

## Article

# Effect of a Plasma Burner on NO<sub>x</sub> Reduction and Catalyst Regeneration in a Marine SCR System

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**Abstract:** The problem of environmental pollution by the combustion of fossil fuels in diesel engines, to which NO<sub>x</sub> emission is a dominant culprit, has accelerated global environmental pollution and global and local health problems such as lung disease, cancer, and acid rain. Among various De-NO<sub>x</sub> technologies, SCR (Selective Catalytic Reduction) systems are known to be the most effective technology for actively responding to environmental regulations set by the IMO (International Maritime Organization) in marine diesel applications. The ammonia mixes with the exhaust gas and reacts with the NO<sub>x</sub> molecules on the catalyst surface to form harmless N<sub>2</sub> and H<sub>2</sub>O. However, since the denitrification efficiency of NO<sub>x</sub> can be rapidly changed depending on the operating temperature from 250 °C to 350 °C at 0.1% sur contents of the catalyst used in the SCR, a device capable of controlling the exhaust gas temperature is essential for the normal operation of the catalyst. In addition, when the catalyst is exposed to SO<sub>x</sub> in a low exhaust gas temperature environment, the catalyst is unable to reduce the oxidation reaction of the catalyst, thereby remarkably lowering the De-NO<sub>x</sub> efficiency. However, if the exhaust gas temperature is set to a high temperature of 360–410 °C, the poisoned catalyst can be regenerated through a reduction process, so that a burner capable of producing a high temperature condition is essential. In this study, a plasma burner system was applied to control the exhaust gas temperature, improving the De-NO<sub>x</sub> efficiency from the engine and regenerating catalysts from PM (Particulate Matter), SOOT and ABS (ammonia bisulfate), i.e., catalyst poisoning. Through the burner system, the optimum De-NO<sub>x</sub> performance was experimentally investigated by controlling the temperature to the operating region of the catalyst, and it was shown that the regeneration efficiency in each high temperature (360/410 °C) environment was about 95% or more as compared with the initial performance. From the results of this study, it can be concluded that this technology can positively contribute to the enhancement of catalyst durability and De-NO<sub>x</sub> performance.

**Keywords:** selective catalytic reduction; catalyst; De-NO<sub>x</sub>; plasma burner; regeneration



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## 1. Introduction

As a result of recent environmental pollution by ships, which is now an international issue, the International Maritime Organization (IMO) has issued Tier III for the operation of NO<sub>x</sub> regulated areas for marine diesel engines, which should be installed after 1 January 2016 [1]. De-NO<sub>x</sub> technology uses various post-treatment methods such as Urea-SCR, LNT, and EGR. Urea-SCR, which uses urea as the reducing agent, has been evaluated as the most efficient and suitable technology [2]. In the case of Urea-SCR systems for ships, 40% concentration of urea is injected into the reaction zone and converted into harmless

water and nitrogen using a catalyst [3]. Selective catalytic reduction (SCR) requires reaction temperature of 280–500 °C to remove nitrogen oxides [4].

However, marine engines can be operated at low temperatures depending on operating conditions [5]. When the temperature of the exhaust gas drops, sulfur contained in the fuel and ammonia, which is the reducing agent of the SCR system, reacts to generate ammonia bisulfate (ABS) on the inside and surface of the catalyst, which may seriously affect the performance of the catalyst [6]. In the case of marine engines, heavy fuel oil (3.5% > sulfur) is used as a working fluid in the global sea area, which reduces catalyst performance due to poisoning by sulfur from prolonged exposure of exhaust gases [7]. If the exhaust gas temperature is brought to a high temperature environment (>350 °C), poisoning does not take place and ABS is not produced, so that the catalyst performance can be improved [8]. Thus, the catalyst can be regenerated using such a temperature-raising principle [9]. In this study, a plasma burner system is introduced to generate a high temperature environment verified by lab scale test. The ignition characteristics, temperature control and catalyst regeneration characteristics were investigated through scale-up production for actual ship engines with the plasma burner system. From the results of the demonstration tests, it is suggested that this technology can be employed to improve the De-NO<sub>x</sub> efficiency and durability of the catalyst and can be adapted for practical use.

## 2. Experimental Details

### 2.1. WIW Catalyst

A newly developed SCR catalyst is employed for this study, named WIW (Washcoat In the Wall) catalyst, developed by STX company to cover IMO Tier III regulations. The WIW catalyst is produced by applying an active catalyst component washcoat, V<sub>2</sub>O–WO<sub>3</sub>/TiO<sub>2</sub>, on a high porosity wall [10]. Since the thickness of the washcoat is very thin as shown in the SEM (Scanning Electron Microscopy) images in Figure 1, it has advantages of both coated and homogeneously extruded catalysts, simultaneously [11]. The images demonstrate that the washcoat thickness of the WIW catalyst is near zero, and thus contact efficiency with the exhaust gas is improved and backpressure decreases compared to the normal coated catalyst [12]. The WIW catalyst retains good performance when eroded under high dust conditions and has an advantage of containing a substrate with higher mechanical strength by controlling porosity in the substrate, resulting in a high cell density substrate with higher OFA (open frontal area) [13].

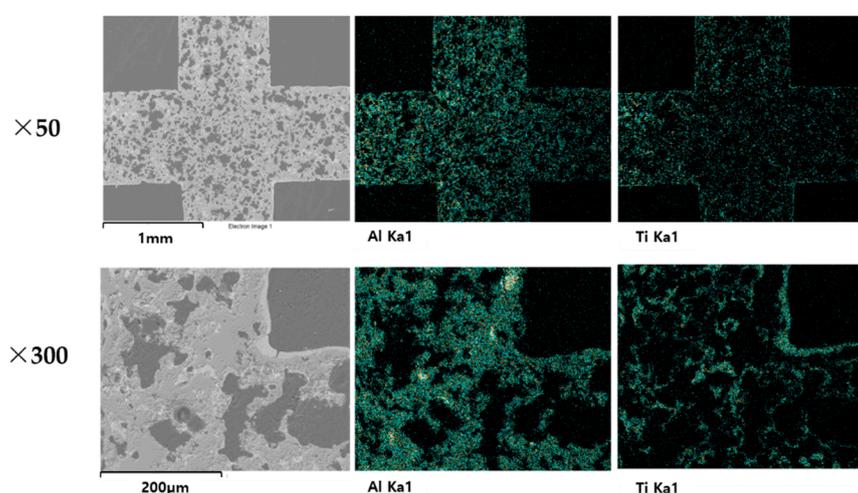


Figure 1. SEM image of catalyst.

