Hindawi
Adsorption Science & Technology
Volume 2022, Article ID 8803585, 8 pages
https://doi.org/10.1155/2022/8803585

Research Article

Development of Active CO_2 Emission Control for Diesel Engine Exhaust Using Amine-Based Adsorption and Absorption Technique

Solomon Jenoris Muthiya,[1] **L. Natrayan**,[2] **L. Yuvaraj**,[3] **Mohankumar Subramaniam**,[4] **Joshuva Arockia Dhanraj**,[5] **and Wubishet Degife Mammo**[6]

[1]*Department of Automobile Engineering, Dayananda Sagar College of Engineering, Bengaluru 560078, India*
[2]*Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai, 602105 Tamil Nadu, India*
[3]*Department of Automobile Engineering, Acharya Institute of Technology, Bangalore, 560107 Karnataka, India*
[4]*Department of Automobile Engineering, Kumaraguru College of Technology, Coimbatore 641006, India*
[5]*Center for Automation and Robotics (ANRO), Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Padur, Chennai 603103, India*
[6]*Mechanical Engineering Department, Wollo University, Kombolcha Institute of Technology, South Wollo, Kombolcha, 208 Amhara, Ethiopia*

Correspondence should be addressed to Solomon Jenoris Muthiya; jenoris.555@gmail.com, L. Natrayan; natrayanphd@gmail.com, and Wubishet Degife Mammo; wubishetdegife7@gmail.com

Received 27 November 2021; Revised 18 January 2022; Accepted 1 February 2022; Published 14 February 2022

Academic Editor: Lakshmipathy R

Diesel-powered transportation is considered an efficient method of transportation; this sees the increase in the demand for the diesel engine. But diesel engines are considered to be one of the largest contributors to environmental pollution. The automobile sector accounts for the second-largest source for increasing CO_2 emission globally. In this experiment, a suitable postcombustion treatment to control CO_2 emission from IC engine exhaust is developed and tested. This work focuses to control CO_2 emission by using the chemical adsorbent technique in diesel engine exhaust. An amine-based liquid is used to adsorb the CO_2 molecules first and absorb over the amines from the diesel engine exhaust. Three types of amino solutions (L-alanine, L-aspartic acid, and L-arginine) were prepared for 0.3 mole concentrations, and the CO_2 absorption investigation is performed in each solution by passing the diesel exhaust. A suitable CO_2 adsorption trap is developed and tested for CO_2 absorption. The experiments were performed in a single-cylinder diesel engine under variable load conditions. The eddy current dynamometer is used to apply appropriate loads on the engine based on the settings. The AVL DIGAS analyzer was used to measure the CO_2, HC, and CO emissions. An uncertainty analysis is carried out on the experimental results to minimize the errors in the results. The effective CO_2 reduction was achieved up to 85%, and simultaneous reduction of HC and CO was also observed.

1. Introduction

Global climate change is one of the main problems addressed by many researchers. The increase of greenhouse gases such as carbon dioxide (CO_2), methane, and nitrous oxide [1] has raised the global earth temperatures by around 2° since the preindustrial revolution [2]. Globally, humans are the main contributors to emitting 36 billion tonnes of CO_2 per year, and this trend continues to increase every year [3, 4]. The world's largest CO_2-emitting countries are China, the USA, Russia, Japan, and India. India contributes 7% of global CO_2 rise; a definitive

Figure 1: Amine salts.

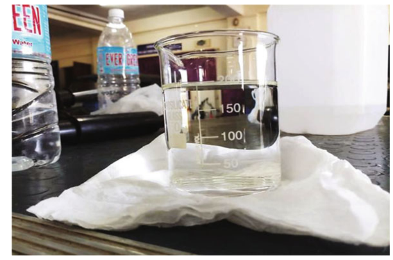

Figure 2: Preparation of amine solution.

method to control the CO_2 emission should be in place, or by the year 2030, it is expected to increase the global earth temperature to 3.1°C-3.7°C [5]. CO_2 emissions are considered to be a dangerous pollutant liberated from the internal combustion engines (ICE). The combustion of any fuel in an IC engine produces CO_2 emission as a byproduct. In an IC engine, complete combustion leads to higher power and also reduced HC, CO, and smoke in the exhaust [6]. But the CO_2 emission increases when the fuel is completely burnt [7]. The main technologies for postcombustion CO_2 capture are membrane separation, amine absorption, cryogenic separation, and physical adsorption. These are the technologies followed by the industry or power plant to control CO_2 emission [8]. Amine absorption and physical absorption techniques are the most effective methods followed in the industry for postcombustion treatment of flue gases [9]. In this work, an novel attempt is made to utilize an amine-based solution to trap the CO_2 gas directly from the tailpipe of the diesel engine exhaust.

