Journal of Mines, Metals and Fuels, *73(5): 1331-1341; 2025. DOI: 10.18311/jmmf/2025/48623*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Wet Scrubber System for Exhaust Gas Emission Reduction

Pushparaj S. Warke[1]*, Devendra M. Chaudhari[1], Vedant S. Naik[1], Deepti D. Patil[1], Sunil S. Dhokale[1], Kamalkishor G. Maniyar[1]* and Ganesh H. Patil[2]

[1]Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Pimpri, Pune - 411018, Maharashtra, India; pushparaj.warke@dypvp.edu.in

[2]Department of Electrical Engineering, Dr. D. Y. Patil Institute of Technology, Pimpri, Pune - 411018, Maharashtra, India

Abstract

Air pollution is a complex issue with numerous causes and effects and few remedies, which is exacerbated globally by environmental pollutants from automobiles, factories, and chemicals found in consumer goods. "Wet Scrubber" is one of the solutions utilised as a pollution control device. An apparatus called a wet scrubber eliminates impurities from flue gas and other gas streams. The scrubbing liquid and the dirty gas stream come into contact in a wet scrubber. To get rid of the impurities, the cleaning liquid is sprayed over the flue gas. The only air pollution management technology that can typically remove both gas pollutants and particulate matter is a wet scrubber. When a cleaning agent like lime or water is used, the big particles are easily caught since the dirty gases are soluble in the liquid. Although there are many different kinds of wet scrubbers, the design of Spray Towers is the focus of this paper. After tracking the air emissions with the intended parameters under varying conditions throughout time, the author of this work constructed the Spray Tower for a 100TPD cement factory using Vertical Shaft Technology (VSK). Over 95 percent of the Spray Tower's efficiency has been achieved through its design.

Major Findings: *It is a flexible solution in the battle against vehicle emissions because of its scalable architecture, which also permits possible uses across a range of vehicle types, from heavy-duty trucks to passenger cars. All things considered, the effective creation of such a system might greatly lessen the negative environmental effects of transportation, assisting international initiatives to lower carbon emissions and enhance air quality.*

Keywords: *Analysis, Apparatus, Gas Emission, System, Wet Scrubber*

1.0 Introduction

Citizens, particularly those who suffer from ailments brought on by exposure to air pollution, should be aware of the daily levels of air pollution. Furthermore, the support of a country's population, who are aware of the state of mitigation efforts and the local and national air pollution issues, is essential to the country's ability to improve air quality[1,2] Therefore, a straightforward but efficient way to communicate the air quality is critical for citizens, particularly those who suffer, to be aware of the daily levels of air pollution[3,4]. For air quality communication and decision-making, several nations adopt the idea of an Air Quality Index (AQI), which converts weighted values of various air pollution-related criteria (such as SO_2, CO, visibility, etc.) into a single number or collection of numbers[5,6]. An AQI system is developed following a review of the literature (on AQI),

**Author for correspondence*

air quality monitoring methodologies and processes, Indian National Air Quality Standards (INAQS), and the dosage response relationships of contaminants. The maximal operator of a function, or choosing the maximum of sub-indices of various pollutants to create an overall AQI, is the foundation of the AQI system[7,8]. An AQI's goal is to rapidly (nearly instantly) distribute information about air quality, which includes accounting for pollutants that have immediate effects. For the near real-time distribution of AQI, eight factors with short-term standards (PM10, PM2.5, NO_2, SO_2, CO, O_3, NH_3, and Pb) have been taken into consideration[9,10]. It is acknowledged that Pb concentrations in the air cannot cause AQI because they are not known in real time[11,12]. As seen below, the suggested index comprises six categories with a sophisticated colour scheme, Good (0-50), Acceptable (51-100), Mildly Polluted (101-200), Impoverished (201-300), Extremely Impoverished (301-400) and Extreme (> 401)[13-15].

To determine breakpoint amounts for every AQI category, a scientific foundation for meeting air quality standards and dose-response relationships of different pollutant characteristics has been developed[16,17]. It is suggested that AQI be reported for as many metrics as feasible in almost real-time for continuous air quality stations. The daily AQI for manual stations is released one week behind schedule to guarantee that manual data are examined and accessible for AQI[17,18]. To provide consistency and clarity on data sources, AQIs from continuous or manual stations must be identified. For a prompt, easy, and visually appealing response to an AQI query, a web-based AQI dissemination system has been designed. The website's other functions include health impacts, contaminants that exceed regulations, and the reporting of pollutants that are accountable for the index[19,20].

1.1 Objectives

The primary objective of utilising wet scrubbers for NOx emission control is to facilitate the chemical reaction between NOx compounds and water, leading to their conversion into less harmful substances such as nitrites and nitrates. By introducing water droplets into the exhaust gas stream, wet scrubbers create a large interfacial area for mass transfer, enhancing the absorption of NOx compounds into the liquid phase. The subsequent neutralization of NOx species through chemical reactions contributes to the overall reduction in NOx emissions from industrial sources.

