

# Analysis of Capacity and Design Criteria Assessment of a Microalgae-Based Water Filter for the Exhaust Emission Load of a Fire Pump: A Case Study at AFT Husein Sastranegara

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## ABSTRACT

The diesel fire pump at the Husein Sastranegara Aviation Fuel Terminal releases CO, NO<sub>x</sub>, and other pollutants through its stack. CO is closest to its emission standard, so the company made it the control target and applied a microalgae-based water filter to the stack. This study analyzed the capacity and design criteria conformity of an unbaffled acrylic cylindrical chamber holding 80 L of water with *Chlorella* sp. to the pump exhaust load. Pre- and post-installation emission tests, chamber specifications, the engine datasheet, and the pump operating pattern were used to calculate the aeration rate, gas dissolution capacity, CO<sub>2</sub> fixation capacity, and hydrostatic pressure against literature ranges. The aeration rate reached 14.6–123.8 vvm, 15–124 times the upper literature limit, and the water became saturated with CO<sub>2</sub> within 0.4–6.4 s and with CO and NO in under half a second. One 15–20 min running test delivered 1.1–23.0 kg of CO<sub>2</sub>, whereas the weekly fixation capacity of the culture was only about 386 g. The hydrostatic pressure (2.9–3.1 kPa) was below the engine's 7.5 kPa back-pressure limit. Measured CO decreased by 19.9% and measured NO<sub>x</sub> increased by 18.6%, whereas concentrations corrected to 15% O<sub>2</sub> decreased by 40.7% and 12.3%, all meeting the 101–500 kW class standard. Different O<sub>2</sub> contents between tests indicate different engine loads, so these reductions cannot yet be attributed to chamber performance. Development could focus on matching gas flow to culture volume, adding baffles, catalytic oxidation for CO, and simultaneous inlet and outlet measurements at the same engine load.

**Keywords:** *Chlorella* sp.; carbon monoxide; exhaust emission; fire pump; microalgae; water filter

## INTRODUCTION

The fire pump at AFT Husein Sastranegara is driven by a diesel engine that releases CO, NO<sub>x</sub>, and other pollutants through its stack. The emission standards for this engine are set by Minister of Environment and Forestry Regulation No. 11 of 2021, which also covers standby engines, and are expressed at 15% O<sub>2</sub> [1]. The November 2025 emission test showed corrected concentrations of 113 mg/Nm<sup>3</sup> for CO and 440 mg/Nm<sup>3</sup> for NO<sub>x</sub> [2]. These values were below the standards for the 101–500 kW class [1, 3], but CO was the parameter closest to its limit, so the company made it the control target [3].

This emission control is related to PROPER, the government assessment of corporate environmental management performance [4], and to worker safety, because CO binds to hemoglobin and reduces the oxygen supply to body tissues [5]. The company then applied a microalgae-based water filter to the pump stack. The initial chamber was box-shaped and was later replaced with an acrylic cylinder 40 cm in diameter to improve flow and reduce deposits in the corners [3]. During the May 2026 emission test, the cylindrical chamber contained a single algal species, *Chlorella* sp. [6].

Microalgae such as *Chlorella* and *Scenedesmus* use CO<sub>2</sub> for photosynthesis and have been tested for treating exhaust gas. Reported removals vary: about 60% CO<sub>2</sub>, 70% NO, and 50% SO<sub>2</sub> for coke oven flue gas [7]; 77% CO<sub>2</sub>, 71% NO<sub>x</sub>, and 53% SO<sub>2</sub> for motor generator exhaust [8]; and 44% CO<sub>2</sub> and 33% NO in a closed photobioreactor [9]. The recommended aeration rate for closed cultivation is 0.1–1 vvm because excessive rates increase shear stress on cells [10], and the average CO<sub>2</sub> removal efficiency is only 17.5% when measured directly with sensors [11]. CO<sub>2</sub> fixation rates also differ between species, namely 0.69 g/L/day for *Chlorella vulgaris* and 0.212 g/L/day for *Scenedesmus obliquus* [12], and fall from 0.95 to 0.25 g/L/day when the system is scaled up to pilot scale [13].

Removal also depends on gas transfer into water. Gases with low solubility, such as CO and NO, transfer to the liquid only when the contact time and gas–liquid interfacial area are sufficient [14]. In bubble column photobioreactors, this contact is governed by the aeration rate; the highest biomass production of *Chlorella vulgaris* was achieved at 0.16 vvm, whereas biomass production decreased at the highest rate tested, 0.19 vvm [15]. Tube diameter also limits the light reaching cells in the center [13]. Evidence of CO removal by algae remains limited because CO has only been reported as a minor pollutant absorbed into the culture medium [13].