### 2.2. Plasma Burner Assisted SCR System

Figure 2 shows a photograph of the plasma burner-assisted SCR system. The system consists of a medium-speed engine (STX-MAN 6L 27/38, STX Korea), a SCR system, and a plasma burner [14]. The operating conditions of the engine are listed in Table 1.

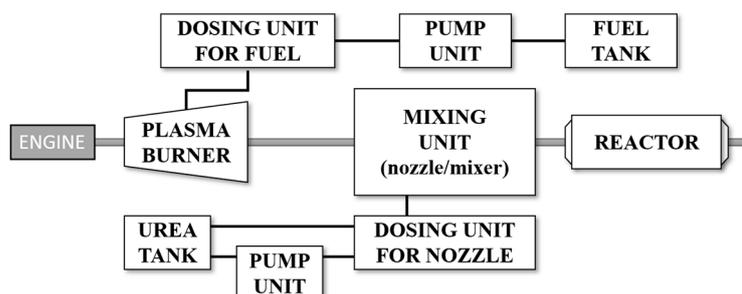


**Figure 2.** Direct photos of the plasma burner assisted SCR system.

**Table 1.** Operating conditions of medium speed marine engines.

	Description	Unit	Design Value
Engine	Power	kW	250–500
	Speed	Rpm	750
	Exhaust gas flow rate	Kg/h	3500–4500
	Exhaust gas temperature	°C	280
	Before SCR chamber	°C	260

The SCR system is composed of a reactor (Reactor), a urea water supply unit (Dosing Unit), a mixer (Mixer and Nozzle), and a control unit. Figure 3 exhibits the schematic drawing of the actual behavior of the rotating arc and operating motions of the plasma burner developed by the Korea Institute of Machinery & Materials (KIMM, Korea) [15].



**Figure 3.** Schematic drawing with actual behavior.

The combustion system inside the plasma burner is designed such that it can rotate the arc discharge and its structure and characteristics are similar to that of the plasma burner applied to a high-speed engine, in which the De-NO<sub>x</sub> ability of catalyst regeneration was verified. The plasma arc is rotated by the internal rotational flow and works as an ignition source, which enables continuous ignition (or pilot heat source). In addition, the plasma burner can ensure stable combustion even under low air conditions of less than 40% air-fuel ratio, and it is not sensitive to changes in composition and flow rate of exhaust gas. It is an obvious advantage that combustion performance is close to complete combustion and it means combustion is secured by utilizing oxygen in the exhaust gas. The plasma burner is located after the turbo charger of the engine using approximately 20 m straight pipe, so that the flow does not deviate through the two curved pipes due to inertia, as shown in Figure 4. The fuel supply system of the exhaust gas heating part consists of a pump for supplying fuel, an air blower for plasma discharge air, and a power supply unit for generating plasma.



**Figure 4.** SCR system with a plasma burner.

### 3. Results and Discussion

#### 3.1. Characteristics of WIW Catalyst

##### 3.1.1. Mechanical Characteristics

Table 2 shows the durability of the catalysts to vibration from diesel engines. As shown, the CPSI of Cat 1 is medium. For surface area, that of Cat 1 is close to Cat 3. The open frontal area is the smallest at Cat 1. Mechanical strength tests were performed using a UTM (Universal Testing Machine). The compressive strength is measured in the direction of gas flow through the catalyst, and the result is shown in Table 3. Obviously, Cat 2 has a much higher compressive strength than the others due to its metal substrate. But Cat 1 has a higher compressive strength than commercially available Cat 3. It is therefore good enough for marine applications even under a worse stress condition. The compressive strength of Cat 1 could be further increased by controlling the pore structure, as previously mentioned.

**Table 2.** Properties of the catalysts.

Property	Cat 1	Cat 2	Cat 3
Type	WIW	Metal	Homogeneously extruded
Cell density (CPSI)	45.9	100	35
Geometric surface area (m <sup>2</sup> /m <sup>3</sup> )	882	1522	807
Open frontal area (%)	68.7	79	74.7

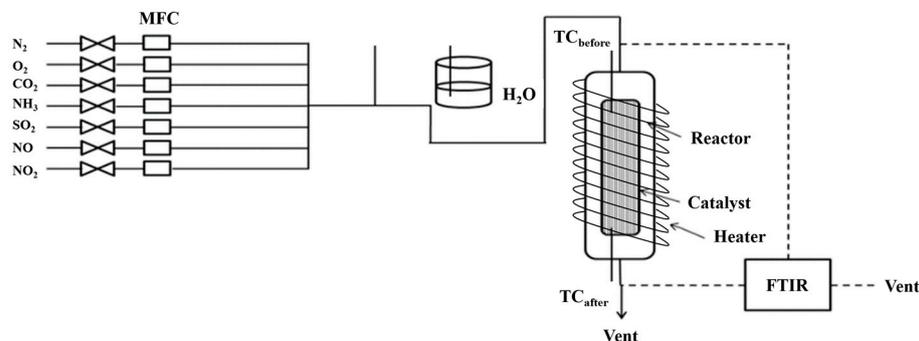
**Table 3.** Compressive strength of the catalysts.

	Compressive Strength (kgf/cm <sup>2</sup> )
Cat 1	68
Cat 2	2200
Cat 3	37

##### 3.1.2. Reactive Characteristics

To compare the ammonia adsorption capacities of the catalysts, a micro reactor system was used on a laboratory scale, as shown in Figure 5. The test gas was prepared by employing N<sub>2</sub>, O<sub>2</sub>, CO<sub>2</sub>, NH<sub>3</sub>, SO<sub>2</sub>, NO, and NO<sub>2</sub>, which are used in a ship. The make-up gas is N<sub>2</sub> to control the total flow rate. The flow gas components are examined before and after the catalysts using FTIR (AVL). The tests were conducted at 250 °C and 350 °C, the general temperature range in an engine. Since the ammonia adsorption capacity is affected much more by active material loading and temperature than space velocity [16], catalyst samples were exposed to simulated gases for 90 min at each temperature with the same NH<sub>3</sub> concentration (400 ppm) and SV (Space Velocity) (18,000 1/h). When the catalyst was

completely saturated with ammonia, the measured ammonia concentration downstream became the same as that of the inlet concentration. Thus, the temperature was increased to 450 °C to desorb ammonia at a heating rate of 10 °C/min after the ammonia concentration downstream of the catalyst had stabilized.