2.0 Literature Review

The history and background of the design and experimental study of wet scrubber systems for exhaust gas temperature reduction by spraying water with a NOx mixture using an experimental model can be traced back to the increasing awareness of environmental pollution and adverse effects on health and the ecosystem[21,22]. Wet scrubbers have long been recognised as effective pollution control devices for removing particulate matter, sulfur dioxide (SO_2), and other harmful pollutants from industrial exhaust gases[23,24]. However, the focus on reducing NOx emissions and exhaust gas temperatures through wet scrubber systems has gained prominence in recent years due to stricter environmental regulations and the growing concern over air quality and climate change[25,26].

In the realm of environmental engineering, the reduction of pollutants emitted from industrial processes stands as a paramount challenge. Among these pollutants, Nitrogen Oxides (NOx) present a significant environmental and public health concern due to their contribution to smog formation and adverse respiratory effects[27,28]. Wet scrubber systems have emerged as promising solutions for mitigating NOx emissions while also addressing the issue of elevated exhaust gas temperatures, which can have detrimental effects on equipment and the environment[29,30]. By introducing water droplets into the exhaust gas stream, wet scrubbers facilitate the absorption of NOx compounds into the liquid phase, where subsequent chemical reactions occur, leading to their neutralisation[31,32].

By offering comprehensive insights into the flow behavior, heat transfer processes, and chemical reactions taking place within the scrubber, the integration of experimental research employing A software has completely changed the design and optimisation of wet scrubber systems[33,34]. Experimental simulations allow engineers to visualise and analyse complex fluid flow phenomena, such as turbulence, mixing, and droplet dynamics, which are critical for understanding the

performance of wet scrubber systems under different operating conditions[35,36].

2.1 Literature Summary

A survey of existing literature reveals a growing body of research focused on the design and experimental study of wet scrubber systems for exhaust gas temperature reduction and NOx emission control[37,38]. Studies have investigated various aspects of wet scrubber design, including spray nozzle configurations, droplet size distributions, residence time, and mixing efficiency, to optimise the performance of the scrubber in terms of NOx removal efficiency and energy consumption[39,40]. Furthermore, researchers have explored different chemical reaction mechanisms and kinetics to accurately model the absorption and neutralisation of NOx species within the scrubber[41,42].

2.1.1 "Wet Scrubbers – Design of Spray Tower to Control Air Pollutants" by Dr. Akshey Bhargava.

To control air pollutants, Akshey Bhargava researched spray tower designs and suggested that wet scrubbers are suitable and efficient devices for controlling air pollution because they can stop the release of harmful gases and particulates from industrial processes. Although there are many different kinds of wet scrubbers, the design of Spray Towers is the focus of this paper. After tracking the air emissions in relation to the intended parameters under varying conditions throughout time, the author of this work constructed the Spray Tower for a 100 TPD cement factory using Vertical Shaft Technology (VSK). Over 95 percent of the Spray Tower's efficiency has been achieved through its design[43,44].



Figure 1. Typical scrubber bar[3].

To reduce particulate matter emitted from a cement factory in the State of Rajasthan with a capacity of 100TPD based on Vertical Shaft Kiln Technology (VSK), the author has attempted to construct a Spray Tower as a wet scrubbing device. The Spray Tower was chosen because it was thought to be appropriate for controlling particulate matter, since the particulate matter from these VSK plants has moisture. Therefore, the Spray Tower was intended to reduce the starting concentration of particulate matter from 2000 mg/Nm3 to an outlet concentration of 100 mg/Nm3, resulting in an efficiency of 95 percent. This has caused the pollution level to drop well below the 250 mg/Nm3 recommended limit, making it safe. To regulate particle matter below acceptable limits, such Spray Towers can be constructed and placed in small cement plants based on VSK[45,46].

2.1.2 "An Experimental Study of Parameters of Wet Scrubber for Environmental Benefit

Faraz Ahmad *et al.* looked at an experimental study of wet scrubber parameters for environmental benefit and concluded that, globally, air pollution is a complex issue with many causes and effects and few solutions. Environmental pollution is caused by automobiles, industries, and chemicals from consumer goods. "Wet scrubbers" are among the most widely utilised pollution control systems in industry and transportation. One tool for eliminating contaminants from furnace flue gas or other gas streams is a wet scrubber. The scrubbing liquid and the dirty gas stream come into contact in a wet scrubber. To get rid of the impurities, the cleaning liquid is sprayed over the flue gas. The only air pollution management technology that can typically remove both gas pollutants and particulate matter is a wet scrubber. When a cleaning agent like lime or water is used, the big particles are easily caught since the dirty gases are soluble in the liquid[47,48].

2.1.3 *"Study of a Wet Scrubber Network in the Air Remediation of Industrial Workplaces: Benefit for the City Air Quality"*

In their investigation on the benefits of a wet scrubber network for improving the air quality in urban areas, Avveduto *et al.* concluded that industrial operations conducted in confined spaces are typified by a certain kind of air pollution. Long-term exposure to this type of pollution is frequently quite detrimental, having a significant impact on safety and health. Usually installed at the emission locations, indoor industrial abatement systems are used to filter the air. After processing, the air is released outdoors. The three-stage wet scrubber systems that were installed in the industrial workplaces of a waste-to-energy plant, which has a very high particulate matter level, and a fiberglass processing plant, where the highest exposure levels to volatile compounds are currently monitored, are the experimental results of this study. The technology that has been adopted to be utilised as a supplementary strategy does not require particular disposal procedures, and the workers profit from the fact that the processed air is re-emitted in the same building. In the two environments under investigation, the scrubber network's operation during working activities has a) decreased the level of volatile compounds by roughly 40% and b) kept the particulate matter concentration PM > 1 at a very low level. Megacities are home to numerous industrial plants, which are hazardous sources of diffuse pollution emissions. The air quality of our cities greatly benefits from the remediation of extremely polluted industrial plants located within our towns, particularly for the emissions that are typically left untreated[49,50].