These studies used reactors designed specifically for algal cultivation, model flue gas, or laboratory scale [7–9, 11–13]. A microalgae-based water filter installed directly on a fire pump stack has not been assessed for the conformity of its capacity and design criteria to the actual exhaust gas load. The novelty of this study lies in assessing the unbaffled cylindrical chamber installed during the May 2026 test using field emission data, through calculations of the aeration rate, gas dissolution capacity, CO<sub>2</sub> fixation capacity per pump operating cycle, and back pressure against operating ranges from the literature.

The choice of microalgae for a CO target needs explanation because CO is not used directly in photosynthesis [13]. CO was chosen as the control target because it was closest to its standard, at 113 mg/Nm<sup>3</sup> against a limit of 170 mg/Nm<sup>3</sup>, whereas NO<sub>x</sub> was 440 mg/Nm<sup>3</sup> against a limit of 3,400 mg/Nm<sup>3</sup> [1–3]. The 17% CO reduction target in the company program was derived from CO<sub>2</sub> removal [3], not from CO removal data, and is consistent with the average CO<sub>2</sub> removal efficiency of 17.5% under direct sensor measurement [11]. Thus, CO reduction by microalgae in this program is a hypothesis without a direct basis, and this study tests whether the observed reduction can be attributed to the chamber.

Therefore, this study aimed to analyze the conformity of the capacity and design criteria of the cylindrical chamber to the pump exhaust gas load, covering the aeration rate, gas dissolution capacity,

CO<sub>2</sub> fixation capacity per operating cycle, back pressure, diameter and light path, and algal species, against operating ranges from the literature. This study also analyzed the observed reduction in CO and NO<sub>x</sub> concentrations between the emission tests before and after chamber installation.

## METHODS

### Research Object

The research object was a microalgae-based water filter on the stack of a Clarke diesel fire pump at PT Pertamina Patra Niaga Aviation Fuel Terminal (AFT) Husein Sastranegara. The pump engine belongs to the 101–500 kW capacity class [2, 3]. The water filter is an acrylic cylindrical chamber 40 cm in diameter and 80 cm long, with a total volume of 100.48 L and an effective water volume of 80 L. During the May 2026 test, the chamber was a single unbaffled compartment containing one microalgal species, *Chlorella* sp. Exhaust gas flows from the stack into the water in the chamber, and the chamber is installed horizontally on a support frame at a location exposed to sunlight [3]. The cylindrical chamber replaced an earlier box chamber that suffered from uneven flow, deposits in the corners, and algal accumulation on one side. The company is currently adding four compartments and three baffles so that the chamber can hold two algal species, *Chlorella* sp. and *Scenedesmus obliquus*. This modification has not been tested and was therefore not evaluated in this study.

### Data Type and Sources

Emission data came from monitoring conducted by PT Pertamina Patra Niaga Aviation Fuel Terminal Husein Sastranegara through KAN-accredited laboratories at the fire pump stack. The monitoring consisted of a November 2025 test before the emission control program [2] and a May 2026 test after the cylindrical chamber containing *Chlorella* sp. was installed [6]. Both tests covered CO, NO<sub>x</sub>, O<sub>2</sub>, and gas flow, whereas SO<sub>2</sub> and CO<sub>2</sub> were measured only in the second test. The November 2025 test used method AI-IKP-53 Part 6B, 6C, and 6D with direct reading and electrochemical sensors for NO<sub>x</sub>, CO, and O<sub>2</sub>, and SNI 7117.14:2009 for the gas flow rate [2]. The May 2026 test used method IKP-002-MTD with electrochemical sensors for all parameters [6]. Specifications of the cylindrical chamber and the microalgal species were obtained directly from the company. Supporting data came from scientific journals and relevant regulations, with Minister of Environment and Forestry Regulation No. 11 of 2021 as the reference for emission standards and publications on the use of microalgae for exhaust gas treatment as the reference for design criteria.

### Data Analysis

The analysis was quantitative and used secondary data from the pre- and post-installation emission test reports, equipment specifications, and engine technical data from the company. Exhaust gas concentrations were analyzed on two bases, measured values and oxygen-corrected values, through the following eight calculation steps.

