Evaluation of various wet scrubbing solutions for CI engine exhaust

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Abstract. Automotive sector emissions, including nitrogen oxide (NO), Carbon monoxide (CO), and hydrocarbons (HC), are extremely hazardous. For environmental regulations, the scrubber technique is commonly used in naval application. In this investigation, a Diesel Plastic Oil Blend (DPB) is used to minimize the emissions. Sodium hydroxide (NaOH), Sodium bicarbonate (NaHCO₃), Lime soda (NaCl), and potassium permanganate (KMnO₄) solutions were used to reduce the amount of pollution. The evaluation was done using a computerized, water-cooled, 4-stroke, Mono-cylinder, 5.2 kW diesel engine with a scrubber to ascertain its emission and performance characteristics. The experiments were conducted under several loading conditions. The NaOH, KMnO₄, and NaHCO₃ solutions were found to reduce the NO emission. The NaOH and KMnO₄ solution minimized the HC emission. Additionally, the NaHCO₃ solution minimized the smoke emission, and the NaCl solution reduced the CO and CO₂ emissions effectively.

Keywords: Plastic oil; Wet scrubber; NaOH; NaHCO₃; NaCl; KMnO₄.

1. Introduction

Environmental pollution, which is resultant of automobiles, is a major point of concern. Automotive pollution affects both rustic and urban zones in both developed and developing countries. Pollution has emerged as the primary focus of environmental regulations because it is inadequately regulated in many countries. Invariably, pollution is a major problem that threatens the entire environment [1]. The main objective of the national energy council is to completely decrease the crude dependency in a stage process so that the energy demand is decreased from 20% to 4% [2]. Alternative fuels are considered an excellent choice for reducing emissions in IC engines as the usage of traditional fuels is very expensive. Plastic usage has also increased exponentially. Due to this, the recycling of plastic waste has become a prominent area for analysis. The procurement of plastic from the waste plastic material through pyrolysis is a very important process that will significantly replace conventional fuels. It is also considered for petroleum reserve preservation, import reduction, and environmental protection. Several researchers have established that the plastic derived from waste plastic materials using the pyrolysis process enhances the brake thermal efficiency and reduces undesirable emissions [3].

In India, the emission norms are strictly followed for all vehicles. The after-treatment processes are considered for the fulfillment of the emission norms. The mentioned after-treatment methods are found to effectively reduce the emissions. Scrubber processes are widely applied in many industries, including thermal power plants, pharmaceuticals, chemicals, steel, and iron melting in gas purification. Research has established that the liquid and gas as a two-phase flow pattern is directly used for the removal of impurities. The pressure levels are also reduced. Consequently, the perfect identification of the flow pattern has helped in the removal of dust. This results in an augmentation of purification efficiency and energy levels [4]. Furthermore, scrubber technology plays a vital role in reducing harmful emissions, particularly the NOx levels. The scrubber treatment method is adopted due to its lower expenditure [5].
The technique primarily consists of a packed column tank where the fluid-gas flow phases occur concurrently facilitating the reduction of emissions. These scrubber treatment processes are optimally designed to be interfacial and colloidal with each other towards reducing emission in liquid phases [6]. The reactants induce a negative outcome due to the non-reactive tendency of the chemical solutions [7].\( \text{H}_2\text{O}_2 \) as scrubber solution was used for NOx and SOx reduction in a 2 stroke heavy oil fuelled naval vessel. Consumption level of the solution was determined based on the sailing conditions. Economic feasibility was analyzed based on the various costs involved. NPV was reasonably better than other practices and was assessed as 3.26% higher. These methods can be easily adopted by retrofitting with the prevailing systems. Simulation studies shows the \( \text{H}_2\text{O}_2 \) usage in ECA and non ECA as 757.38 & 10.37 kg/h, which was much lower than the regulation levels for NOx. This method can be installed comfortably in vessels having scrubber and EGR for the NOx and SOx diminutions [8].

To eliminate NOx pollutants, sodium chloride is detected during such a scrubber treatment. To reduce pollutants, a \( \text{NaClO}_2 \) solution is used. It is easily adsorbed because the gas and liquid phases are coincident. Because \( \text{NaClO}_2 \) liquid but rather gas are colloidal with one another, they easily remove pollutants in aqueous content liquid solutions. This automatically reduces temperature and NOx emissions. In addition, the velocity as well as diameter of the fluid is evaluate [9].