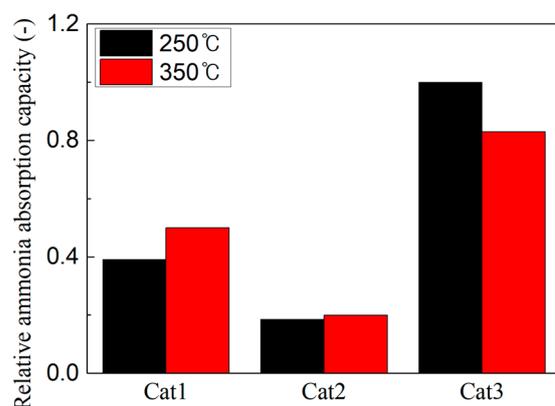


**Figure 5.** Schematic diagram of the micro reactor.

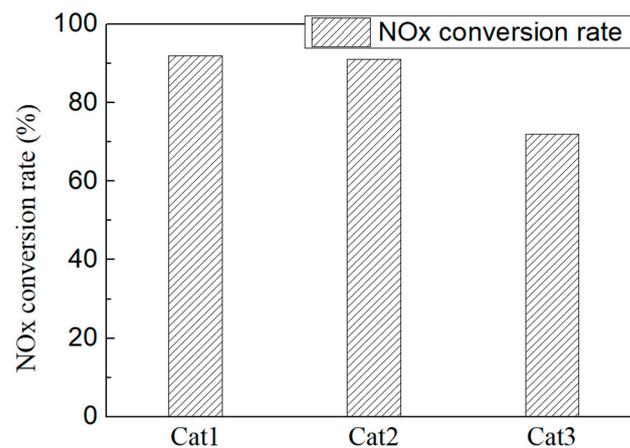
The relative ammonia adsorption capacities of the catalysts are shown in Figure 6. The ammonia adsorption capacity of Cat 3 was the highest; approximately 2.6–3.0 and 4.0–6.0 times larger than that of Cat 1 and Cat 2 at 250 °C and 350 °C, respectively. The De-NO<sub>x</sub> rate of the catalysts was examined at the same AV (Area Velocity) of 25 m/h calculated by Equation (1) and at 340 °C due to the different cell densities of the catalysts. To stabilize the AV, the total gas flow was adjusted to a constant flow rate of 0.9 Nm<sup>3</sup>/h. The simulated gases (10% O<sub>2</sub>, 8% H<sub>2</sub>O, 400 ppmv NO<sub>x</sub>, and 400 ppmv NH<sub>3</sub>) and N<sub>2</sub> balance gas were flowed over the catalyst for 60 min.

$$AV = \frac{Q_{ext}}{V \times S_g} \quad (1)$$

where  $Q_{ext}$  and  $V$  are the exhaust gas (Nm<sup>3</sup>/h) and the volume of the catalyst (m<sup>3</sup>), respectively.  $S_g$  is the geometric surface area (m<sup>2</sup>/m<sup>3</sup>) of the catalyst. Figure 7 exhibits the De-NO<sub>x</sub> rate of the catalysts. The NO<sub>x</sub> conversion rate of Cat 1 and 2 reached 92.6% and 91.8%, respectively, while Cat 3 showed a 20% lower NO<sub>x</sub> conversion rate under the same AV. This means the new catalyst can be designed to have a compact volume and minimized.



**Figure 6.** Relative ammonia adsorption capacity at 250 °C and 350 °C.



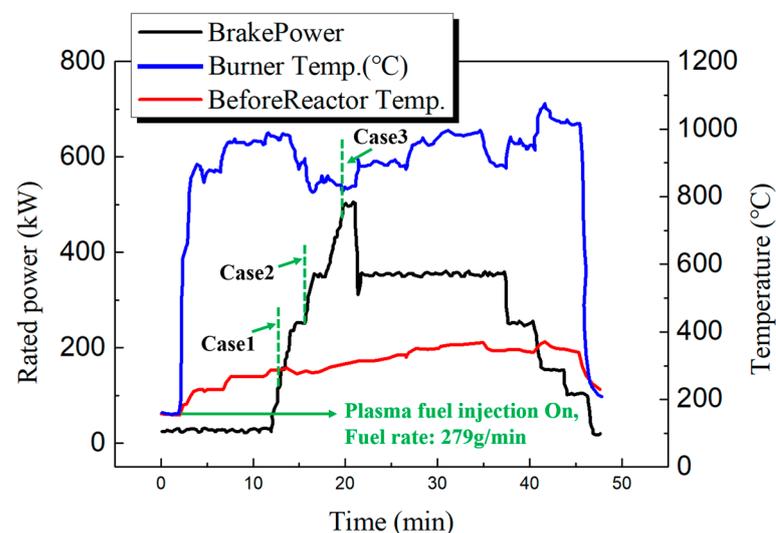
**Figure 7.** NOx conversion rates of the catalysts at AV 25 m/h and 340 °C.

### 3.1.3. Evaluation of Durability

To evaluate the durability of the catalyst to sulfur, it is exposed to the exhaust gas flow at SV 41 k/h and a temperature of 250 °C for 10 h using a 2 l diesel engine. Fuels for the aging test are used to distinguish between the effect of SOF (Soluble Organic Fraction) and ABS, ULSD (Ultra Low Sulfur Diesel), and ULSD-added sulfur (0.5wt% sulfur), respectively. The aged catalysts are evaluated at SV 21 k/h and temperatures of 230 °C, 260 °C, 300 °C, 350 °C, 390 °C and 430 °C.

### 3.2. Operating Characteristics of the Plasma Burner

Figure 8 and Table 4 demonstrates that all cases fired correctly despite the load change, and the stable combustion pattern was stable. However, as indicated by the temperature distribution after approximately 450–500 kW engine power, the reason for the unstable combustion can be observed as a change in the driving conditions of the engine and an increase in the amount of exhaust gas as the load increases. It was considered that unstable combustion occurs due to excess oxygen flowing into the reactor. However, despite the high flow rate (~50 m/s) of the exhaust gas flowing into the plasma burner, stable ignition characteristics could be observed through the oxygen in the exhaust, that is, approximately 500 kW engine power. From this result, it can be observed that combustion can be controlled independent of the engine operating condition with high variability, and the temperature can be controlled in the various operating ranges of the engine.