The adsorption and absorption technique is considered as one of the alternatives because of the wide range of operating temperatures, pressure, low energy consumption, and cost-effectiveness [10]. The experimental work conducted by Jenoris et al. states that the usage of solid adsorbent can reduce CO_2 emission when the exhaust gas is maintained at less than 100°C [2]. At higher temperature, the solid adsorbent does not effectively capture CO_2 less than 30% reduction as possible. For the effective CO_2 reduction, the adsorbent material should have the durability with high CO_2 selectivity, good regeneration, adsorption capacity, and adsorption/desorption kinetics for CO_2 [11]. The predominantly available method to capture CO_2 is amine-based processes and amine scrubbing [12, 13]. Amine scrubbing is the process of capturing CO_2 by passing the gases over the amine solution [14, 15].

In this work, an attempt has been made to control CO_2 emissions from diesel engine using an amine scrubbing method. In this research, three different amine solutions are prepared with different concentrations to identify its CO_2 trapping efficiency with real diesel exhaust. The amines used are L-arginine, L-alanine, and L-aspartic acid. The prepaid amine solution is tested for CO_2 reduction by passing the diesel exhaust in to the solution. In this research, a suitable CO_2 trap was designed, fabricated, and retrofitted in the tailpipe of the single-cylinder diesel engine. The experimental test was carried out by varying the loads from 0 to 100%. And mission testing was carried out for the CO_2 trap.

2. Materials and Methods

2.1. Amine Solution Preparation. In this work, the investigation is carried out to find an effective amine solution to effectively trap the CO_2 molecule. The amino slats used L-Arginine, L-alanine, and L-aspartic acid. Figure 1 shows the amine salts used in preparing amine solution. Initially, various trial experiments are made in preparing the amine solution with various concentrations varying from 0.01 to 0.3. It was observed at initial experiments that 0.3 mole concentration of amino salt solution has a good tendency to trap the CO_2 molecule [15]. So, with L-arginine, L-alanine, and L-aspartic acid amino salts, 0.3 mole concentration is fixed to prepare an amino salt solution to test in diesel exhaust. The amine solution is to be prepared by mixing the amino salt and sodium hydroxide in the deionized water as per the mole solubility and molecular weight of the chemicals. At first, 0.01 m of concentration has been mixed in the 4 lit of deionized water based upon the molecular weight of the chemical. And further, the mole concentration of amino salt has been increased from 0.01 m to 0.3 m. By increasing the mole concentration, the amino acid concentration level is increased which can be effective to absorb more CO_2 molecules. For example, to prepare amine solution as per the mole concentration and molar mass, the mole concentration of 0.01 and the molar mass 174.2 is dissolved in the 4 lit of deionized water; $(0.01 \times 174.2 \times 4) = (6.96)$ gm of amino salt has to be dissolved in the 4 lit of deionized water. This is for arginine amino salt for 0.01 m concentration. For 0.3 m mole concentration, 209 gm of amino salt is added to prepare the solvent solution [16]. Sodium hydroxide (NaOH) of 1.6 gm has been added to the chemical solution as per the mole concentration in the amino solution for better and efficient absorption. Similarly, for L-arginine, L-alanine, and L-aspartic acid, 0.3 mole concentrations of amine solution are prepared and tested for CO_2 emissions trapping in the diesel engine exhaust.

Amine solutions are prepared as per the mole concentration and molar mass. Figure 2 shows prepared amine

Table 1: Important properties of amines used.

Properties	Sodium hydroxide	L-Alanine	L-Aspartic acid	L-Arginine
Molecular formula	NaOH	$C_3H_7NO_2$	$C_4H_7NO_4$	$C_6H_{14}N_4O_2$
Molecular weight (g/Mol)	40.00	89.09	133.1	174.2
Appearance	Powder	Crystalline	Powder	Powder
Colour	White	White	White	Colourless
pH at 25°C	12 - 13	5.6	2.7	11.24
pKa	13.7	2.35, 9.86	1.88, 9.61	2.18, 9.08
Melting point (°C)	315	314	260	240
Boiling point (°C)	140	188	323	365
Density (g/cm^3)	2.11	1.422	1.662	1.662

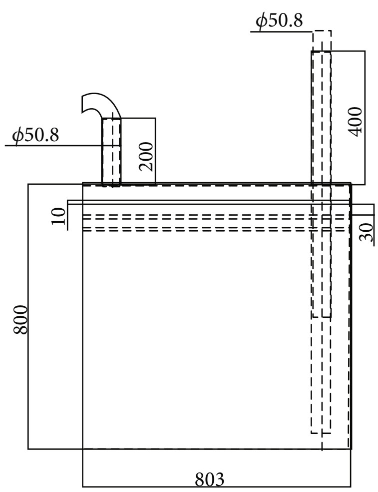

Figure 3: The line diagram of CO_2 reduction trap with dimensions.

