NOx emissions are highest values. The model is similar to those without microwave activation of the selective catalytic reduction system. Our conclusion as to the influence of microwave energy on the reduction of NOx emissions is that the microwave power contributes only to a reduction in the heating time. The NOx reduction mechanism is not determined by the level of microwave injected power.

4. Conclusions

Microwave technology combined with a selective catalytic reduction device can be used for reducing NOx emissions from inland ships in order to increase the sustainability of inland waterway transport. The MW-SCR device can be applied to new engines as well as old engines.

The research presented in this article is focused on the introduction of microwave technology as an additional heating source for cold engines in order to avoid higher emissions of NOx when the cold start effect occurs. The results obtained prove that the technology proposed is applicable even to very old engines in order to increase the sustainability of inland waterway transport. Compared to the Stage V limitations, in terms of NOx emissions, the MW-SCR aftertreatment system contributes to a reduction of 89% of the emissions for idling operating regimes of naval ships. The performance of MW-SCR is similar for nominal regimes for both upstream/downstream navigation conditions, with a reduction of 85% of NOx emissions being recorded for an 1100 rpm engine speed and a constant load. Figure 9 presents the evolution of NOx emissions for different operating regimes of a ship engine compared with the Stage V limitations. The NOx emissions without the MW-SCR system decrease when the engine speed increases. On the other hand,
NOx emissions reduction through microwave heating of the SCR device is not affected by the engine speed. Only for a very low engine speed (700 or 800 rpm) do the NOx emissions depend on the speed and microwave injected power. Above 900 rpm, the reduction of NOx depends only on the heating speed of the cordierite core.

The MW-SCR functioning conditions are limited to 600 W microwave injected power in order to obtain uniform and stable heating of the ceramic core. However, an improvement in the microwave heating process can be achieved for a maximum of 1200 W, but the risk of thermal runaway is very high.

Author Contributions: Conceptualization, R.C.M. and S.V.S.; methodology, S.V.S., I.D., D.T. and A.D.; software, A.B.O. and A.M.; validation, I.D.S.; investigation, R.C.M., I.D.S. and A.B.O.; resources, S.V.S.; writing—original draft preparation, S.V.S. and R.C.M.; writing—review and editing, S.V.S., A.D., I.D.S. and D.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and the APC was funded by University of Craiova.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of University of Craiova.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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