
DEVELOPMENT OF A CYCLONIC LIQUID SPRAY SCRUBBER FOR EMISSION CONTROL

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ABSTRACT

This study presents the design, fabrication, and performance evaluation of a cyclonic liquid spray scrubber for controlling exhaust emissions from an internal combustion engine. The scrubber was fabricated from mild steel and equipped with an exhaust gas inlet and outlet. Its performance was evaluated using the exhaust emissions from a four-stroke, single-cylinder gasoline engine. Emission measurements were conducted using a Brain Bee Automotive Gas Analyzer located in the Heat Engine Laboratory, Department of Mechanical Engineering, Ahmadu Bello University, Zaria. The scrubber was connected to the engine exhaust system, and emission levels were measured under identical operating conditions with and without the scrubber. The results showed that the scrubber reduced the concentrations of carbon monoxide (CO), carbon dioxide (CO₂), and unburned hydrocarbons (HC) by 15.6%, 9% and 19% respectively and surprisingly increased excess oxygen (O₂) emissions by approximately 2%. The average equivalence ratio decreased from 0.2595 without the wet scrubber to 0.2250 with the wet scrubber. Although the prototype exhibited demonstrable effectiveness under the test conditions, the study establishes the feasibility of developing a cyclonic liquid spray scrubber for exhaust gas treatment. With further optimization of its design and operating parameters, the system has the potential to reduce emissions from both stationary and mobile combustion sources.

Keywords: Emission Control; Cyclonic; Liquid Scrubber; Gas Analyser; Exhaust

1. INTRODUCTION

Air pollution remains a major environmental and public-health challenge, especially in rapidly urbanising and industrialising countries such as Nigeria. Increasing energy demand, vehicular activity, industrial production, open waste burning, biomass combustion, diesel generation and artisanal petroleum refining has heightened to emissions. Such emissions include particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂), volatile organic compounds (VOCs), and other hazardous pollutants. Recent studies in the Niger Delta have reported significant pollution from petroleum-related and artisanal refining activities, with potential consequences for respiratory health and the wider environment (Ephraim-Emmanuel *et al.*, 2023; Onakpohor *et al.*, 2020; Igibah *et al.*, 2024).

Exposure to fine particulate matter and gaseous pollutants is linked to respiratory and cardiovascular diseases, lung cancer and premature mortality. Globally, air pollution was associated with approximately 7.9 million deaths in 2023, while Nigeria recorded more than 200,000 attributable deaths (Health Effects Institute, 2025). These impacts, together with the environmental and climate consequences of atmospheric emissions, emphasize the importance of controlling pollutants at their sources rather than relying solely on ambient-air monitoring.

Scrubbing is an established engineering approach for controlling industrial air emissions. Wet scrubbers remove pollutants by bringing contaminated gas into contact with liquid droplets, through mechanisms such as inertial impaction, interception, diffusion and absorption. Although venturi scrubbers can achieve high removal efficiencies for fine particles, they require substantial pressure drops and energy input. Cyclonic wet scrubbers provide a potentially attractive compromise by combining centrifugal separation with gas-liquid interaction, offering effective particulate removal with relatively moderate energy requirements (Krames, 1994; Mukherjee *et al.* 2024).

Recent numerical and experimental studies have demonstrated that improvements in scrubber geometry, droplet distribution and particle–droplet interaction can significantly enhance collection performance (Oliveira et al. 2019; Hoyos *et al.*, 2024). Such developments are relevant to Nigeria, where emission-control technologies must be affordable, robust, energy-efficient, easy to maintain and suitable for local fabrication.

This study focuses on the design and development of a cyclonic wet scrubber for controlling gasoline-engine exhaust emissions. The study evaluates the system with particular attention to pollutant-removal performance. The paper demonstrated the potential of a locally adaptable cyclonic wet-scrubbing system as a practical point-source emission-control technology for improving air quality and supporting cleaner energy and industrial practices in Nigeria.

2. METHODOLOGY

2.1 Design Calculations

This section involves calculating the parameters needed for designing the wet scrubber. The parameters, their respective equations and calculations shown in Table 1, included Cunningham slip correction factor, Aerodynamic geometric mean diameter, Gas and liquid flow rates, Droplet diameter, Inertial parameter for mass median diameter, Reynolds number, Drag coefficient of liquid, Parameter characterizing L/G ratio, and Overall penetration and collection efficiency.