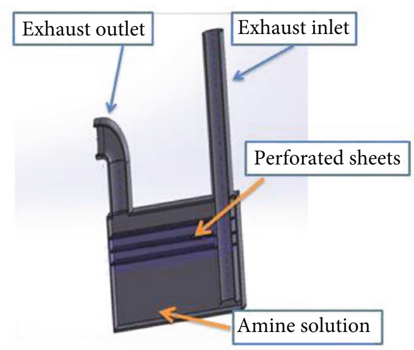

Figure 4: The design model of CO_2 reduction trap.

Figure 5: The image of fabricated of CO_2 reduction trap.

solution. Table 1 shows the physical and chemical properties of amines used.

The CO_2 absorption mechanism in the amine solution is given in the below reaction.

$$\begin{aligned} &2\text{-OOC-R-NH}_2 + CO_2 \xrightarrow{\text{ABSORPTION}} {}^{-}\text{COO-R-NH-COO}^{-} \\ &\quad + {}^{-}\text{OOC-R-NH}_3^{+} \xrightarrow{0} \\ &{}^{-}\text{COO-R-NH}_2^{+}\text{-HCO}_3^{-} \\ &\quad + {}^{-}\text{OOC-R-NH}_3 \xrightarrow{\text{DESORPTION}} 2\text{-OOC-R-NH}_2 + CO_2 \end{aligned} \tag{1}$$

2.2. CO_2 Reduction Trap. CO_2 reduction trap is designed in such a way that the exhaust gas can easily pass over the amine solution and react for trapping the CO_2 molecules. Figure 3 shows the line diagram of the CO_2 reduction trap. The CO2 trap has an inlet pipe that is extended to the bottom of the reactor. The exhaust gas enters into the inlet pipe and mixes into the amine solution which is filled inside the reactor. Finally, exhaust gas bubbles out of the solution at the outlet pipe which is fixed at the top of the reactor section. A stack of the perforated sheet is placed in the reactor to arrest the return flow solution leak in the holes of the pipes. The designing of a CO_2 trap is carried out to eliminate the backpressure by reducing the obstacles in the flow of exhaust. Figure 4 shows the design model of the CO_2 reduction trap. The design plays a key role in the CO_2 trap, in which the exact components like inlet and outlet pipes and also the inbuilt perforated metal sheets all are been fabricated and placed as per the design. CO_2 trap is fabricated using stainless steel material. It is corrosion-resistant and light in

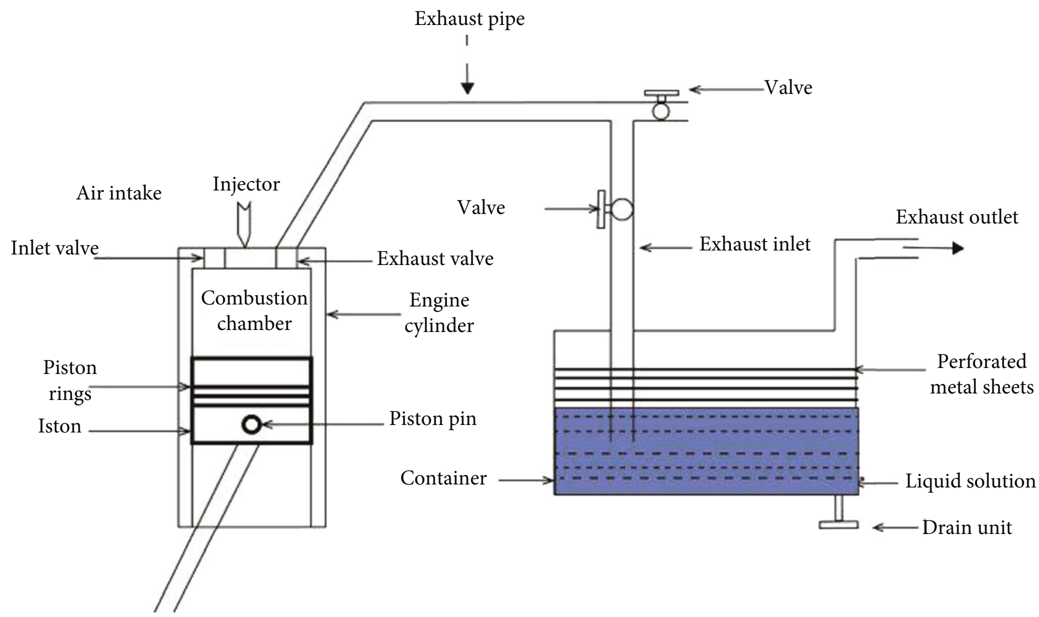

Figure 6: Layout of CO_2 reduction trap.

weight. Figure 5 shows the image of the fabricated CO2 reduction trap. The layout of the CO_2 reduction trap is shown in Figure 6.