Scrubbing is a widely used method in naval applications and coal based thermal energy stations for removing SO2 emissions with seawater as scrubber solution. A stringent protocol leads the research to concentrate on scrubber design for greater efficiencies with packing rather than spray columns. These scrubber designs are based on coefficient of mass transfer and equilibrium concentration. Three different solutions (distilled water, seawater and seawater + \( \text{NaOH} \)) were taken and studied for SO2 levels. For the liquid to gas ratio (mass) of 2.91 kg/kg, 98% reduction of SO2 was observed. Prediction of experimental data’s was obtained by modelling for the research studies. \( \text{NaOH} \) was added with seawater to raise the solubility of SO2 in seawater [10]. Throughout this data analysis, the wet scrubbing techniques were investigated, primarily as an efficient way of flue gas implementation. A diesel engine was investigated at exhaust gas temperatures ranging from 500 to 800 °C [11-12].

Pre-heating increases engine performance and efficiency due to its reduced power consumption. The developments and implementations in this paper include similar functionalities on a single cylinder CI engine to reduce congestion and enhance performance. Wet scrubbing techniques which use water are revealed to reduce the flue gas levels and temperature. Under varying load conditions, the water scrubbing treatment method effectively reduced both NOx and smoke [13-14].

In this study, DEA (Di-Ethanolamine) and \( \text{Ca(OH)}_2 \) solutions were used to reduce CO2 and hydrogen sulfur content. The DEA solutions are widely used to determine the pollution concentrations. These treatment processes had slightly elevated alkaline content similar to the DEA solution. The acid levels are easily reduced and the absorption levels facilitated the removal of CO2. The DEA is typically administered at a low concentration. The DEA solution was further compared with the \( \text{Ca(OH)}_2 \) solution in this analysis. Under comparison, it was revealed that the DEA possessed a very low concentration and a very moderate absorption rate. However, the DEA had a higher energy requirement and absorption process than the \( \text{Ca(OH)}_2 \) solution. Hence, the present investigation is oriented towards the enhancement of the absorption quality. The enhancement augments heat integration and facilitates low hybrid amine mixtures [15].

In this study, the performance of the FGD (Fluid Gas Desulphurization) as both spray and structural packing is compared to obtain the mass of the fluid transfer model requirement as a cost-effective design for reducing the pollutants in naval applications. The primary contribution of this work is to analyze the fluid flow mass transfer rate in a spray tower. Scrubber treatments are widely used in naval applications to reduce emissions. Modeling a mass transfer model needs to be facilitated throughout this process. The design was done with the help of the comparative analysis of the spray tower. The packing spray was collected for the design of the scrubber waterfall. This modeling study primarily reduces the flue gas pollutants. This is frequently used because the packed columns are very effective in the absorption of the flue gases. A liquid-packed column seems is highly effective towards liquid flow, as it possesses very high removal efficiency. During this experiment, these structures along with the low-pressure drops were also analyzed [16].

The functionality of urea, urea peroxide, and urea hydrogen peroxide are compared to analyze the reduction in the NO removal efficiency. Because of the adsorbent concentration, and reaction temperature, the liquid-gas ratio was colloidal with one another. It is also an important parameter implemented for evaluating the NO removal efficiency. In simulated analysis, the role of the liquid and
gas ratios in the scrubbing solution flow was analyzed. A circulating pump was used to control the liquid flow level. The NO removal efficiency was achieved by passing the liquid with the exhaust gas. When the liquid-gas ratio exceeded 4 litres/m³ of the liquid-gas ratio, the NO levels normally decreased. Another analysis witnessed the influence of the variation in temperature levels on the NO removal efficiency. The temperature increased from 23 °C to 30 °C in a step-by-step manner. The liquid–gas ratio influenced the NO removal efficiency. The liquid-gas ratio was adjusted by varying the pump levels which automatically decreased the NO. The reason is the proportionality of the NO decrease with the liquid-gas ratio. Also, this influenced the concentration of free radicals with NO as the scrubber space increased. The augmentation of temperature due to the L/G ratio as a result of the urea peroxide solution mostly removed the NO. The urea peroxide concentration levels augment the liquid phases increase the urea peroxide increases the oxidizing levels due to the existence of the oxygen molecules as free radicals. These factors result in enhanced NO oxidation efficiency [17]. Because of the non-suitability of the acid scrubbers in the reduction of pollutant levels, the NOx in the gas form must be eliminated with the help of scrubber treatment. Water is widely sprayed into the flue gas which functions as a wet scrubber and a packing material. Urea is also used as a solution in scrubber treatment. In these investigations, the liquids and gas are found to be colloidal with each other. The mass transfer flow was evaluated towards the facilitation of emission reduction [18-19].