Table 1: Design calculations

[illegible]

Initial data	Calculations	Result
$R_{CO_2} = 188.92$ $R_{H_2O} = 188.92$ $R_{N_2} = 296.8$ $T_g = 650^0$ $P_g = 4 \text{ bar}$ $\%CO_2 = 13\%$ $\%H_2O = 13\%$ $\%N_2 = 74\%$ μ_g $= 3 \times 10^{-4} \text{ g/cms}$ ρ_g $= 1.804$ $\times 10^{-6} \text{ g/cm}^3$ $v_{gt} = 864 \text{ (m/s)}$ $d_d = 0.058 \text{ m}$ $v_g = 0.166 \text{ (cm}^2/\text{s)}$	Reynolds number $\rho_{CO_2} = \frac{\rho_g}{R_{CO_2} T_g}$ $= \frac{188.92 \times (273 + 650)}{4 \times 10^5}$ $\rho_{H_2O} = \frac{\rho_g}{R_{H_2O} T_g} = \frac{188.92 \times (273 + 650)}{4 \times 10^5}$ $\rho_{N_2} = \frac{\rho_g}{R_{N_2} T_g} = \frac{296.8 \times (273 + 650)}{4 \times 10^5}$ $\rho_g \Rightarrow \%CO_2 (\rho_{CO_2}) + \%H_2O (\rho_{H_2O}) + \%N_2 (\rho_{N_2})$ $\Rightarrow \rho_g = 0.13(2.29 + 1.17) + 0.74(1.83)$ $v_g = \frac{\mu_g}{\rho_g}$ $\text{hence } v_g = \frac{3 \times 10^{-4}}{1.804 \times 10^{-3}}$ $N_{R_0} = \frac{v_{gt} d_d}{v_g}$ $\Rightarrow N_{R_0} = \frac{864 \times 0.058}{0.166}$	ρ_{CO_2} $= 2.29 \times 10^{-3} \text{ g/cm}^3$ ρ_{H_2O} $= 1.17 \times 10^{-3} \text{ g/cm}^3$ ρ_{N_2} $= 1.83 \times 10^{-3} \text{ g/cm}^3$ ρ_g $= 1.804 \times 10^{-3} \text{ g/cm}^3$ $v_g = 0.166 \text{ cm}^2/\text{s}$ $N_{R_0} = 301.34$
$N_{R_0} = 301.34$	Drag coefficient of liquid $C_D = 0.22 + \frac{24}{N_{R_0}} (1 + 0.15 N_{R_0}^{0.6})$ $\Rightarrow 0.22 + \frac{24}{301.34} (1 + 0.15(301.34)^{0.6})$	$C_D = 0.67$
ρ_l $= 1.59$ $\times 10^{-3} \text{ g/cm}^3$ ρ_g $= 1.804$ $\times 10^{-3} \text{ g/cm}^3$ $C_D = 0.67$ $\bar{P}_t = 0.25$	Parameter characterizing L/G ratio $sB = (L/G) \frac{\rho_l}{\rho_g C_D}$ $= \frac{0.00159.1000}{1.804 \times 0.67}$ Overall penetration $\bar{P}_t = 0.25;$ Collection efficiency $\eta = 1 + \bar{P}_t = 1 - 25\%$	$B = 1.32$ $\eta = 75\%$

2.2 Fabrication Process

The barrel cylinder forms the main body of the scrubber. It is fabricated from 2 mm mild-steel sheet, rolled into a cylinder of approximately 350 mm diameter and 497 mm overall height. The sheet is cut, manually formed, and seam-welded. Flange rings are welded to the top and bottom to allow the end plates to be securely bolted in place.

The top cover is a 2 mm mild-steel circular plate fitted with a central opening for the gas outlet pipe. It is bolted to the upper flange using a gasketed joint to prevent gas or water leakage. A mesh outlet filter, installed beneath the gas outlet, serves as a mist eliminator by removing entrained water droplets and fine particles before the cleaned gas leaves the scrubber. The mesh can be removed for cleaning or replacement.

Inside the barrel, a straightening vane is installed below the spray zone. It helps reduce excessive swirling and distribute the gas more uniformly through the spray, thereby improving gas–liquid contact and pollutant removal.

Two lifting handles are welded to opposite sides of the barrel to facilitate handling and movement of the unit.

The gas inlet is a mild-steel pipe welded tangentially to the lower section of the barrel. Its tangential arrangement induces a cyclonic motion in the incoming exhaust gas, promoting centrifugal separation and improving contact with the scrubbing liquid.

The scrubber is supported by a mild-steel stand consisting of three or four welded legs fitted with castor wheels. The stand provides ground clearance for the gas inlet and dirt outlet while allowing the unit to be moved easily.

The spray system consists of two to four fine-mist hollow-cone nozzles mounted on an internal spray header above the straightening vane. The nozzles atomise water across the gas flow path, increasing gas–liquid contact and enhancing pollutant capture. Water is supplied through a threaded water inlet connected to an external pump or recirculation line.