3. Experimental Methods and Testing

3.1. Experimental Setup. To analyze the emission characteristic of the CO_2 trap, a single-cylinder four-stroke direct injection diesel engine is coupled with eddy current dynamometer to power take-off shaft. The coolant used in the engine is water, and it is recirculated using a conventional pump. To compare the emission characteristics, an AVL Digas analyzer and an AVL smoke meter are connected to the tailpipe. Figure 7 shows the layout of the experimental setup.

3.2. Experimental Procedure. The initial condition such as engine oil level and the condition, coolant water feed rate, and its overhead tank capacity is tested at engine rest position to confirm normal working throughout the experiment. To avoid any variance, the experimental setup is started and run on neat diesel for about 10 to 15 minutes at the idle condition to reach the nominal operating temperature. During this phase, the calibration is executed on the dynamometer to eliminate loading error. After the warm-up, the exhaust emission measurement is done by running the engine for 15-20 minutes at each load condition. The emission concentration is noted by installing the emission analyzer probe in the tailpipe. Figure 8 shows the image of the experimental setup. Then, the engine is run at various load instances (0%, 25%, 50%, 75%, and 100%), and the results are obtained. The experiment is conducted in two phases, one without connecting the CO_2 trap and one with connecting the CO_2 trap in the tailpipe of the engine. Initially, a baseline reading is taken without connecting the CO_2 trap. Next, the CO_2 trap is connected to the tailpipe of the engine, and readings are taken to evaluate its performance and emission characteristics.

4. Results and Discussion

In this work, CO_2 reduction trap is designed and tested for its performance and emission reduction characteristics in a single-cylinder diesel engine. The experiment is conducted by retrofitting the CO_2 reduction trap in the tailpipe of the diesel engine.

4.1. Performance Characteristics. The performance of the engine after fixing the CO2 reduction trap can be analyzed by evaluating the Brake thermal efficiency and brake-specific fuel consumption. In this experiment, the baseline reading was taken without connecting the CO_2 reduction trap in the engine tailpipe, and readings were taken after connecting the CO_2 trap in the engine tailpipe. Figure 9 shows the variation of brake thermal efficiency with respect to engine load. It is observed that the brake thermal efficiency of the engine was not much affected after connecting the CO_2 trap. This is because the back pressure is not increased after connecting the trap and the design is safe.

Figure 10 shows the deviation of specific fuel consumption with respect to engine load. It is observed from the graph that specific fuel consumption for baseline does not vary after connecting the CO_2 reduction device. This is because the CO_2 reduction trap does not impact any load to the engine, and the fuel consumption range does not increase. And with the CO_2 reduction trap, the backpressure does not affect the engine performance.

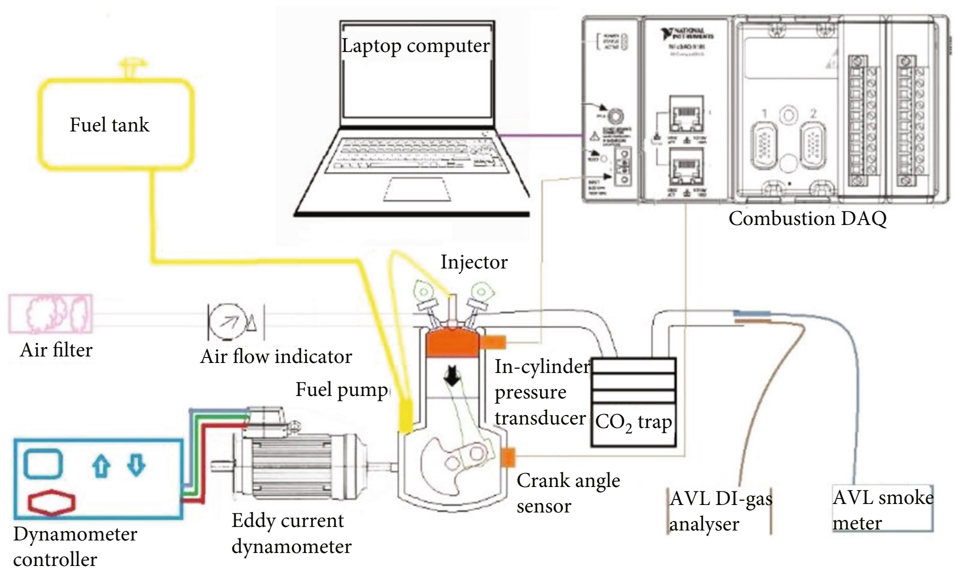

Figure 7: Layout of experimental setup.