**Figure 8.** Combustion pattern as load change.

**Table 4.** Experimental conditions for ignition.

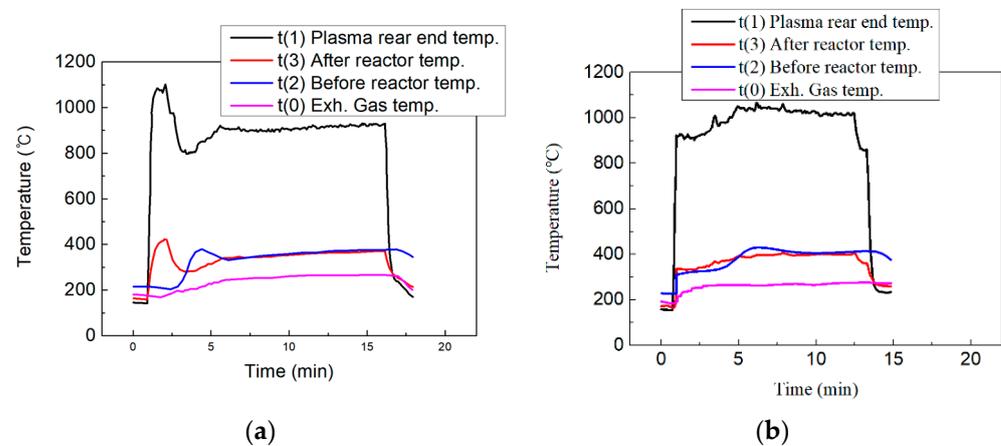
Condition	Burner Fuel Rate [g/min]	Engine Power [kW]	Exh. Flow Rate [kg/h]	Exh. Flow Velocity [m/s]
Case1	180	250	3500	25
Case2	180	350	4000	35
Case3	180	500	4500	45

Two temperature conditions are investigated to verify the performance of the plasma burner, as presented in Table 5. The exhaust gas temperature ( $t_0$ ), the plasma rear end temperature ( $t_1$ ), the reactor front temperature ( $t_2$ ), and the reactor end temperature ( $t_3$ ) results are shown in Figure 9a,b. As shown in the figures, both cases exhibit a stable combustion pattern, and the exhaust gas temperature constantly increases.

**Table 5.** Experimental conditions for plasma burner performance.

Description	Unit	Design Value	
		Case1	Case2
Plasma burner	Before SCR chamber		260
	Specific heat of exh. Gas		1.116
	Rising Temp.	100	150
	Required heat (*)	97.7	168.8
	Required fuel rate (**)	167.4	279.0

(\*) Required heat: specific heat of exh.gas  $\times$  flowrate of exh.gas  $\times$  difference of exh.temp. (\*\*) Required fuel rate: required heat/combustion heat of fuel  $\times$  margin rate (1.2).

**Figure 9.** Temperature profiles of the plasma burner operation; (a) Case1, (b) Case2.

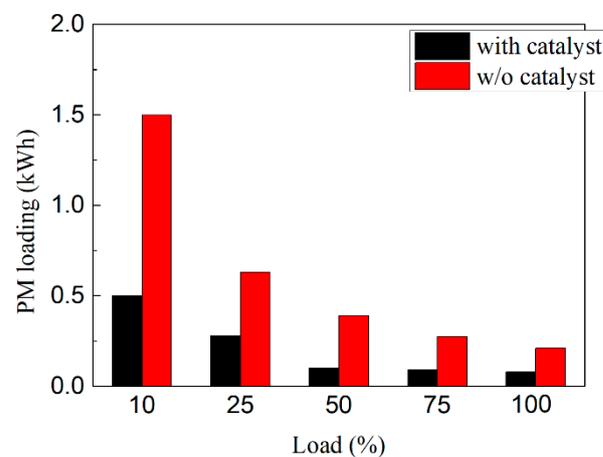
As shown in Table 6, the predicted temperature when the supplied fuel is completely burned, assuming the exhaust gas composition and condition according to the temperature in each experimental condition, was compared with the temperature at the rear end of the plasma burner. Thus, the efficiency of the burner could be verified. From the result of the calculation, it can be confirmed that at least 95% of the heat generated from combustion of the supplied fuel is used to raise the temperature of the exhaust gas, that is, approximately 12%  $O_2$  of exhaust gas emitted from the engine. This indicates that the combustion process is close to complete combustion. Therefore, when the plasma burner is used, the air-fuel ratio can be lowered and the combustion performance near complete combustion can be verified by utilizing oxygen in the exhaust gas.

**Table 6.** Estimation of combustion efficiency by comparing measured and calculated temperature.

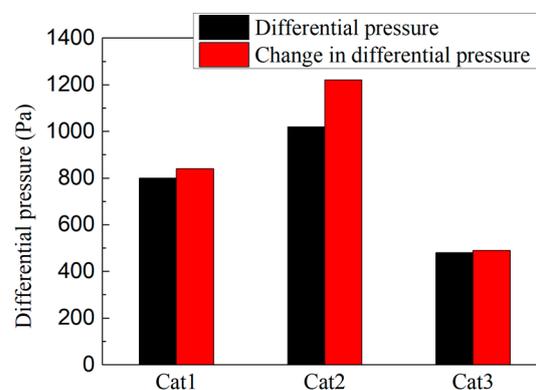
Condition	Fuel Rate [g/min]	T <sub>measure</sub> [°C]	T <sub>calculation</sub> [°C]	E <sub>thermal</sub> [%]
Case1	167.4	349	350	99
Case2	279.0	409	410	99

### 3.3. Differential Pressure

The pressure is changed through the SCR system due to stacked PM from the engine. The amount of stacked PM is measured using a dilution type SPC-472 (AVL) by following the test procedure in accordance with ISO-8178-1 (Incl. EPA CFR40. 1065) with a D2 test cycle mode. Figure 10 shows a comparison of the amount of PM loading with and without catalyst at different engine loads. More than 50% PM was deposited in the catalysts at all loads, causing high differential pressure. Secondly, the differential pressure of the catalysts was measured and then re-measured after 6 h at an engine operation SV of 11 k/h.