2.1.4 *Performance Evaluation of Wet Scrubber System for Industrial Air Pollution*

After evaluating the effectiveness of a wet scrubber system for controlling industrial air pollution, Bashir Ahmed Danzomo *et al.* concluded that the concentrations of pollutants released from industrial production are typically toxic and hazardous, which can pose a serious risk to human health in addition to respiratory conditions like asthma, bronchitis, and tuberculosis, as well as to plant photosynthesis. Using information gathered from the cement sector, a pilot scrubber system for PM10 control

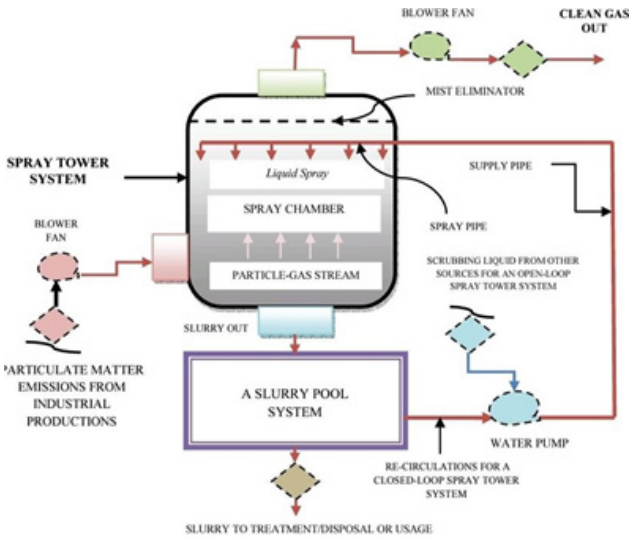


Figure 2. Wet scrubber process in the pray tower scrubber system[5].

has been constructed in this study. Using Langmuir's approximations and a model for the total collection efficiency of the countercurrent scrubber system, the system's performance was predicted by taking into account droplet sizes of 500, 1000, 1500, and 2000μm. The range of liquid to gas ratios suggested by the US Environmental Protection Agency (EPA) has been used to determine the ideal ratio for the system's best performance[51,52].

Negative collection efficiency for the 1μm dust particle was obtained because of reversed flow in the Langmuir's approximation. The highest collection efficiency for 5μm and 10μm dust particles was found to be 99.988% and 100,000% at 500μm droplet size and 2.7 l/m3, while the lowest was found to be 43.808% and 58.728% at 2000μm droplet size and 0.7 l/m3. The World Health Organisation (WHO) PM10 air quality standard was then used to confirm the scrubber system's anticipated performance[53,54].

2.1.5 *Evaluating the Performance of a Turbulent Wet Scrubber for Scrubbing Particulate Matter*

With a 36cm liquid head and a 7 m^3/min gas flow rate, a maximum pressure drop of 217mm H_2O was recorded. Except for smaller particles, the contacting power attained by the turbulent scrubber is superior, according to the Number of Transfer Units (NTU) analysis for the

efficiencies attained over the particle range. Compared to other conventional or higher energy scrubbers, the turbulent scrubber is more effective in removing particulate matter, especially PM2.5, and it uses about the same amount of energy as other wet scrubbers of its type. The turbulent scrubber is being evaluated to bring a new scrubber to the list of wet scrubbers for industrial applications that is easy to use, simple to construct, more compact, and has excellent efficiency while using less energy. Therefore, if the gases are soluble in the medium employed for particle capture, the turbulent scrubber can be utilised to absorb gaseous pollutants in addition to fighting particulates from industrial gaseous effluents.

2.1.6 Treatment of Air Discharges

Scrubbers use several methods to remove the dusty gas particles, such as contact with wet solid surfaces or water droplets produced by spray nozzles and liquid stream disruption (venturi scrubbers). Compared to venturi scrubbers, tray scrubbers are a little more comprehensive. For some air streams, tray scrubbers can be employed as the sole treatment or as pretreatment. A tray scrubber's essential components comprise a set of trays, which may be perforated, and a set of orifices, sometimes known as nozzles. Tray scrubbers eliminate particles from gas streams using the following mechanism: The trays are coated with the scrubber fluid, and the gas stream is directed onto them by orifices or nozzles. The gas stream's velocity increases fairly abruptly as it passes through the orifices. The particles are taken out of the air stream by inertia, which carries them into the scrubber fluid. A second function of the gas's high velocity as it hits the fluid-covered plates is to make the fluid frothy, which significantly increases the fluid's surface area and, consequently, particle-capture efficiency.

2.1.7 Using Circular Economy Principles to Recycle Materials in Guiding the Design of a Wet Scrubber-Reactor for Indoor Air Disinfection from Coronavirus and other Pathogens

There is a pressing need to find quick fixes to stop the coronavirus from spreading more quickly, particularly in indoor spaces like workplaces, hospitals, and airports.