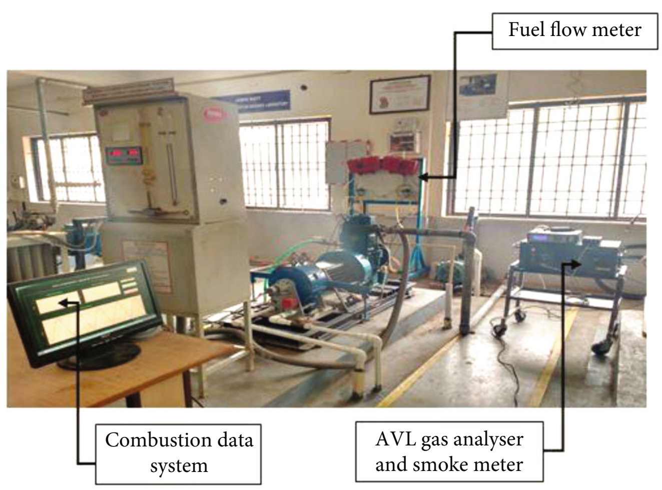

Figure 8: The image of experimental setup.

4.2. Emission Characteristics. The emission testing is carried out for an amine solution of 0.3 mole concentration. At 0.3 moles, the CO_2 absorption was observed effectively. So, for all different amine solutions, 0.3 is fixed as an effective absorption concentration. The prepared solution is filled inside the CO_2 reduction trap, and it is checked for the maximum level of filling the solution. The exhaust flow inside the CO_2 reduction trap is designed in such ways that exhaust gas passes over the amine solution and gets scrubbed. The diesel exhaust continuously passes over the CO_2 reduction trap and reacted with the amine solution for emission reduction. The experiment is conducted by varying the load. The concentration of exhaust is also varied by switching the load. The graphs are plotted with respect to various emissions for the given engine load and explained below.

Figure 11 shows the variation of CO_2 emission with respect to engine load. It is observed from the graph that the CO_2 emission concentration varies with respect to supplied engine load. The CO_2 emission increases due to the complete combustion of fuel [17]. The maximum level of CO_2 emission from the exhaust was 6.4% which is liberated at the full load condition of the engine. After in connection with the CO_2 reduction trap, the CO_2 level was dramatically reduced. It is due to the effective wet scrubbing of exhaust gas over the amine solution.

The double-bond CO_2 molecules get adsorbed and absorbed over the amine solution. L-Alanine and L-arginine absorbent shows moderated reduction of 27% and 55% in CO_2 emission. It is due to poor absorption of CO_2 with respect to L-alanine and L-arginine. Compared with baseline reading, L-aspartic acid shows a maximum

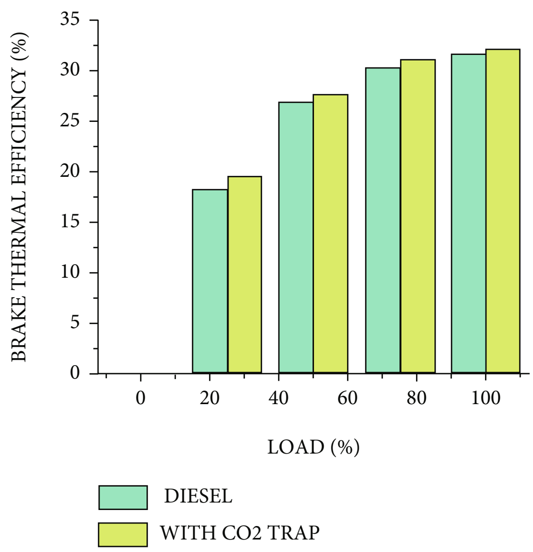

FIGURE 9: Variation of brake thermal efficiency with respect to engine load.

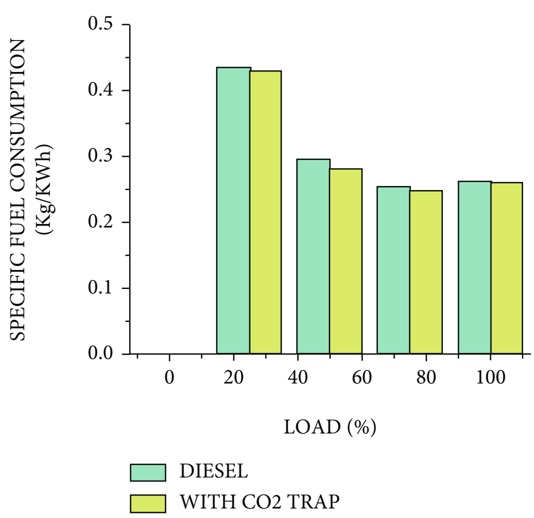

FIGURE 10: Effect of CO_2 reduction trap on specific fuel consumption.