### 1. Oxygen Correction

In accordance with the emission standards for stationary internal combustion engines (Minister of Environment and Forestry Regulation No. 11 of 2021) [1], pollutant concentrations corrected to a reference oxygen content of 15% were calculated using:

$$C_k = C_u \times \frac{21 - O_{ref}}{21 - O_u} \quad (1)$$

Where  $C_k$  is the corrected concentration ( $\text{mg}/\text{Nm}^3$ ),  $C_u$  is the measured concentration ( $\text{mg}/\text{Nm}^3$ ),  $O_u$  is the measured  $\text{O}_2$  content (%),  $O_{ref}$  is the reference  $\text{O}_2$  content of 15%, and 21 is the  $\text{O}_2$  content of air (%). The results of Equation (1) differed by  $-5.4\%$  to  $-7.1\%$  from the corrected values in the laboratory reports. The May 2026 report stated corrected values on a dry basis, but neither report gave the correction formula used, so the cause of this difference is unknown. The subsequent analysis used the corrected values from the laboratory reports, and the difference is discussed as a data inconsistency.

### 2. Observed Concentration Reduction

The reductions in CO and NOx concentrations were calculated as the percentage difference between concentrations before and after chamber installation, on both measured and corrected bases:

$$\eta = \frac{C_{before} - C_{after}}{C_{before}} \times 100\% \quad (2)$$

Where  $C_{before}$  and  $C_{after}$  are the concentrations before and after installation ( $\text{mg}/\text{Nm}^3$ ). A negative value indicates an increase in pollutant concentration at the sampling point, which may be caused by variation in engine operation or fluctuation in test load. Because each condition was represented by only one sample and tested by different laboratories, the result is called an observed reduction rather than the performance efficiency of the unit. The observed reductions were then compared with removal efficiencies reported in microalgal studies on exhaust gas.

### 3. Compliance Status

Compliance status was determined by comparing the corrected CO, NOx, and  $\text{SO}_2$  values with the standards in Minister of Environment and Forestry Regulation No. 11 of 2021 [1]. The reference class was 101–500 kW according to the engine capacity [2, 3]. Corrected values were also expressed as a percentage of the standard to show the parameter closest to its limit.  $\text{SO}_2$  was measured only after installation and has no standard in the 101–500 kW class.

### 4. Gas Flow Rate and Aeration Rate (vvm)

The exhaust gas flow rate was expressed as two values: the reported flow rate from the pre-installation test report and the calculated flow rate from the post-installation test data. The reported flow rate is the gas flow rate of  $0.165 \text{ m}^3/\text{s}$ , or about  $9.9 \text{ m}^3/\text{min}$ , in the pre-installation test report based

on SNI 7117.14:2009 [2]. The Clarke JU4HNL54 engine datasheet lists an exhaust gas flow rate of  $21.7\text{--}33.8 \text{ m}^3/\text{min}$  at an exhaust temperature of  $592\text{--}611 \text{ }^\circ\text{C}$  [16]. The calculated flow rate was obtained from the stack diameter of 0.05 m and the flow velocity of  $9.94 \text{ m/s}$  in the post-installation test report [6] using:

$$Q = \pi \left(\frac{d}{2}\right)^2 v \quad (3)$$

Where  $Q$  is the gas flow rate ( $\text{m}^3/\text{s}$ ),  $d$  is the stack diameter (m), and  $v$  is the flow velocity ( $\text{m/s}$ ). The aeration rate is expressed as the gas volume per water volume per minute:

$$vvm = \frac{60Q}{V_{water}} \quad (4)$$

Where  $V_{water}$  is the effective water volume of the chamber,  $0.08 \text{ m}^3$ . The gas fed to the chamber came only from the fire pump stack, and the generator set exhaust was not fed to the chamber [16]. This calculation assumes that all pump exhaust gas passes through the chamber. The corrected value columns for the flow rate and flow velocity in both reports were empty, whereas the stated normal conditions of  $25 \text{ }^\circ\text{C}$  and 1 atm refer to corrected concentrations [2, 6], so the reference temperature of the flow rate is unknown and vvm was calculated directly from the reported values. The vvm values were compared with the recommended range for closed cultivation, 0.1–1 vvm [10], and with the optimum aeration rate of 0.16 vvm in a pilot-scale bubble column photobioreactor [15] by expressing them as multiples of both values. The reported and calculated flow rates were also compared through their ratio and against the flow rate in the engine datasheet to show the magnitude of the difference between reports.