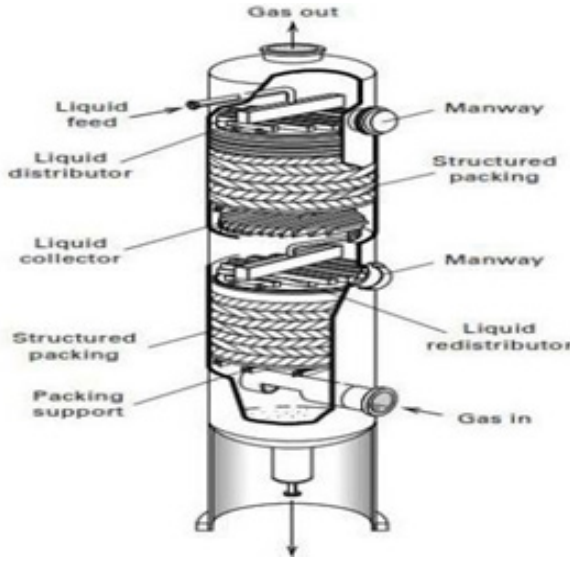


Figure 3. Wet scrubber-reactor for indoor air disinfection[7].

Disinfecting the air, particularly indoors, could be one such step. The purpose of this work is to use the concepts of the circular economy to suggest a new design for a wet scrubber-reactor that will deactivate airborne bacteria. The technology here will destroy airborne microorganisms (bioaerosols) like SARS-CoV-2 based on Fenton's reaction mechanism.

The highly porous clay-glass open-cell structure used in the suggested design is a readily replicable and reasonably priced material. This method's basic idea is the in-situ breakdown of hydrogen peroxide into free radicals and extremely reactive oxygen species. A customised ceramic structure's high porosity creates a large surface area for contact with supplied contaminated air, free radicals, and atomised oxygen. It is demonstrated that the design satisfies the requirements for accomplishing sustainable development goals.

3.0 Proposed System

While Wet Scrubbers are effective at removing particulate matter and certain gases like SO_2 and NO_x, the efficiency of removal for other pollutants, such as Volatile Organic Compounds (VOCs), ammonia, or heavy metals, remains an area of improvement. Development of more effective scrubbing liquids that can target a broader range of pollutants. Research into hybrid systems that

combine Wet Scrubbers with other air pollution control technologies to improve overall efficiency. Optimisation of scrubber designs for enhanced mass transfer and contact time between the exhaust gases and the scrubbing liquid. Wet Scrubbers typically generate wastewater that contains pollutants and can require complex treatment before disposal or reuse. This is particularly problematic in water-scarce regions or industries with high emission loads. The hydrodynamics and flow patterns within Wet Scrubber systems are crucial for their efficiency, but are often not well understood or optimized. Inadequate fluid flow can lead to reduced contact time between the gas and the scrubbing liquid, thus lowering pollutant removal efficiency.

3.1 Objectives of the System

- To create a robust exhaust gas purification system that integrates a wet scrubber and carbon filters, ensuring optimal removal of pollutants and reduction of gas temperature.
- To utilise a water and NaOH mixture sprayed in the first chamber to neutralise acidic gases and capture particulate matter.
- To achieve significant temperature reduction of the exhaust gases through the wet scrubbing process.
- To circulate the scrubbed exhaust gas through carbon filters in the second chamber to adsorb residual pollutants and fine particulates.
- To develop a prototype of the system and validate its performance against emission standards and operational efficiency criteria.

3.2 Methodology

The methodology for the design and experiment study of a wet scrubber system aimed at reducing exhaust gas temperature by spraying water with a NOx mixture using experimental modal typically involves several key steps:

1. Problem definition and objectives clearly define the objectives of the study, including the desired reduction in exhaust gas temperature and NOx emissions. Identify the specific operating conditions and design parameters to be investigated.

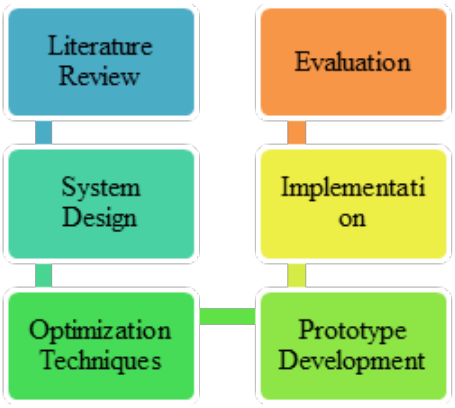


Figure 4. Methodology[9]

2. Geometry and mesh generation develop the 3D geometry of the wet scrubber system, including the inlet and outlet ducts, spray nozzles, baffles, and any other relevant components, using CAD software. A high-quality computational mesh that accurately captures the geometry's details and ensures convergence of the experiment is generated.
3. Boundary conditions and operating parameters specify the inlet conditions for the exhaust gas stream, including temperature, velocity, and composition (e.g., NOx concentration). It defines the properties of the water spray, such as flow rate, droplet size distribution, and spray angle. It also sets boundary conditions for the walls, including thermal properties and surface roughness.
4. Simulation of heat transfer and fluid flow transport in the wet scrubber system can be simulated using the experimental model. Utilising suitable turbulence models (such as the Reynolds-averaged Navier-Stokes or k-epsilon models), solve the continuity, momentum and energy equations associated with fluid dynamics. Add multiphase flow modeling to take into consideration the interplay between the liquid phase (water spray) and gas phase (exhaust gas).
5. Chemical reactions and species transport implement chemical reaction models to simulate the absorption of NOx compounds into the water phase and their subsequent neutralisation. Define species transport equations to track the concentrations of NOx species and other pollutants throughout the domain. Consider the

kinetics of chemical reactions and mass transfer processes between the gas and liquid phases.