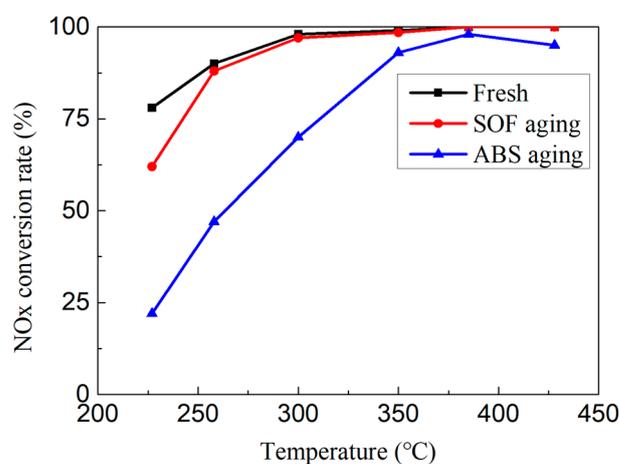
**Figure 10.** PM loading with and without catalyst at different engine loads.

The differential pressure of the catalysts increased by 70, 220 and 4 Pa for Cat 1, 2 and 3, respectively, as shown in Figure 11. The higher the cell density, the greater the change in differential pressure. Catalysts with high cell density have the advantage of compact volume, but can also have a high differential pressure due to PM. Conversely, catalysts with low cell density can be less sensitive to changes in differential pressure caused by PM, but have a higher volume. Therefore, the total volume of the catalyst is designed after selecting the cell density and considering the change in differential pressure caused by PM.

**Figure 11.** Change in differential pressure after 6 h.

### 3.4. Catalyst Aging and Evaluation

Since the fuel used in marine applications is of low quality with a high sulfur content, catalyst deactivation can occur, in particular via the formation of a soluble organic fraction (SOF) composed of heavy hydrocarbons with high boiling temperature and/or ammonium bisulfate (ABS) at low temperature. Because both SOFs and ABS are deposited on the pores and surface of the catalyst, they cause deactivation. To evaluate the durability of the developed catalyst to sulfur, it was exposed to the exhaust gas flow at SV 41 k/h and a temperature of 250 °C for 10 h using a 2 l diesel engine. Fuels for the aging test were used to distinguish between the effect of SOF and ABS, ultra low sulfur diesel (ULSD), and ULSD-added sulfur (0.5 wt % sulfur), respectively. The aged catalysts were evaluated at SV 21 k/h and temperatures of 230 °C, 260 °C, 300 °C, 350 °C, 390 °C, and 430 °C. As shown in Figure 12, catalyst deactivation by SOF occurs below 230 °C, but only slightly. The performance of the catalyst aged by SOF was regenerated perfectly upon exposure to temperatures above 260 °C. In contrast, deactivation of the catalyst by ABS occurs sharply below 350 °C. Catalyst deactivation is influenced more by ABS than SOF.

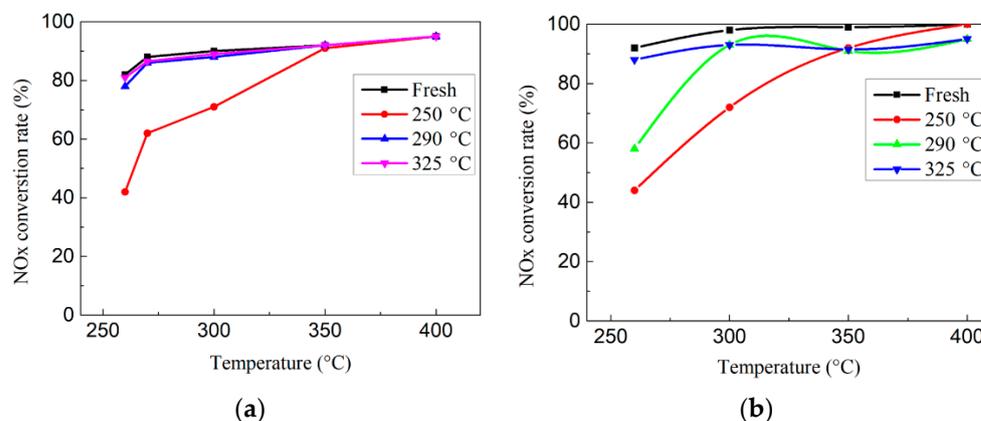


**Figure 12.** Evaluation of the performance of catalysts aged by SOF and ABS at 250 °C for 10 h.

### 3.5. Aged Catalyst

The SCR catalyst is generally deactivated for several chemical and mechanical reasons such as sulfation (ABS/AS by reaction of SO<sub>x</sub> and NH<sub>3</sub>), unburned fuel, inorganic elements, soot, de-lamination, and erosion. The presence of SO<sub>x</sub> in the exhaust gas is a major source of catalyst deactivation, but most fuels used in marine applications unfortunately contain a high sulfur concentration. Since the fuel used in marine applications is of low quality with a high sulfur content, catalyst deactivation can occur, in particular via the formation of a soluble organic fraction (SOF) composed of heavy hydrocarbons with high boiling temperature and/or ammonium bisulfate (ABS) at low temperature. Because both SOF and ABS are deposited on the pores and surface of the catalyst, they cause deactivation. To simulate those conditions, catalyst aging is performed by lab scale experiments. Four catalysts are prepared for lab scale experiments. One is fresh and the others were aged for 10 h by sulfur at temperatures of 250 °C, 290 °C, and 325 °C, respectively. Each catalyst was exposed to each measurement temperature (250 °C, 300 °C, 350 °C and 400 °C) for 15 min after the NO<sub>x</sub> conversion ratios were measured. The NO<sub>x</sub> conversion ratios were calculated by measuring the NO<sub>x</sub> concentration value before and after the catalyst. Catalysts in a SCR system without a bypass are exposed to sulfur species in the exhaust gas, regardless of whether the SCR system operates. Sulfur species in the exhaust gas adsorb on the catalyst. If urea is injected into the catalyst at low temperature, the adsorbed sulfur species and ammonia react to form ABS, causing deactivation. We therefore performed aging experiments without and with injection of urea. The catalyst was aged without and with injection of urea at SV 41 k/h and a temperature range of 250–325 °C for 10 h. Both aged

catalysts were evaluated over a temperature range of 260–400 °C while a urea solution corresponding to an NSR (Normalized Stoichiometric Ratio) of 1.0 was injected. The result for the aged catalyst with non-injection urea is shown in Figure 13a. When the urea solution was injected after aging below 250 °C, catalyst deactivation was visibly decreased. When the catalyst was exposed to 350 °C, the NO<sub>x</sub> conversion rate was regenerated.