### 5. $\text{CO}_2$ Load and Fixation Capacity

The  $\text{CO}_2$  load was calculated from the reported and calculated flow rates, assuming that both values are actual flow rates at the gas temperature and 1 atm and that the gas behaves ideally. The gas temperature at the sampling point was not given in the test reports. The engine datasheet lists an exhaust temperature of  $592\text{--}611 \text{ }^\circ\text{C}$  at the engine outlet [16], but this value is not necessarily the same as the gas temperature at the sampling point. Therefore, the calculation used two temperatures,  $25 \text{ }^\circ\text{C}$  for the maximum load and  $300 \text{ }^\circ\text{C}$  for the minimum load. The  $\text{CO}_2$  mass flow rate was calculated as:

$$m_{\text{CO}_2} = \frac{3600 Q y_{\text{CO}_2} M}{R T} \quad (5)$$

Where  $m_{\text{CO}_2}$  is the  $\text{CO}_2$  mass flow rate ( $\text{kg}/\text{h}$ ),  $Q$  is the reported or calculated gas flow rate ( $\text{m}^3/\text{s}$ ),  $y_{\text{CO}_2}$  is the  $\text{CO}_2$  volume fraction from the test, 0.0646,  $M$  is the molar mass of  $\text{CO}_2$  ( $44.01 \text{ g/mol}$ ),  $R$  is the gas constant ( $0.08206 \text{ L}\cdot\text{atm}/(\text{mol}\cdot\text{K})$ ), and  $T$  is the gas temperature (K). The fixation capacity of the chamber was calculated from the microalgal  $\text{CO}_2$  fixation rate per water volume:

$$K = \frac{r V_{\text{water}}}{24} \quad (6)$$

Where K is the fixation capacity (g/h), r is the CO<sub>2</sub> fixation rate of 0.69 g/L/day, and V<sub>water</sub> is the effective water volume in L. The value of r is the CO<sub>2</sub> fixation rate of *Chlorella vulgaris* under model power plant flue gas with 15% CO<sub>2</sub> [12]. This CO<sub>2</sub> concentration is higher than that of the pump exhaust, so r was used only as an approximation. The value lies within the range of *Chlorella* CO<sub>2</sub> fixation rates reported in other studies, namely a maximum of 2.22 g/L/day at 6.5% CO<sub>2</sub> [17], 0.74–1 g/L/day at 5% CO<sub>2</sub> [18], and 0.25–0.95 g/L/day from laboratory to pilot scale [13]. The load was compared with the capacity through the ratio:

$$\beta = \frac{1000 m_{\text{CO}_2}}{K} \quad (7)$$

A β value greater than 1 means that the CO<sub>2</sub> load exceeds the fixation capacity. The culture volume required to fix CO<sub>2</sub> as fast as the gas enters was calculated by dividing the CO<sub>2</sub> load rate during pump operation by the fixation rate per culture volume. The pump is operated in weekly running tests of 15–20 min [16]. The CO<sub>2</sub> load per running test was calculated as the CO<sub>2</sub> mass flow rate multiplied by this duration and then compared with the weekly fixation capacity of the culture, r × V<sub>water</sub> × 7 days, on the condition that the CO<sub>2</sub> from one running test could be stored and fixed over one week.

**6. Hydrostatic Pressure against the Back-Pressure Limit**  
The pressure experienced by the exhaust gas as it passes through the water column was estimated as hydrostatic pressure:

$$P = \rho gh \quad (8)$$

Where P is the pressure (Pa), ρ is the water density (1000 kg/m<sup>3</sup>), g is the gravitational acceleration (9.81 m/s<sup>2</sup>), and h is the water depth (m). The chamber is installed horizontally with a water level of about 80% [16], giving a water depth of about 0.30 m for a water volume of 80 L and 0.32 m for a water level of 80% of the tube diameter. The result was converted to kPa and compared with the maximum exhaust back-pressure limit of 7.5 kPa in the datasheet of the Clarke JU4HNL54 engine [16], the pump engine on site, rated at 160 BHP at 2960 rpm [3]. The chamber was considered to conform if P did not exceed this limit. This calculation includes only the hydrostatic pressure and does not yet include pressure losses in the diffuser or piping.