6. Sensitivity study and optimisation conduct sensitivity analyses to assess the impact of varying design parameters (e.g., spray nozzle configuration, water flow rate) on the performance of the wet scrubber system. Utilise optimisation techniques, such as parametric studies or response surface methodologies, to identify optimal design configurations that maximise exhaust gas temperature reduction and NOx removal efficiency.
7. Validation and verification validate the experiment simulations by comparing the predicted results with experimental data or analytical solutions, if available, for relevant test cases. Verify the accuracy and reliability of the numerical predictions by assessing convergence, grid independence, and sensitivity to modeling assumptions.
8. Study of the results and conclusions analyses the experiment results to evaluate the effectiveness of the wet scrubber system in reducing exhaust gas temperature and NOx emissions under different operating conditions. The study concludes the impact of design parameters on system performance and provides recommendations for optimising the design and operation of wet scrubber systems for exhaust gas treatment.

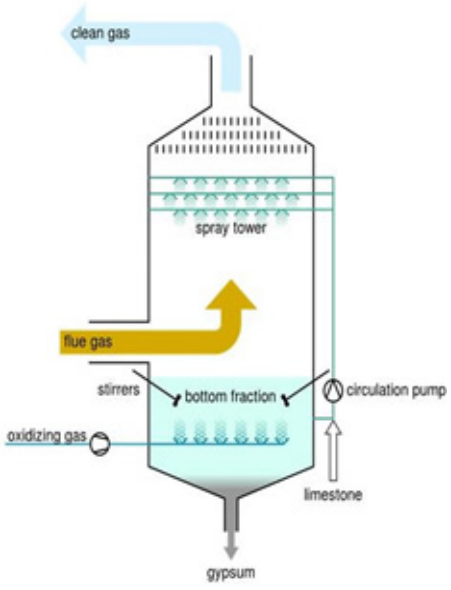


Figure 5. Existing system[11].

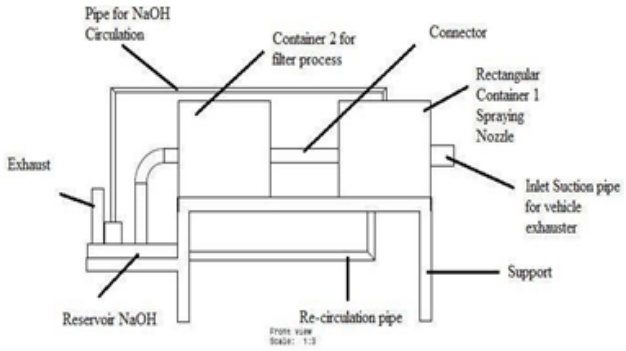


Figure 6. Concept design[13].

4.0 Working of Proposed Method

After leaving the car, the exhaust enters circuit 1. The exhaust is being sprayed from above with liquid NaOH. SO_2 reacts with HC and NaOH as it moves through the baffles. To a certain degree, it eliminates the Sox and HC contaminants. After that, it moves on to circuit 2, where cotton is positioned on the baffles using an aluminum net. It is trapped by carbon particles, which extract the carbon. After that, it exits the NaOH reservoir, which eliminates Sox contaminants. At the base of circuit 1, drainage pipes are available. They are attached to a reservoir so that liquid NaOH can circulate continuously. Finally, the natural air is permitted to enter the atmosphere.

4.1 Components Used in the System

System uses components like L-angle or hollow frame, sheet metal or acrylic transparent sheet for making Wet Scrubber chamber, PVC pipes, mini diaphragm water pump, digital temperature sensor, nozzles, storage for water and NaOH mixture, carbon filters, inlet and outlet pipes for exhaust gas circulation.

4.2 Application of System

Reduces carbon content from the exhaust gas. This can be mounted in the public sector, Wet Scrubbing is done via a pump base. It is cost-effective and easy to install.

5.0 Benefits of the Wet Scrubbing

5.1 Good Health and Well-Being

Sulfur dioxide and particulate matter, two dangerous air pollutants that can lead to respiratory disorders and other

health concerns, are reduced by wet scrubbing. The wet scrubbing system is crucial in lowering air pollutants and toxic emissions from industrial operations that are bad for human health, like sulfur oxides, nitrogen oxides, and particulate matter.

5.2 Clean Water and Sanitation

Wet scrubbers use water or aqueous solutions to capture and remove pollutants from exhaust gases. While the system helps clean the air, it also requires proper water management to avoid contamination. This system utilises water in the form of a NaOX-water solution for scrubbing pollutants, and the recycling of this solution in the closed-loop storage tank with the pump optimises water usage and minimises waste.