**Figure 13.** NO<sub>x</sub> conversion rate of the aged catalyst; (a) with non-injection urea, (b) with injection urea.

In terms of marine applications, if a catalyst is exposed to exhaust gases at low temperature for a long time in a non-ECA (Emission Control Area), the ship must operate a SCR system in a high temperature environment to retain the performance of the catalyst when the ship is entering an ECA. If the exhaust gas temperature from the engine is low, an additional heating system must be installed to maintain the performance of the catalyst. The results for the aged catalyst with injection of urea are shown in Figure 13b. The NO<sub>x</sub> conversion rates of the aged catalyst decreased sharply below 290 °C. When the catalyst was exposed to 300 °C, the NO<sub>x</sub> conversion rate was regenerated to that of the fresh catalyst. Aging below 290 °C increases deactivation and the regeneration temperature. This means that if the SCR system operates below 300 °C for a long time, deactivation of the catalyst by ABS will take place. To regenerate and/or maintain catalyst performance, the engine load should at times be controlled so that the exhaust gas temperature is above 300 °C.

### 3.6. Effect of Exhaust Gas Temperature on the Catalyst

The influence of exhaust gas temperature on the WIW catalyst was verified using two types of 2MW marine diesel engine. Performance evaluation was carried out using fuel containing 0.2% S. The SV was 11 k/h, and the exhaust gas temperature was 340 °C (engine 1) and 270 °C (engine 2). After installing and evaluating the catalyst in engine 1, it was re-installed in engine 2. The results are shown in Figure 14.

At an exhaust gas temperature of 340 °C (engine 1), the NO<sub>x</sub> conversion rate was maintained at approximately 90% during an operation time of 175 h. On the other hand, the NO<sub>x</sub> conversion rate in engine 2 at a lower temperature decreased by approximately 15% during an operation time of 70 h. Contrary to our expectations, the NO<sub>x</sub> conversion rate is too low compared to the performance of the fresh catalyst. The catalyst used in engine 2 was analyzed in order to identify the cause of deactivation by using a micro reactor. The front and rear parts of the catalyst (samples 1 and 2, respectively) were chosen for analysis. Sample 1 was more discolored by PM than sample 2, as shown in Figure 15.

The catalysts were evaluated at different temperatures at SV 20 k/h. As shown in Figure 16, the performance of sample 1 was lower than that of the fresh catalyst by 5–15%. What is most interesting is that the performance of the catalyst is regenerated after exposure to temperatures above 400 °C. If the cause of deactivation is the formation of ABS, a temperature of 300 °C or 350 °C is sufficient for regeneration, according to the results obtained for the 2 l engine. Furthermore, the performance of sample 2 remained the

same as that of the fresh catalyst. For these reasons, we analyzed another source of catalyst deactivation.

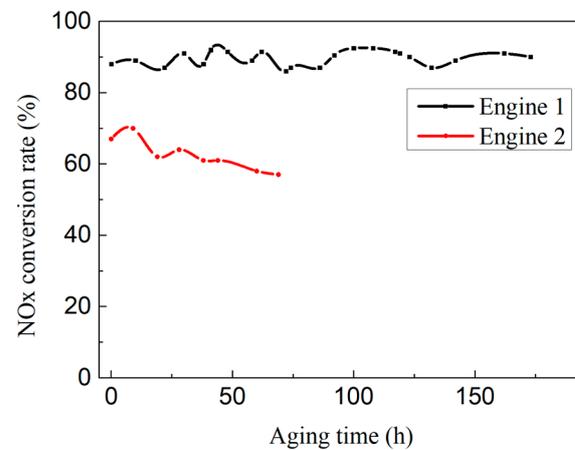


Figure 14. NOx conversion rate for engine 1 and 2 as a function of operating time.

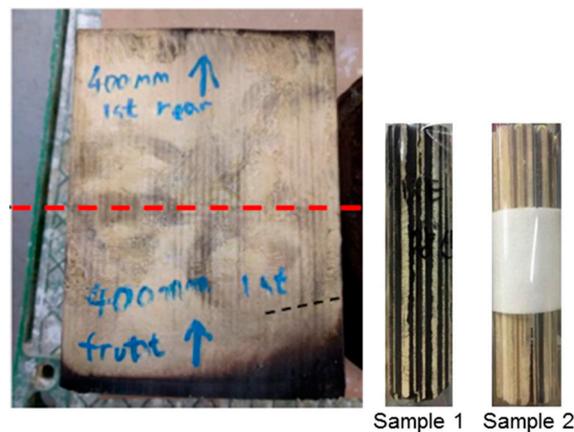


Figure 15. Sampling positions and condition of the used catalyst before and after regeneration.

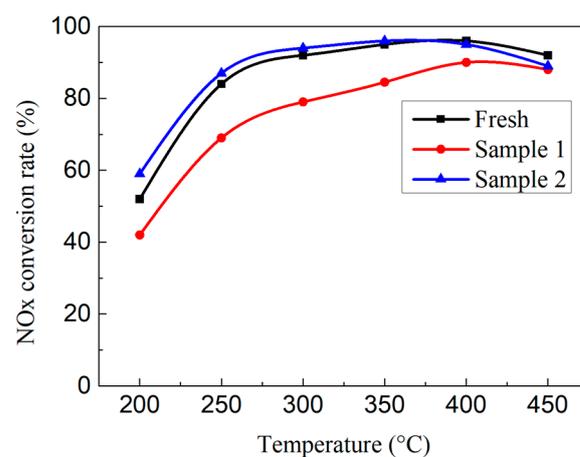
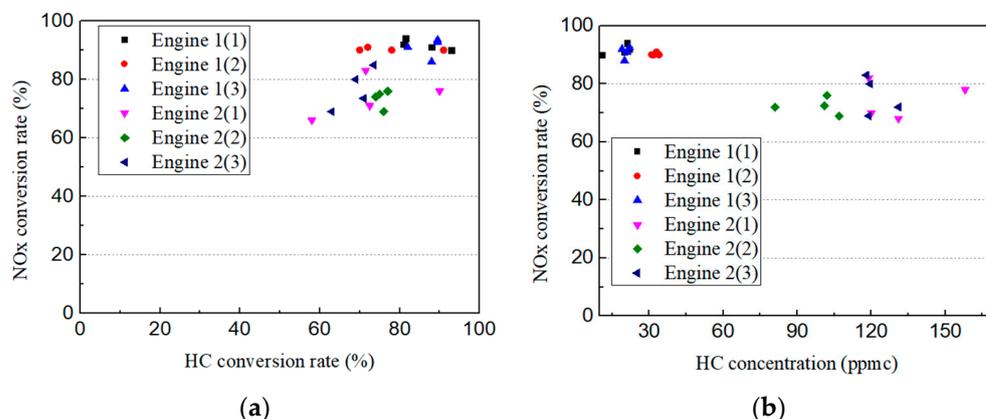


Figure 16. Evaluation of sample 1 and 2 at different temperatures.