### 7. Gas Dissolution Capacity in Water

The capacity of the chamber water to dissolve CO<sub>2</sub>, CO, and NO was calculated using Henry's law. The mass of gas that can dissolve until the water is saturated is:

$$m_{\text{sat}} = K_H p_i M_i V_{\text{water}} \quad (9)$$

Where m<sub>sat</sub> is the mass of dissolved gas at saturation (g), K<sub>H</sub> is the Henry's law constant at 25 °C (mol/(L·atm)) [19], p<sub>i</sub> is the partial pressure of the gas (atm) calculated from the measured concentration in the post-installation test, M<sub>i</sub> is the molar mass of the gas (g/mol), and V<sub>water</sub> is the water volume (L). NO<sub>x</sub> was assumed to be entirely NO. The time to saturation was calculated from this mass and the incoming gas mass flow rate:

$$t_{\text{sat}} = \frac{60 m_{\text{sat}}}{\dot{m}_i} \quad (10)$$

Where t<sub>sat</sub> is the time to saturation (s) and  $\dot{m}_i$  is the incoming gas mass flow rate (g/min) for both flow rates and both temperatures. Because the water in the chamber is not replaced during pump operation, a short t<sub>sat</sub> means that the dissolution capacity is quickly exceeded and subsequent gas leaves without dissolving.

### 8. Consistency of O<sub>2</sub> and CO<sub>2</sub> Contents

The O<sub>2</sub> and CO<sub>2</sub> contents of exhaust gas are interrelated because both are determined by the amount of excess air. The CO<sub>2</sub> content corresponding to the measured O<sub>2</sub> content on a dry gas basis was calculated as:

$$CO_{2,\text{exp}} = CO_{2,\text{max}} \times \frac{21 - O_2}{21} \quad (11)$$

Where CO<sub>2,exp</sub> is the expected CO<sub>2</sub> content (%), CO<sub>2,max</sub> is the CO<sub>2</sub> content of stoichiometric combustion on a dry basis (%), and O<sub>2</sub> is the measured O<sub>2</sub> content (%). The CO<sub>2, max</sub> value of 15.0–15.5% was calculated from the stoichiometry of diesel fuel combustion with an H/C atomic ratio of 1.8–2.0 [20]. The expected value was compared with the measured CO<sub>2</sub> content in the May 2026 test to check the consistency of the two parameters underlying the O<sub>2</sub> correction and the CO<sub>2</sub> load calculation.

Design parameters that were not calculated, namely the chamber diameter, which determines the light path, and the algal species used, were compared directly with the values and species reported in the literature.

## RESULTS AND DISCUSSION

### Emission Characteristics and Compliance Status

The emission data analyzed came from two tests at the fire pump stack. The first test was conducted by AdhikariLab in November 2025 before the emission control program [2], and the second by Mahatidana Laboratorium in May 2026 after the cylindrical chamber containing *Chlorella* sp. was installed [6]. During the second test, the chamber was a single unbaffled compartment. The results of both tests are presented in Table 1.

**TABLE 1:** Exhaust Emission Concentrations of the Fire Pump and Emission Standards for the 101–500 kW Class (mg/Nm<sup>3</sup>).

| Parameter                             | Measured |       | Corrected |       | Limit |
|---------------------------------------|----------|-------|-----------|-------|-------|
|                                       | Before   | After | Before    | After |       |
| CO (mg/Nm <sup>3</sup> )              | 151      | 121   | 113       | 67    | 170   |
| NO <sub>x</sub> (mg/Nm <sup>3</sup> ) | 586      | 695   | 440       | 386   | 3,400 |
| SO <sub>2</sub> (mg/Nm <sup>3</sup> ) | –        | 172   | –         | 95    | –     |
| O <sub>2</sub> (%)                    | 13.55    | 10.78 | –         | –     | –     |
| CO <sub>2</sub> (%)                   | –        | 6.46  | –         | –     | –     |

**Source:** AdhikariLab [2] and Mahatidana Laboratorium [6] emission test reports; emission standards from [1].

Measured CO decreased from 151 mg/Nm<sup>3</sup> to 121 mg/Nm<sup>3</sup>, whereas measured NO<sub>x</sub> increased from 586 mg/Nm<sup>3</sup> to 695 mg/Nm<sup>3</sup>. Concentrations corrected to 15% O<sub>2</sub> showed CO decreasing from 113 mg/Nm<sup>3</sup> to 67 mg/Nm<sup>3</sup> and NO<sub>x</sub> from 440 mg/Nm<sup>3</sup> to 386 mg/Nm<sup>3</sup>. All corrected concentrations were below the standards for the 101–500 kW class. The corrected values as a percentage of the standard were calculated as follows.