5.3 Affordable and Clean Energy

By reducing emissions from industrial plants, including power generation facilities, wet scrubbers support the transition to cleaner energy. Wet scrubbers help industries manage emissions that result from energy production, particularly those using fossil fuels.

5.4 Sustainable Cities and Communities

Wet scrubbers improve air quality by removing airborne pollutants, which is crucial for creating healthier, more sustainable urban environments. Reducing air pollution contributes to safer and more livable cities. This system contributes to improved urban air quality, which is essential for sustainable cities.

5.5 SDG 13: Climate Action

Wet scrubbing reduces the release of pollutants that contribute to climate change, such as sulfur dioxide, which can form acid rain. By controlling emissions, the technology indirectly supports efforts to mitigate climate change. By capturing pollutants from flue gases, the system directly reduces greenhouse gas emissions and mitigates the overall impact on global warming.

5.6 Life on Land

Wet scrubbers help reduce air pollution that can deposit harmful substances onto land, including heavy metals and acid rain. This helps protect terrestrial ecosystems, reducing soil and plant contamination. Pollutants from industrial flue gases can deposit on soil and plants, adversely affecting ecosystems, agriculture, and biodiversity.

6.0 Conclusions

The design and development of a wet scrubbing system for vehicle exhaust gas reduction presents an effective solution to address the growing concerns over air pollution and vehicle emissions. By utilising a wet scrubbing mechanism, harmful pollutants such as particulate matter, NOx, and sulfur compounds can be effectively removed from the exhaust gases before being released into the atmosphere. The system's ability to capture and neutralise these pollutants ensures that vehicles comply with stringent environmental standards, thus contributing to cleaner air and improved public health. Through the integration of efficient scrubbing liquids, optimised flow dynamics, and advanced filtration materials, the wet scrubbing system demonstrates both high efficiency and sustainability.

Furthermore, its scalable design allows for potential applications across various types of vehicles, from passenger cars to heavy-duty trucks, making it a versatile solution in the fight against vehicle emissions. Overall, the successful development of such a system holds the potential to significantly reduce the environmental impact of transportation, supporting global efforts toward reducing carbon footprints and improving air quality.

7.0 References

1. Arshad AK, Hussain N, Ashraf MH, Saleem MZ. Air pollution and climate change as grand challenges to sustainability. Sci Total Environ. 2024; 928:172370. https://doi.org/10.1016/j.scitotenv.2024.172370 PMid:38604367.
2 Imam M, Adam S, Dev S, Nesa N, Air quality monitoring using statistical learning models for sustainable environment. Int J Intell Syst. 2024; 22(200333). https://doi.org/10.1016/j.iswa.2024.200333
3. National ambient air quality status and trends; 20219.
4. Praveen S, Jegan J, Bhagavathi Pushpa T. Air quality index for environmental impact assessment of the port