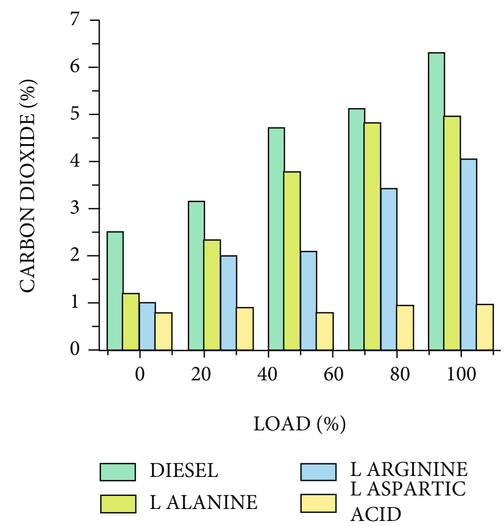

FIGURE 11: Variation of carbon dioxide with respect to engine load.

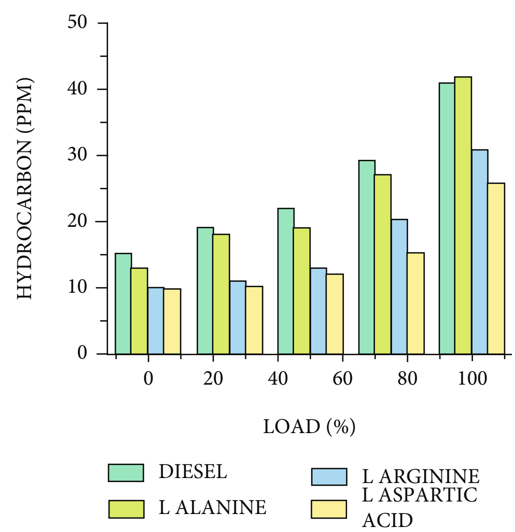

FIGURE 12: Variation of hydrocarbon with respect to engine load.

reduction of 85% in CO_2 emission. It is due to the suitable amine properties of L-aspartic acid in absorbing the CO_2 molecules.

Figure 12 shows the variation of HC emission with respect to engine load. In a diesel engine, HC emission rises due to the incomplete combustion of fuel [18]. The maximum concentration of 48 PPM was liberated from the diesel engine at full load conditions. After in connection with the CO_2 reduction trap, the HC emission also tends to be reduced. It is due to the absorbent reaction of amine solution with the HC molecules. L-Alanine and L-arginine have 7% and 25% CO_2 reduction. L-Aspartic acid shows a maximum reduction of 37% HC emission. It is due to the suitable amine properties of L-aspartic acid in absorbing the HC molecules.

Figure 13 shows the variation of CO emission with respect to engine load. In the diesel engine; CO emission increases due to less oxygen concentration during combustion [19, 20]. Also, the CO emission increases with a rich mixture [21]. After in connection with the CO_2 reduction trap, the CO emission slightly decreases. It is due to the reaction of amine solution with the CO molecules. L-Alanine and L-arginine absorbent shows slight reduction in CO. L-Aspartic acid shows maximum reduction of CO emission when compared with L-alanine and L-arginine absorbents. It is due to the suitable amine properties of L-aspartic acid in absorbing CO molecules.

NO_x emission increases in diesel engines due to high peak cycle temperature. At high combustion temperatures, NO and O_2 undergo endothermic reactions to form NO_x [22]. Figure 14 shows the variation of NO_x emission with

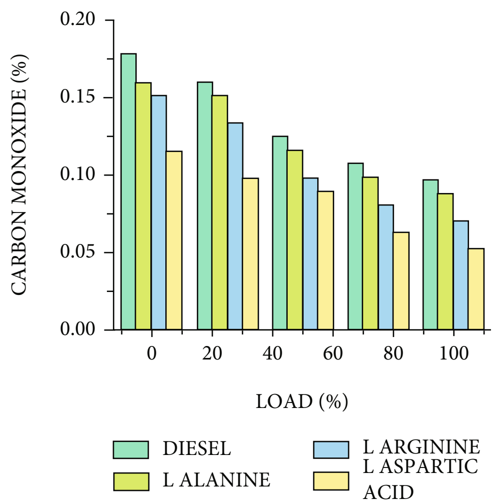

Figure 13: Variation of carbon monoxide with respect to engine load.