The bottom plate, also made from 2 mm mild steel, seals the lower end of the barrel and is bolted to the lower flange with a gasket. It also supports the stand and provides the mounting point for the dirt outlet, which is fitted with a ball valve. The valve allows accumulated water, soot, and captured particulate matter to be drained during cleaning or maintenance.

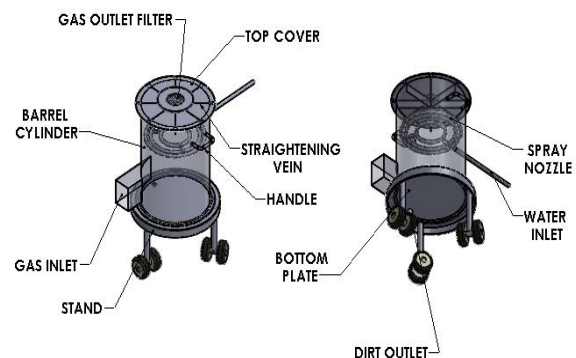


Figure 1: Assembly of the wet scrubber

Assembly Procedure

Fabrication begins with the barrel, top cover, and bottom plate. The internal components—including the straightening vane, spray header and nozzles, and outlet filter—are then installed before the end plates are closed. The top and bottom plates are fitted with gaskets and bolted to the barrel flanges using a cross-tightening sequence to achieve an even, leak-tight seal. Finally, the handles, stand, water inlet, and dirt outlet are installed. The completed unit is inspected for leaks and structural integrity before painting and commissioning.

2.3 Working Principle of Cyclonic Liquid Spray Scrubber Device

The scrubber was built to serve both the dry cyclone and wet spray chamber to remove pollutants from gas streams. For the wet scrubber; raw exhaust from the gasoline powered internal combustion engine enters the system.

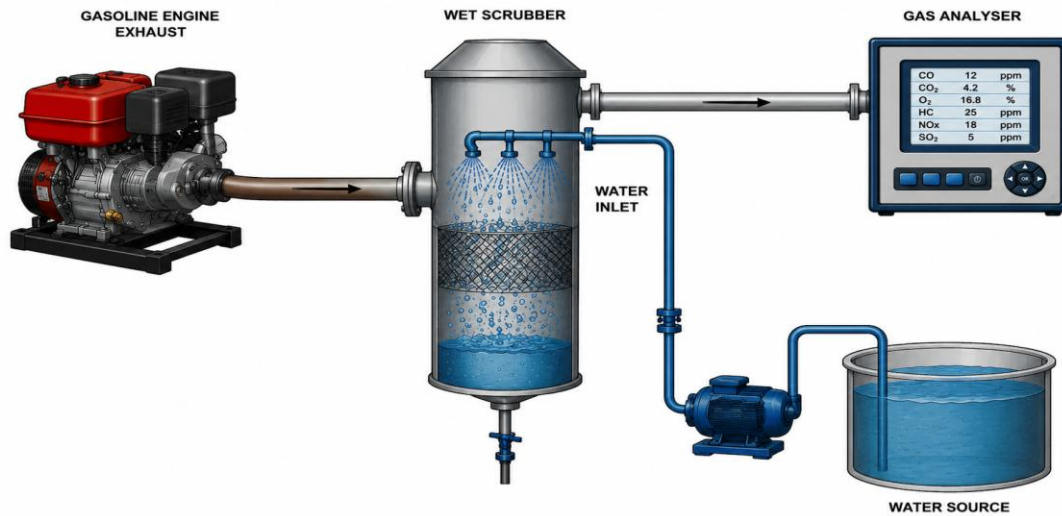


Figure 2: Experimental working assembly of the wet scrubber system

The scrubber consists of empty cylindrical chamber in which the exhaust gas stream is contacted with water droplets. Water spray, generated by the spray nozzles, captures particulate and exhaust gases. The cleaned gas exits to the gas analyser for exhaust gas composition measurements. Water is then recirculated from the water source via the pump and the blowdown removes accumulated contaminants. Two repeated measurements were recorded for each exhaust gas, and the average reading was used for further analysis.

3. RESULTS AND DISCUSSION

The constructed wet scrubber was tested using an internal combustion engine (4-stroke, single cylinder gasoline engine), Brain Bee automotive gasoline gas analyzer and a water source.