2. Methods
The investigation is done with the help of a 5.2 kW single-cylinder engine. The specifications include Natural aspiration, 1500 rpm, a water-cooled power train, and an eddy current load cell. The AVL di gas 444 was embedded in the exhaust pipe. The smoke sensor was receptor-related to measure the exhaust emission, as revealed in figure 1.

The chemical solution's physico-chemical properties are revealed. Table 1 depicts the structure.

| S.I | Solution                              | Structure          |
|-----|--------------------------------------|--------------------|
| I   | Sodium hydroxide (NaOH)              | ![Na-O-H]           |
| II  | Lime Soda (NaCl)                     | ![Na⁺⁺C⁺⁺Na⁺⁺]       |
| III | Sodium Bicarbonate (NaHCO₃)          | ![HO⁻⁻ONa⁺⁺]        |
| IV  | Potassium Permangent (KMnO₄)         | ![K⁺⁺O⁻⁻MnO−−O⁻⁻]   |
3. Fabrication of Scrubber and Nozzle spray

Figure 2 depicts the test engine. The dynamometer is often used to determine the speed and performance across the engines required to be operated in various ranges. In general, divergent methods are used to calculate the CI engine's output energy. The engine exhaust emissions are evaluated using the AVL gas analyser and smoke analyser. The scrubber is made from hollow sheet metal. The main section (length 320mm and width 150mm) is often used in making the scrubber material. A solution reservoir was used as the scrubber tank (length 120mm and width 40mm). Additionally, four nozzles were installed inside the scrubber tank. Figure 3 depicts the spray structure with the nozzles.
3.1 Preparation of KMnO₄
Potassium permanganate exists as a crystal structure. It is prepared by forming a solution initially, which is injected subsequently into a scrubber treatment solution. This is done by combining water and potassium permanganate crystal form as a solution. 1 liter of water and 100 milligrams of potassium permanganate are mixed, resulting in a pink-colored solution, as shown in fig 4.

![Figure 4: Preparation of KMnO₄](image)

3.2 Preparation of NaCl
NaCl exists as powder form in a chemical solution. 9g of NaCl powder is mixed with 750 ml of distilled water to form a chemical solution. This is stirred for 15 minutes resulting in the formation of NaCl solution as a final product as shown in fig 5. The formed NaCl solution is sprayed for the scrubber treatment.

![Figure 5: Preparation of NaCl](image)

3.3 Preparation of NaOH
Fig. 6 reveals the sodium hydroxide, which is developed using electrolytic chloralkali methodology similar to the procedures involved in industrial applications. Here, an aqueous sodium chloride solution is electrolyzed to yield chlorine gas and sodium hydroxide.

![Figure 6: Preparation of NaOH](image)

3.4 Preparation of NaHCO₃
The 0.5g sodium bicarbonate solvent is revealed in Fig 7. About 42 g of sodium bicarbonate (NaHCO₃) is liquidated in 0.72 g of sodium hydroxide (NaOH) powder in 850 ml of de-ionized water. The pH is adapted to 9.5 with a saturated solution of NaOH or concentrated H₂SO₄ and 1 liter of de-ionized water.
4. Results and Discussion

The scrubber setup was fitted in the diesel engine's exhaust system. The fuel used and the gas temperature at the outlet was monitored in the gas treatment process at loads of 0, 1.32, 2.6, 3.9, and 5.2 kW. The engine speed was kept constant at 1500 rpm throughout all the load conditions.