development at Beypore. Indian Journal of Ecology. 2018; 45(4):768-773.
5. National air quality index, control of urban pollution series, CUPS/82/2014-15.
6. Sharma R *et al*. Inferring air pollution from air quality index by different geographical areas: Case study in India. Air Qual Atmos Health. 2019; 12:1347-1357. https://doi.org/10.1007/s11869-019-00749-x
7. Sharma M, Maheshwari M, Sengupta B, Shukla BP, Design of a website for dissemination of air quality index in India. Environ Model Softw. 2003; 18(5):405-411. https://doi.org/10.1016/S1364-8152(03)00003-3
8. Pak S, Chang K. Performance estimation of a venturi scrubber using a computational model for capturing dust particles with liquid spray. J Hazardous Mater. 2006; 138(3):560-573. https://doi.org/10.1016/j.jhazmat.2006.05.105 PMid:16860933.
9. Ali M, Yan C, Sun Z, Wang J, Gu H. CFD simulation of dust particle removal efficiency of a venturi scrubber in CFX Nucl Eng Design. 2013; 256:169-177. https://doi.org/10.1016/j.nucengdes.2012.12.013
10. Supaporn W *et al*. Parametric analysis and design optimization of wet SOx scrubber system in the marine industry. Fuel. 2021; 304: 121369. https://doi.org/10.1016/j.fuel.2021.121369
11. Ali M, Yan C, Sun Z, Gu H, Mehboob K Dust particle removal efficiency of a venturi scrubber. Ann Nucl Energy. 2013; 54:178-183. https://doi.org/10.1016/j.anucene.2012.11.005
12. Lehner M. Aerosol separation efficiency of a venturi scrubber working in self-priming mode. Aerosol Sci Technol. 1998; 28(5):389-402. https://doi.org/10.1080/02786829808965533
13. Mukherjee S, Siddiqi H, Maiti P, Parmar P, Meikap BC, A comprehensive analysis of removal of hazardous dust particulates from chemical and process industries off gases by advanced wet scrubbing techniques - A review. J Loss Prev Process Ind. 2024; 91(105406). https://doi.org/10.1016/j.jlp.2024.105406
14. Maniyar KG, Ingole DS. Influence of EDM control factors for aluminium hybrid composites. Lect Notes Multidiscipl Indust Eng. 2018; 275-284. https://doi.org/10.1007/978-3-319-76276-0_27
15. Maniyar KG. An experimental analysis of aluminium hybrid metal matrix composites, Mater Today Proc. 2024. https://doi.org/10.1016/j.matpr.2024.01.021
16. Maniyar KG, Marode RV, Chikalthankar SB. Optimization of EDM process parameters on MRR and TWR of Tungsten Carbide by Taguchi method. Int J Eng Adv Technol. 2016; 5:112-116. https://doi.org/10.1016/j.matpr.2024.01.021
17. Maniyar KG. Analysis of EDM process parameters on material removal rate of WC. 2nd Nat Conf Recent Inno Sci Eng. 2017; 5(9):37-39.
18. Maniyar KG, Agrawal SK, Ingole DS. Optimization of multiple performance characteristics in EDM: A critical literature review. Int J Innov Technol Explor Eng. 2016; 5(10):27-33.
19. Maniyar KG, Deore HV. Design and testing of carbon fiber composite material with comparative analysis. Int Res J Eng Tech. 2020; 7(8):1120-1122.
20. Maniyar KG, Ingole DS. Current research development in machining of hybrid metal matrix composites: A review. Int J Recent Innov Trends Comput Commun. 2016; 4(7):150-154.
21. Jadhav PA, Maniyar K, Evaluation and characterization of aluminum silicon carbide Metal Matrix Composites. AIP Conf Proc. 2024. https://doi.org/10.1063/5.0227945
22. Maniyar K, Jadhav P, Biradar R, Gawande J. An experimental study of process parameters for nano composites. Nano World J. 2024; 10(S1):S209-S211.
23 . Maniyar K, Jadhav P, Biradar R, Gawande J. Effect of nano-lubricants on journal bearing for performance enhancement. NanoWorld J. 2024; 10(S1):S206-S208.
24. Maniyar K, Suhane S. Parametric analysis of electric discharge machining for nano composites. Nano World J. 2024; 10(S1):S63-S65.
25. Maniyar K, Puri A, Pawar P, Patil V, Jadhav P, Patil G, *et al*. The comprehensive study for machining of metal matrix composites. AIP Conf Proc. 2024; 3196:040005. https://doi.org/10.1063/5.0227955
26. Maniyar K, Warke P, Jadhav P, Waware S, Harsur S, Biradar R. An extensive study of mechanical properties and tribological characteristics for hybrid composites. AIP Conf Proc. 2024; 3203:030038. https://doi.org/10.1063/5.0224994
27. Maniyar K, Pawar P, Kolhe P, Ingale M, Patil P, Sarode G. The comprehensive study of synthesis and characterization of hybrid nano fluids. AIP Conf Proc. 2024; 3149: 030048. https://doi.org/10.1063/5.0224988
28. Priti R. Ghutepatil; Sarika Khapare; Rujuta Barve Joshi; Kamalkishor G. Maniyar. A critical review of nanotechnology in various fields of engineering. AIP Conf Proc. 2024; 3149:030002. https://doi.org/10.1063/5.0224984
29. Thamke V, Saravade N, Banarase S, Maniyar K. Seismic performance and cost analysis of AAC blocks vs. fly ash bricks: A comparative study utilizing STAAD