The testing of liquid wet scrubber was carried out at Heat Engine Workshop, Department of Mechanical Engineering, Ahmadu Bello University, Zaria. The experimental procedure was carried out with gasoline fuel using different exhaust emission such as Carbon II Oxide (CO), Carbon IV Oxide (CO₂), Unburn Hydrocarbon (HC), and Excess Oxygen O₂. The test was carried out on two stages. A four stroke, single cylinder gasoline engine was initially fuelled with a gasoline fuel until steady-state was confirmed. The exhaust emissions from the engine were measured using the Brain bee automotive gasoline gas analyzer. The gasoline engine was run again with the wet scrubber attached to the engine exhaust and to the Brain bee automotive gasoline gas analyzer. The exhaust gases CO (%/vol); CO₂ (%/vol); HC (ppm) and O₂ (%/vol) were recorded. Tables 2 and 3 show the emission readings from the gas analyser without and with the scrubber. Two readings were recorded in both Tables 2 and 3, and the average readings

Table 2: Exhaust Emission without wet scrubber

Experiment no.	Exhaust gas parameters (mass fraction)					
	λ	CO (%/vol)	CO ₂ (%/vol)	HC (ppm)	O ₂ (%/vol)	$\phi = 1/\lambda$
First reading	3.811	2.56	1.1	142.0	17.50	0.2624
Second reading	3.896	2.41	1.1	154.0	17.20	0.2566
Average	3.854	2.485	1.1	148.0	17.35	0.2595
Standard Deviation	0.06	0.106	0	8.485	0.212	0.004

Table 3: Exhaust Emission with wet scrubbers

Experiment no.	Exhaust gas parameters					
	λ	CO (%/vol)	CO ₂ (%/vol)	HC (ppm)	O ₂ (%/vol)	$\phi = 1/\lambda$
First reading	4.468	2.090	1.1	109.0	18.20	0.2238
Second reading	4.430	2.104	0.9	130.0	17.20	0.2262
Average reading	4.449	2.097	1.0	119.5	17.70	0.2250
Standard Deviation	0.027	0.01	0.141	14.8	0.707	0.0017

Table 2 shows the mass fraction of the exhaust gas constituents as well as their respective equivalent ratios (ϕ) when wet scrubber wasn't used in cleaning the exhaust gases. The average exhaust gas mass fraction of λ , CO, CO₂, Hydrocarbon and O₂ were obtained to be 3.854, 2.485 %/vol, 1.1 %/vol, 148.0 %/vol and 17.35 %/vol respectively. λ is a parameter obtained from the gas analyzer known as the inverse equivalence ratio, while ϕ is the equivalence ratio obtained from an experimental run.

Table 3 rather shows the mass fraction of the exhaust gas constituents as well as their respective equivalent ratios (ϕ) when wet scrubber was used in cleaning the exhaust gases. The average exhaust gas mass fraction of CO, CO₂, Hydrocarbon and O₂ were obtained to be 2.097%/vol, 1.0 %/vol, 119.7ppm, and 17.7 %/vol respectively. The results from Table 2 and 3 showed that the scrubber reduced the concentrations of carbon monoxide (CO), carbon dioxide (CO₂), and unburned hydrocarbons (HC) by 15.6%, 9% and 19% respectively and surprisingly increased excess oxygen (O₂) emissions by approximately 2%. The percentage reduction was calculated from: (concentration without scrubber – concentration with scrubber) x100%/ concentration without scrubber. The unexpected increase in O₂ after the gases pass through the scrubber could be due to air ingress through the scrubber, dilution effects from water vapor displacing gas, or analyzer calibration effects. The average equivalence ratio decreased from 0.2595 without the wet scrubber to 0.2250 with the wet scrubber. Comparing the predicted maximum 75% collection efficiency from the design calculations, with the percentage reductions of maximum of 15.6% for HC; the discrepancy shows more room for cleaning exhaust gases. Two readings per test condition were taken mainly to confirm basic repeatability of the exhaust measurements rather than to establish a statistically robust estimate, given practical constraints such as limited test-rig time, the risk of engine drift over longer runs, and the exploratory, proof-of-concept scope of the study; however, this small sample size (n = 2) has notable statistical limitations, including an unreliable estimate of variance, no ability to check low statistical power to detect true differences, high sensitivity to outliers, and limited generalisability beyond the specific test conditions. The percentage reductions should be viewed as indicative rather than precise.

4. CONCLUSION

1. A functional prototype was successfully built and tested. The cyclonic wet scrubber was fabricated and evaluated on a 4-stroke, single-cylinder gasoline engine, using a Brain Bee automotive gas analyser to measure exhaust composition before and after treatment.

2. The scrubber significantly reduced key pollutant concentrations. CO, CO₂, and unburned hydrocarbons (HC) were reduced by 15.6%, 9%, and 19% respectively when the scrubber was fitted, demonstrating measurable emission-control performance.

3. An unexpected rise in excess oxygen was observed. Excess O₂ concentration increased by approximately 2% with the scrubber in place; a surprising result that warrant further investigation

4. The equivalence ratio shifted toward a leaner mixture. The average equivalence ratio dropped from 0.2595 (without the scrubber) to 0.2250 (with the scrubber), consistent with the observed reductions in CO/CO₂/HC and the rise in excess O₂.

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