Fig 8 illustrates the different NO emission combinations for DPB without the need for a scrubber and DPB with such a scrubber for possible solutions. While compared to the DPB without a scrubber and other related chemicals such as NaHCO₃, KMnO₄, and NaCl, the NO emissions were almost less similar to the NaOH solution. The main cause of NO emissions is the extreme heat prevailing in the result of this, oxygen levels in the combustion chambers fall during its formation. It could be the primary cause of the rise in emission levels. The DPB, DPB with NaCl, DPB with KMnO₄, DPB with NaHCO₃, and DPB with NaOH revealed reduced NO emissions. In contrast to the other solutions, the NaOH solutions functioned as extremely reducing agents. The reason was due to a highly alkaline solution with a pH range of 7 to 10. As a consequence, the NO emissions in these scrubber treatments were reduced drastically.

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\text{NO} + \text{NaOH} \rightarrow \text{NaNO}_{2} + \text{H}_2\text{O} - \text{HNO}_3
\]
The variations among the HC emission and the brake power were shown in Fig 9. The levels of HC emissions increased to an absolute maximum. This was due to a step-by-step increase in fuel which was responsible for the synchronous increase in the HC emissions. Also, the oxygen level reduced, which was directly proportional to the increase in the HC emissions. Other considerations, including certain cylinder wall oil overlaps, were also considered as responsible for the reduction of HC emissions. The emission levels under DPB without a scrubber, when compared to the different scrubber solutions, were seen to be marginally reduced. When compared to the other solutions, DPB with NaHCO₃, DPB with NaCl, DPB with KMnO₄, and DPB with NaOH scrubber solution witnessed reduced emissions.

Fig 10 illustrates the different CO emission fluctuations from minimal to full load conditions. The CO emission predominantly consists of a high equivalence ratio, a shorter reaction period, and low oxygen levels, which combined contributed to an increase in the CO emission levels [19]. The DPB, DPB with NaOH, DPB with NaHCO₃, DPB with KMnO₄, and DPB with NaCl were measured for CO emission. However, when compared to the other solutions, the NaCl revealed the lowest CO emissions.
Figure 11 depicts the maximum to minimum load as a result of the variations in smoke emission versus BP. The opacity values measured in a smoke meter for DPB without scrubber, DPB + NaOH, DPB + NaHCO₃, DPB + KMnO₄, and DPB + NaCl are 25, 29, 45, 42, and 35 %, respectively. The bulk of the smoke emissions were due to the soot particles in the exhaust gas. The smoke is created by a homogeneous charge within the engine wall due to the premixing during the combustion process. Another rationale for the decreased smoke emission is the usage of different chemical solvents in the DPB with and without scrubbers.

Fig 12 depicts the thermal efficiency of the brakes power with and without the scrubber in various solutions. The plot also reveals the power output as a functionality of the brake thermal efficiency. This is primarily determined from the fuel's cetane number, density, calorific value, and other physical and chemical properties. The diesel as a fuel regularly possesses a normal brake thermal efficiency. The DPB also is seen to have a normal brake thermal efficiency when compared with the base fuel.
5. Conclusion
In this study, an exhaustive treatment configuration both for the DPB fuels implementation were developed and evaluated. The following significant results are given as follows.
1. When compared to the DPB without scrubber, and also under the usage of different chemical solutions, the NO dropped significantly by 25% at maximum load. This was due to the chemical reaction of the NaOH solution.
2. When compared to the DPB without scrubber, the HC emissions were reduced by 14% at full load in the NaOH chemical solution. The reasons were due to the chemical solution's enhanced alkaline content.
3. The CO and smoke emissions were drastically reduced.