Comparing the exhaust gas concentrations of engines 1 and 2 showed that the HC (hydro-carbon) concentration is significantly different. The measured HC concentration upstream and downstream of the catalyst from engine 2 was higher than that of engine 1. The correlation between HC and NOx was compared, as shown in Figure 17; NOx conversion is not affected by the HC conversion rate (Figure 17a), but the higher the HC concentration

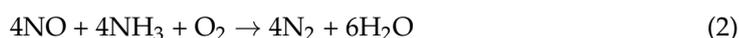
from downstream of the catalyst, the lower the NO<sub>x</sub> conversion rate (Figure 17b). Below 300 °C, HC competes with ammonia to adsorb on the active site. When HC has significantly adsorbed on the active site, ammonia adsorption is reduced, causing a low NO<sub>x</sub> conversion rate [17]. It seems that the catalyst performance is negatively affected above a certain HC concentration. This means that the catalyst should be designed considering HC concentration from downstream of the catalyst.



**Figure 17.** NO<sub>x</sub> conversion rate as a function of (a) HC conversion and (b) HC concentration from downstream of the catalyst.

#### Catalyst Regeneration and De-NO<sub>x</sub> Performance

The catalyst regeneration and De-NO<sub>x</sub> performance were investigated with the verified plasma burner. As presented in Table 7, the initial De-NO<sub>x</sub> rate, De-NO<sub>x</sub> rate in the poisoned state and De-NO<sub>x</sub> rate after regeneration were compared and verified. To verify the De-NO<sub>x</sub> performance, urea water solution, which is the reducing agent of the SCR system, was supplied under the condition that the ammonia slip is minimized, assuming 1:1 reaction of nitrogen oxides (NO<sub>x</sub>) and ammonia as given in Equation (2).

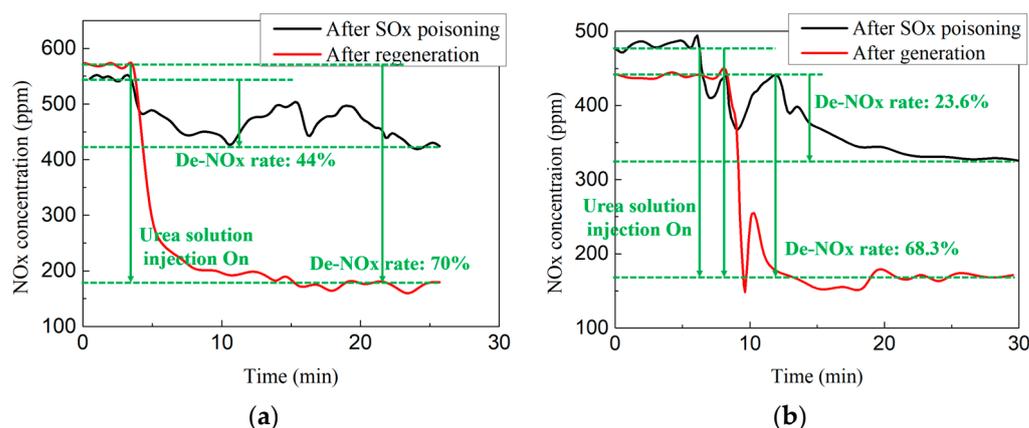


**Table 7.** De-NO<sub>x</sub> performance with plasma burner operation at different temperatures (exhaust condition refer to Table 3).

Description	Urea Flow Rate	Differ. Press.	De-NO <sub>x</sub> Rate
	[L/min]	[Pa]	[%]
Catalyst Regeneration @ 360 °C [Case 1]			
Fresh condition		1384	68.3
After SO <sub>x</sub> poisoning	4.61	1539	44.4
After regeneration		1346	70.6
Catalyst regeneration @ 410 °C [Case 2]			
Fresh condition		1391	68.1
After SO <sub>x</sub> poisoning	5.10	1564	23.6
After regeneration		1427	68.3

The results of urea dosing about 5 min after the stabilization of NO<sub>x</sub> was injected are shown in Figure 18. As mentioned above, it has been exposed to sulfur for a long time, and as described in SO<sub>x</sub> poisoning, the initial De-NO<sub>x</sub> rate of the catalyst after the urea injection decreased to 24% and 44% depending on each condition (Case 1) as shown in Figure 18. The results indicate that the De-NO<sub>x</sub> rate of each case rapidly progressed owing to sulfur that is exposed to sulfur oxides at a low temperature range, and the De-NO<sub>x</sub> performance

drastically reduced. It can also be observed that the inter-catalyst pressure differential increases as the poisoning progresses. As the pressure difference increases, the De-NO<sub>x</sub> performance decreases as the reaction area with the catalyst surface decreases. In addition, the De-NO<sub>x</sub> rate of the regenerated catalyst was compared with that of the poisoned catalyst at each case temperature. In general, the catalyst regeneration rate over time at each temperature condition (360 °C and 410 °C) yielded similar results of approximately 95% or more. In other words, it can be said that the initial regeneration covered up to 100% through the catalyst regeneration process. Therefore, the catalyst regeneration rate is the same. As a result, the De-NO<sub>x</sub> performance can be improved while reducing fuel consumption at 360 °C, which is the first condition for the temperature regime of 410 °C for catalyst regeneration. This can reduce fuel consumption of the burner by approximately 30% per hour in comparison to Case 2 under the same engine condition. These results indicate that it is possible to verify the effective performance of catalyst regeneration using a plasma burner, and the efficiency of the entire vessel can be increased by minimizing fuel consumption. This is very valuable in that it can significantly reduce equipment operating costs by regenerating the most expensive consumable catalyst among the SCR components. In addition, the operating conditions can be verified to enable operation in areas of economic efficiency while reducing fuel consumption as much as possible through different regeneration evaluations at regeneration temperature conditions. From the results of the performance test of the ship building engine plasma burner, verifying the regeneration and De-NO<sub>x</sub> performance are important for practical applications.