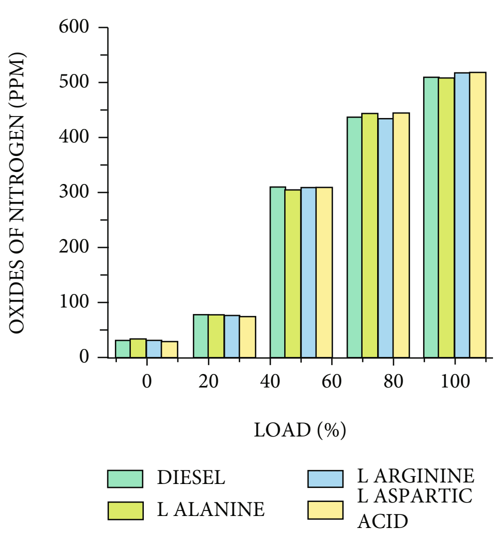

Figure 14: Variation of NO_x concentration with respect to engine load.

respect to engine load for three different amine solutions. It is observed that only slight NO_x reductions of 5-10% were observed with respect to amines. It is due to the poor reduction ability of amines over the NO_x molecule. The amines could not be able to trap the double-bond nitrogen molecules over it. The exhaust NO_x does not cause any effect on CO_2 reduction.

Figure 15 shows the variation of O_2 concentration with respect to load. O_2 concentration of the diesel engine exhaust is varied with respect to load [23]. The exhaust oxygen concentration shows how efficient is combustion [24]. With respect to O_2 concentration, there is not much change with the CO_2 reduction trap. With L-aspartic acid, slight variation in O_2 concentration was observed. It is due to the effective reduction of CO_2 and CO molecules over the amine solution.

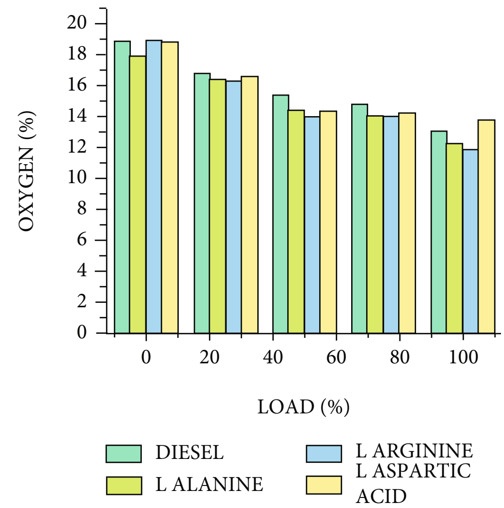

Figure 15: Variation of O_2 concentration with respect to engine load.

5. Conclusion

In this experimental testing, emission investigation test of the engine has been done with and without connecting the trap. The difference in emission percentage levels of HC, CO, CO_2, and O_2 from the diesel engine is analyzed for emission reduction. The preparation of amino solution has been done as per molar solubility and molar concentration; the L-arginine and sodium hydroxide has been mixed with the deionised water as per concentration and solubility quantity; the amino solution has been prepared. Similarly, for L-alanine and L-aspartic acid are used to make an amino solution, the CO_2 reduction trap has been designed, and as per the design and dimensions, the fabrication has also been done. The emission testing is carried out in the experimental setup by connecting the trap in the diesel exhaust. The experiment has been done successfully and the emission reading has been taken by using the AVL di gas analyser. The following results have been obtained from the experiments:

(i) It is observed from the results that L-aspartic acid has a high level of 85% CO_2 reduction rate

(ii) L-Alanine has 27%, and L-arginine has 55% CO_2 reduction

(iii) L-Aspartic acid has a maximum HC reduction of 37% and CO reduction of 45%, and NO_x reduction up to 5-10% was achieved in this work

Form this work, it is recommended that L-aspartic acid is effective in controlling CO_2 emissions. The CO_2 control by a postcombustion method was successfully demonstrated in this work. It is concluded that CO_2 reduction by wet scrubbing can be an effective method to reduce CO_2 over the amine solutions. In future work, the CO_2 reduction tarp will be evaluated for back pressure analysis in CFD. And in experimental, many different biodiesels will be used in diesel engines, and their emission concentrations will be tested with the CO_2 reduction trap.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was performed as a part of the Employment of Kombolcha Institute of Technology, Wollo University, Kombolcha, Amhara, Ethiopia.

References

[1] K. S. Sivaraman and S. Shanmuga Priya, "CO_2 sequestration of vehicular exhaust using synthesized adsorbent," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 4, no. 5, pp. 2833–2839, 2015.

[2] "EPA, USA," 2021, https://www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-temperature.

[3] A. Samimi and S. Zarinabadi, "Reduction of greenhouse gases emission and effect on environment," *The Journal of American Science*, vol. 8, no. 8, pp. 1011–1015, 2012.

[4] G. Liu, Ed., *Greenhouse Gases: Emission, Measurement and Management*, BoD–Books on Demand, 2012.

[5] C. Lin, L. Zhang, and Z. Zhang, "The impact of the rise of emerging economies on global industrial CO_2 emissions: evidence from emerging economies in regional comprehensive economic partnership," *Resources, Conservation and Recycling*, vol. 177, article 106007, 2022.

[6] Y. H. Teoh, H. Yaqoob, H. G. How, T. D. Le, and H. T. Nguyen, "Comparative assessment of performance, emissions and combustion characteristics of tire pyrolysis oil-diesel and biodiesel-diesel blends in a common-rail direct injection engine," *Fuel*, vol. 313, article 123058, 2022.