References
[1] Balaji Gnanasikamani, Sathish Kumar Rajamanickam, Suresh Kumar Kasinathan, and Cheralathan Marimuthu, 2019 Experimental Investigation on an EGR Based Diesel Engine Fueled with the Blend of Diesel and Plastic Oil and an Antioxidant Additive, SAE Technical Paper, pp. 28-0079.
[2] B. Sachuthananthan, R.L Krupakaran, and G. Balaji, 2018 Exploration on the behavior pattern of a DI diesel engine using magnesium oxide nano additive with plastic pyrolysis oil as alternate fuel, International Journal of Ambient Energy, pp 0143-0750.
[3] Sachuthananthan Bharathy, Balaji Gnanasikamani, Krupakaran Radhakrishnan Lawrence, 2019 Investigation on the use of plastic pyrolysis oil as alternate fuel in a direct injection diesel engine with titanium oxide nano additive, Environmental Science and Pollution Research, vol 26, pp.10319–10332.
[4] S. Premkumar, G. Balaji, Experimental investigation of HC and CO emission reduction from a diesel engine powered by plastic oil blend using fly ash as catalyst, 2021 Journal of Thermal Analysis and Calorimetry, 10973 020-10541.
[5] M.Bharathiraja, R. Venkatachalam, V. Senthilmurugan, 2019 Performance, emission, energy and exergy analyses of gasoline fumigated DI diesel engine, Journal of Thermal Analysis Calorimetry, vol 136, pp 281–93.
[6] Z. Han, B. Liu, S.Yang, X.Pan, Z. Yan, 2017 NOx removal from simulated marine exhaust gas by wet scrubbing using NaClO solution, Journal of Chemistry, pp.1-10.
[7] H. Chu, TW. Chien, Li.SY, 2009 Simultaneous absorption of SO₂ and NO from flue gas with KMnO₄/NaOH solutions, Science of the Total Environment, vol 275, pp.127-35.
[8] Yeongryeol Choi, Junghwan Kim, Moon, 2020 Simulation and economic assessment of using H₂O₂ solution in wet scrubber for large marine vessels, Energy, vol 194, pp.116907.
[9] V. Arunkumar, K Krishnamurthy, C Maheswari, B Meenakshipriya and R Vinoth, 2019 Removal of NOx from diesel engine exhaust by using different chemical absorbent in a lab-scale packed column system, Journal of Measurement and Control, vol 52 7-8, pp.1095–1101.
[10] D. Flagiello, A. Ertò, A. Lancia, F. Di Natale, 2018 Experimental and modelling analysis of seawater scrubbers for sulphur dioxide removal from flue-gas, fuel, vol 15 (214), pp.254-263.
[11] Shuai Yang, Xiangdi Zhao, Wanfu Sun, Jiwu Yuan, Zheng Wang, 2019 Effect of ring baffle configuration in a self-priming venturi scrubber using CFD simulations, Particuology, vol 47, pp.63-69.
[12] Wenqiang Sun, Yixin Shao, Liang Zhao, Qiang Wang, 2020 Co-removal of CO₂ and particulate matter from industrial flue gas by connecting an ammonia scrubber and a granular bed filter, Journal of Cleaner Production, vol 1(257), pp.120511.
[13] Manisha Bal, Hammad Siddiqi, Subhrajit Mukherjee, B.C. Meikap, 2019 Design of self-priming venturi scrubber for the simultaneous abatement of HCl gas and particulate matter from the flue gas, Chemical Engineering Research and Design, vol 150, pp.311–319.

[14] N. Abbas pour, M. Haghshenasfard, M.R. Talaei, H. Amini, 2020 Experimental investigation of using nanofluids in the gas absorption in a venturi scrubber equipped with a magnetic field, Journal of Molecular Liquids, vol. 303, pp.112689.

[15] Samuel Eshorame Sanni, Oluranti Agboola, Omololu Fagbiele, Esther Ojima Yusuf, Moses Eterigho Emetere, 2020 Optimization of natural gas treatment for the removal of CO₂ and H₂S in a novel alkaline-DEA hybrid scrubber, Egyptian Journal of Petroleum, vol. 29, pp.83-94.

[16] D. Flagiello, A. Parisi, LanciaCarotenuto, A. Erto, F. Di Natale, 2019 Seawater desulphurization scrubbing in spray and packed columns for a 4.35 MW marine diesel engine, Chemical Engineering Research and Design, vol. 148, pp.56–67.

[17] Jinxi Zhoua, Hewen Wang, 2020 Study on efficient removal of SOx and NOx from marine exhaust gas by wet scrubbing method using urea peroxide solution, Chemical Engineering Journal, vol 390, pp.124567.

[18] Paridhi Goel, Avinash Moharana, Arun K. Nayak, 2019 Numerical simulation of injection characteristics, hydrodynamics and absorption of iodine vapour in a venturi scrubber operating in self-priming mode, vol. 341, pp.360-367.

[19] Balaji Gnanasikamani, Sachuthananthan Bharathy, K. Suresh Kumar, Cheralathan Marimuthu, 2020 Ecological influence of addition of antioxidant and incorporation of selective catalytic reduction on NO emission in off-road engines powered by waste plastic oil blend, Journal of Environmental progress and sustainable energy, Vol. 39.