pro. AIP Conf Proc. 2024; 3196:060006. https://doi.org/10.1063/5.0227895
30. Banarase S, Banarase M, Saravade N, Thamke V, Maniyar K. Evaluation of concrete building strengthening through non-destructive testing methods - A case study. AIP Conf Proc. 2024; 3196: 040001. https://doi.org/10.1063/5.0227927
31. Maniyar KK, Harsur SK, Shinde SN, Shaaikh JA, Chandan MN, Rupanar S. An experimental investigation of machining parameters on aluminum composites. J Polym Compos. 2024; 12(06):8-13.
32. Maniyar KK, Harsur. SK Experimental findings of the EDM process parameters for metal matrix composites. J Polym Compos. 2024; 12(06):14-18.
33. Saravade N, Sedani C, Maniyar K, Nandkishore D, Deshmukh S, Rupanar S, Gidhad B, Surase S. Study on heavy machinery utilizing the most recent technologies for excavation of road construction and mining. J Mines Met Fuels. 2024; 72(7):667-673. https://doi.org/10.18311/jmmf/2024/45327
34. Patil GH, Mishra E, Maniyar K, Rawoot M, Satarkar MFAR. (2024). Study on prediction of lightning impulses on transmission line tower due to harsh field and variable working condition, environmental condition and tower footing resistances. J Mines Mets Fuels, 72(7), 763-769. https://doi.org/10.18311/jmmf/2024/45322
35. Jathar A, Maniyar K, Nawghare B, Ansari S, Ghute Patil P, Mali C, Biradar R, Deshmukh S, Surase S, Gaikar S. (2024). An extensive study of nanomaterial and nanotechnology in the various fields of engineering. J Mines Mets Fuels. 2024; 72(10):1067-1074. https://doi.org/10.18311/jmmf/2024/45658
36. Nawghare B, Maniyar K, Jathar A, Mali C, Pawar D, Jadhav SP, Deshmukh S, Rupanar S, Biradar R, Gawande J, Warghat S. An extensive study of nano fluids and their applications in real life. J Mines Mets Fuels. 2024; 72(10):1119-1124. https://doi.org/10.18311/jmmf/2024/45407
37. Raut P, Maniyar K, Kakade S, Rupanar S, Bhalake S, Mali C, Deshmukh S, Biradar R. A comprehensive analysis of the synthesis, properties and uses of nanofluid. J Mines Mets Fuels. 2024; 72(9):965-971. https://doi.org/10.18311/jmmf/2024/45524
38. Warghat S, Sedani C, Rasane A, Maniyar K, Dhanwate V, Jadhav SP, Deshmukh S, Gawande J, Biradar R. (2024). An extensive study of metal matrix composites and their various properties for different uses. J Mines Mets Fuels. 2024; 72(9):949-955. https://doi.org/10.18311/jmmf/2024/45554
39. Mali C, Maniyar K, Rupanar S, Jathar A, Nawghare B, Kakade N, Modak G, Bhambere V, Deshmukh S, Gawande J, Biradar R. An analysis of nanoparticles in composite materials. J Mines Mets Fuels. 2024; 72(11):1215-1223. https://doi.org/10.18311/jmmf/2024/45579
40. Patil G, Mishra E, Maniyar K, Warke P. Four quadrant operation of induction motor using h-bridge in harsh and noxious environment field with dust, voltage fluctuation and major load variations. J Mines Mets Fuels. 2024; 72(11):1225-1231. https://doi.org/10.18311/jmmf/2024/45557
41. Mhaske M, Gidhad B, Maniyar K, Ghuge G. The role of linear algebra in developing machine learning solutions. 3rd International Conference for Advancement in Technology (ICONAT), Goa, India, 2024; 1-5. https://doi.org/10.1109/ICONAT61936.2024.10775140 PMid:38258445.
42. Ansari S, Vaidya K, Kadu A, Rokade A, Maniyar K. A comprehensive study on modern electronic technologies in the field-based engineering industry. J Mines Mets Fuels. 2025; 73(2):455-465. https://doi.org/10.18311/jmmf/2025/47122
43. Ghodke BS, Maniyar K, Using GeoGebra and SageMath to assist engineering students in tracing different curves and solving numerical methods, communications on applied nonlinear analysis. 2025; 32(6). https://doi.org/10.52783/cana.v32.3310
44. Kakade N, Gaikwad D, Sayyad S, Sedani C, Sayyad F, Rupanar S, Bangar N, Maniyar K, Thermal analytical characterization of gymnema sylvestre using TGA-DTA technique, communications on applied nonlinear analysis. 2025; 32(6-7). https://doi.org/10.52783/cana.v32.3492
45. Maniyar K, Rupanar S, Sayyad F, Sedani C, Gawande J, Pawar P. An analysis of machining parameters for metal matrix composite. J Polym Compos 2025; 13(02):76-85.
46. Maniyar KG, Ingole DS. Mathematical modeling and optimization of EDM process parameters for aluminium hybrid composites. Mater Today Proc. 2018; 5:27700-27709. https://doi.org/10.1016/j.matpr.2018.10.004
47. Maniyar KG, Ingole DS. Multi-response optimization of EDM process parameters for aluminium hybrid composites by GRA. Mater Today Proc. 2018; 5:1983643. https://doi.org/10.1016/j.matpr.2018.06.347
48. Maniyar KG, Ingole DS. Investigation of EDM process parameters for hybrid metal matrix composites. IOP Conf Ser Mater Sci Eng. 2018; 377:012204. https://doi.org/10.1088/1757-899X/377/1/012204

49. Patil S, Kute U, Jakhete M, Ansari S, Maniyar K, Chimkode S, Modak G, Bhambere V, Kolte R, Warghat S, Desai S, Mathur J, Warke P, Patil G, Mishra E. The role of internet of things, cloud computing, artificial intelligence and robotics in the fourth industrial revolution. J Mines Met Fuels. 2025.
50. Mishra E, Jog P, Bugade VS, Patil GH, Jarad RS, Kulkarni B, Maniyar K. Case study on role of solar energy in greenhouse gas emissions reduction in India, Journal of Information Systems Engineering and Management. 2025; 10(19):462-471. https://doi.org/10.52783/jisem.v10i19s.3058
51. Mishra E, Patil GH, Chavan SD, Jarad RS, Satarkar M, Thakare M, Maniyar K. Analysis of impact of STATCOM on distance relay using MATLAB. J Mines Met Fuels. 2025; 73(3):743–750. https://doi.org/10.18311/jmmf/2025/48052
52. Kadam J, Phadtare G, Pawar A, Maniyar K. Offline signature verification using siamese neural network. J Inform Systems Eng. 2025; 10(26s):431-439. https://doi.org/10.52783/jisem.v10i26s.4245
53. Patil G, Upasani S, Vaidya H, Desai K, Satarkar MFAR, Mishra E, Maniyar K. DTMF phone call control home appliance using arduino and GSM Module and home automation. J Inform Systems Eng. 2025; 10(25s):249-257. https://doi.org/10.52783/jisem.v10i25s.3976
54. Choudhari RM, Chopde PV, Kharche NA, Shekokar SR, Kharche YA, Warke P, Maniyar K, Patil G. Determinant factors for the development of rural entrepreneurship. J Inform Systems Eng. 2025; 10(25s):111-118. https://doi.org/10.52783/jisem.v10i25s.3951