**Figure 18.** De-NO<sub>x</sub> performance with burner operation after SO<sub>x</sub> poisoning and after regeneration under different temperature conditions; (a) Case 1, (b) Case 2.

#### 4. Conclusions

In this study, the ignition characteristics, temperature control, and catalyst regeneration characteristics of a De-NO<sub>x</sub> test facility were evaluated based on a plasma burner verified in a lab scale test, and the results are summarized as follows.

- In spite of the high flow rate ( $\sim 50$  m/s) of the exhaust gas into the plasma burner, stable ignition characteristics can be achieved by using oxygen in the exhaust, that is, 250 kW to 500 kW of the engine power. It is possible to secure a design margin close to double.
- It can be confirmed that the ratio of heat generated through combustion of the supplied fuel to the temperature of the exhaust gas is 95% or higher; that is, approximately 12% of the exhaust gas from the engine. Oxygen was used to demonstrate the combustion performance close to complete combustion. Therefore, when the plasma burner was applied, the air-fuel ratio can be lowered and combustion performance near complete combustion can be verified by utilizing the oxygen in the exhaust gas.
- A plasma burner is very valuable because it can significantly reduce the equipment operation cost by regenerating the catalyst, which is the most expensive component of

the SCR components. The operating condition can be determined to enable operation in a more economical way while reducing the fuel consumption as much as possible through different regeneration evaluations under regeneration temperature conditions.

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## References

1. Azzara, A.; Rutherford, D.; Wang, H. Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction. *Int. Counc. Clean Transp.* **2014**, *4*, 1–9.
2. Myśków, J.; Borkowski, T.; Bludszuweit, M.; Fröhlingendorf, W. Marine engine exhaust gas emission aftertreatment system concept. *J. KONES Powertrain Transp.* **2011**, *18*, 307–315.
3. Kartte, K.; Nonnenmaker, H. Selective Removal of Oxides of Nitrogen from Gas Mixtures Containing Oxygen. U.S. Patent 3279884 A, 18 October 1966.
4. Clark, A.H.; Nuguid, R.J.G.; Steiger, P.; Marberger, A.; Petrov, A.W.; Ferri, D.; Nachtegaal, M.; Kröcher, O. Selective Catalytic Reduction of NO with NH<sub>3</sub> on Cu–SSZ-13: Deciphering the Low and High-temperature Rate-limiting Steps by Transient XAS Experiments. *ChemCatChem* **2020**, *12*, 1429–1435. [[CrossRef](#)]
5. Colban, W.F.; Miles, P.C.; Oh, S. Effect of intake pressure on performance and emissions in an automotive diesel engine operating in low temperature combustion regimes. *SAE Trans.* **2007**, *116*, 957–977.
6. Dunn, J.P.; Koppula, P.R.; Stenger, H.G.; Wachs, I.E. Oxidation of sulfur dioxide to sulfur trioxide over supported vanadia catalysts. *Appl. Catal. B Environ.* **1998**, *19*, 103–117. [[CrossRef](#)]
7. Magnusson, M.; Fridell, E.; Ingelsten, H.H. The influence of sulfur dioxide and water on the performance of a marine SCR catalyst. *Appl. Catal. B Environ.* **2012**, *111*, 20–26. [[CrossRef](#)]
8. King, R.T. Design of a Selective Catalytic Reduction System to Reduce NO<sub>x</sub> Emissions of the 2003. Ph.D. Thesis, West Virginia University, Morgantown, WV, USA, 2007; pp. 27–30.
9. Peng, Y.; Li, J.; Si, W.; Luo, J.; Wang, Y.; Fu, J.; Li, X.; Crittenden, J.; Hao, J. Deactivation and regeneration of a commercial SCR catalyst: Comparison with alkali metals and arsenic. *Appl. Catal. B Environ.* **2015**, *168*, 195–202. [[CrossRef](#)]
10. Koltsakis, G.; Skarlis, S.; Nastos, T.; Karamitros, D.; Vogt, C.; Sakashita, S. Model-based optimization of advanced SCR substrates. *Int. J. Automot. Eng.* **2015**, *6*, 45–52.
11. Armor, J.N. Materials needs for catalysts to improve our environment. *Chem. Mater.* **1994**, *6*, 730–738. [[CrossRef](#)]
12. Juan, Y.; Hongtao, M.; Yo, Y.; Jian, Y.; Guangwen, X.; Zhanguo, Z.; Yoshizo, S. SCR catalyst coated on low-cost monolith support for flue gas denitration of industrial furnaces. *Chem. Eng. J.* **2013**, *230*, 513–521.
13. Nova, I.; Bounechada, D.; Maestri, R.; Tronconi, E.; Heibel, A.K.; Collins, T.A.; Boger, T. Influence of the substrate properties on the performances of NH<sub>3</sub>-SCR monolithic catalysts for the aftertreatment of diesel exhaust: An experimental and modeling study. *Ind. Eng. Chem. Res.* **2011**, *50*, 299–309. [[CrossRef](#)]
14. Jang, J.; Park, H. Numerical Study on Urea Spraying and Mixing Characteristics with Application of Static Mixer in Marine SCR System. *Trans. Korean Soc. Mech. Eng.* **2016**, *40*, 429–434. [[CrossRef](#)]
15. Jo, S.; Cho, D.; Lee, D.H.; Kim, K.T.; Lee, J.O.; Song, Y.H.; Jang, J.H.; Roh, H.H.; Bak, G.M.; Lee, T.W.; et al. Plasma Burner Verification for SCR Performance Improvement and Catalyst Regeneration for Marine Engines. *Trans. Korean Soc. Mech. Eng.* **2018**, *42*, 305–312. [[CrossRef](#)]
16. Liu, Z.; Bai, J. Study on Adsorption Properties of Vanadium Catalysts for NH<sub>3</sub>. In Proceedings of the International Conference on Material and Environmental Engineering (ICMAEE 2014), Jiujiang, China, 21–23 March 2014; Atlantis Press: Paris, France, 2014; pp. 116–119.
17. Williams, A.; Ratcliffe, M.; Pederson, D.; McCormick, R. Effect of Unburned Methyl Esters on the NO<sub>x</sub> Conversion of Fe-Zeolite SCR Catalyst. *SAE Int. J. Fuels Lubr.* **2019**, *2*, 273–282. [[CrossRef](#)]