[7] R. Li, Z. Wang, and X. Guangju, "Study on carbonyl emissions of diesel engine fueled with biodiesel," *International Journal of Chemical Engineering*, vol. 2017, Article ID 1409495, 12 pages, 2017.

[8] S. Sharma, G. P. Rangaiah, and F. Maréchal, "Integrated multi-objective differential evolution and its application to amine absorption process for natural gas sweetening," in *Differential Evolution in Chemical Engineering: Developments and Applications*, pp. 128–155, World Scientific, 2017.

[9] M. Bui et al., "Carbon capture and storage (CCS): the way forward," *Energy & Environmental Science*, vol. 11, no. 5, pp. 1062–1176, 2018.

[10] P. Feron, Ed., *Absorption-Based Post-Combustion Capture of Carbon Dioxide*, Woodhead Publishing, 2016.

[11] M. Subramaniam, S. Satish, J. M. Solomon, and R. Sathyamurthy, "Numerical and experimental investigation on capture of CO2and other pollutants from an SI engine using the physical adsorption technique," *Heat Transfer*, vol. 49, no. 5, pp. 2943–2960, 2020.

[12] P. S. Kumar, J. A. Hogendoorn, P. H. M. Feron, and G. F. Versteeg, "Equilibrium solubility of CO_2 in aqueous potassium taurate solutions: Part 1. Crystallization in carbon dioxide loaded aqueous salt solutions of amino acids," *Industrial & Engineering Chemistry Research*, vol. 42, no. 12, pp. 2832–2840, 2003.

[13] C. Bibin, Y. Devarajan, A. Bharadwaj, and P. Y. Patil, "Detailed analysis on nonedible waste feedstock as a renewable cutting fluid for a sustainable machining process," *Biomass Conversion and Biorefinery*, pp. 1–9, 2022.

[14] S. Sharma and F. Marechal, "Carbon dioxide capture from internal combustion engine exhaust using temperature swing adsorption," *Frontiers in Energy Research*, vol. 7, p. 143, 2019.

[15] M. Vijayaragavan, B. Subramanian, S. Sudhakar, and L. Natrayan, "Effect of induction on exhaust gas recirculation and hydrogen gas in compression ignition engine with simarouba oil in dual fuel mode," *International Journal of Hydrogen Energy*, vol. 47, pp. 1–13, 2021.

[16] J. Van Holst, P. P. Politiek, J. P. M. Niederer, and G. F. Versteeg, "CO_2 capture from flue gas using amino acid salt solutions," in *Proceedings of 8th international conference on greenhouse gas control technologies*, Trondheim, Norway, 2006.

[17] M. Karczewski, J. Chojnowski, and G. Szamrej, "A review of low-CO_2 emission fuels for a dual-fuel RCCI engine," *Energies*, vol. 14, no. 16, p. 5067, 2021.

[18] D. Hariharan, S. R. Krishnan, K. K. Srinivasan, and A. Sohail, "Multiple injection strategies for reducing HC and CO emissions in diesel-methane dual-fuel low temperature combustion," *Fuel*, vol. 305, article 121372, 2021.

[19] S. Muthiya, I. S. Jenoris, and G. Balachandran, *Experimental investigation in diesel oxidation catalyst by developing a novel catalytic materials for the control of HC, CO and smoke emissions. No. 2020-28-0458*, SAE Technical Paper, 2020.

[20] Y. Devarajan, B. Nagappan, G. Choubey, S. Vellaiyan, and K. Mehar, "Renewable pathway and twin fueling approach on ignition analysis of a dual-fuelled compression ignition engine," *Energy & Fuels*, vol. 35, no. 12, pp. 9930–9936, 2021.

[21] A. Einbu, T. Pettersen, J. Morud et al., "Energy assessments of onboard CO_2 capture from ship engines by MEA-based post combustion capture system with flue gas heat integration," *International Journal of Greenhouse Gas Control*, vol. 113, article 103526, 2022.

[22] M. A. Fayad, "Investigating the influence of oxygenated fuel on particulate size distribution and NOX control in a common-rail diesel engine at rated EGR levels," *Thermal Science and Engineering Progress*, vol. 19, article 100621, 2020.

[23] J. Park and O. Jungmo, "Study on the characteristics of performance, combustion, and emissions for a diesel water emulsion fuel on a combustion visualization engine and a commercial diesel engine," *Fuel*, vol. 311, article 122520, 2022.

[24] B. K. Selvan, M. Soni Das, R. Chandrasekar et al., "Utilization of biodiesel blended fuel in a diesel engine–combustion engine performance and emission characteristics study," *Fuel*, vol. 311, article 122621, 2022.