$$R_i = \frac{C_{k,i}}{ES_i} \times 100\% \quad (12)$$

Where  $R_i$  is the corrected concentration as a percentage of the standard (%),  $C_{k,i}$  is the corrected concentration of parameter  $i$  (mg/Nm<sup>3</sup>), and  $ES_i$  is the emission standard for parameter  $i$  (mg/Nm<sup>3</sup>). For the 101–500 kW class:

$$\begin{aligned} R_{CO,before} &= \frac{113}{170} \times 100\% = 66\% \\ R_{CO,after} &= \frac{67}{170} \times 100\% = 39\% \\ R_{NOx,before} &= \frac{440}{3,400} \times 100\% = 13\% \\ R_{NOx,after} &= \frac{386}{3,400} \times 100\% = 11\% \end{aligned}$$

Thus, CO before installation was equivalent to 66% of the standard and 39% after installation, whereas NO<sub>x</sub> was only about 13% and 11%. CO remained the parameter closest to its limit, consistent with the reason it was chosen as the control target [3]. SO<sub>2</sub> and CO<sub>2</sub> were measured only in the May test, and SO<sub>2</sub> (95 mg/Nm<sup>3</sup> corrected) has no standard in this class,

so neither the status nor the change of these two parameters could be assessed.

This status applies to the 101–500 kW class used as a basis in [2, 3]. The Mahatidana report also lists a CO limit of 77 mg/Nm<sup>3</sup> for the 501–1000 kW class. The O<sub>2</sub> content decreased from 13.55% to 10.78%. O<sub>2</sub> in diesel exhaust reflects the amount of excess air and decreases as the load increases [20]. This difference indicates that the two tests were likely conducted under different engine operating conditions, and the load during testing was not recorded.

#### Observed Concentration Reduction

The concentration reduction was calculated with Equation (2) on the measured and corrected bases, with  $C_{before}$  and  $C_{after}$  being the concentrations in the November 2025 and May 2026 tests, respectively:

$$\begin{aligned} \eta_{CO,meas} &= \frac{151 - 121}{151} \times 100\% = 19.9\% \\ \eta_{CO,corr} &= \frac{113 - 67}{113} \times 100\% = 40.7\% \\ \eta_{NOx,meas} &= \frac{586 - 695}{586} \times 100\% = -18.6\% \\ \eta_{NOx,corr} &= \frac{440 - 386}{440} \times 100\% = 12.3\% \end{aligned}$$

On the measured basis, CO decreased by 19.9% while NO<sub>x</sub> increased by 18.6% (a negative value indicates an increase in concentration). On the corrected basis of the laboratory reports, CO decreased by 40.7% and NO<sub>x</sub> by 12.3% (Table 2).

**TABLE 2:** Observed Reduction in CO and NO<sub>x</sub> Concentrations on Different Calculation Bases.

| Gas             | Basis                         | Before (mg/Nm <sup>3</sup> ) | After (mg/Nm <sup>3</sup> ) | Observed Reduction (%) |
|-----------------|-------------------------------|------------------------------|-----------------------------|------------------------|
| CO              | Measured                      | 151                          | 121                         | 19.9                   |
| CO              | Corrected (laboratory report) | 113                          | 67                          | 40.7                   |
| NO <sub>x</sub> | Measured                      | 586                          | 695                         | –18.6 (increase)       |
| NO <sub>x</sub> | Corrected (laboratory report) | 440                          | 386                         | 12.3                   |

**Source:** calculated with Equation (2). Negative values indicate an increase in concentration.

The correction factor used by the laboratory was calculated from the measured and corrected values of each test:

$$f = \frac{C_k}{C_u} \quad (13)$$

where  $f$  is the  $O_2$  correction factor,  $C_k$  is the corrected concentration, and  $C_u$  is the measured concentration ( $mg/Nm^3$ ). The results are:

$$\begin{aligned} f_{CO,Nov} &= \frac{113}{151} = 0.748 \\ f_{NOx,Nov} &= \frac{440}{586} = 0.751 \\ f_{CO,May} &= \frac{67}{121} = 0.554 \\ f_{NOx,May} &= \frac{386}{695} = 0.555 \end{aligned}$$

These factors were compared with the factor from Equation (1),  $6/(21 - O_2)$ :

$$\begin{aligned} f_{Nov} &= \frac{21 - 15}{21 - 13.55} = 0.805 \\ f_{May} &= \frac{21 - 15}{21 - 10.78} = 0.587 \end{aligned}$$

$O_2$  correction normalizes concentrations to the same level of air dilution but does not normalize combustion conditions. The decrease in  $O_2$  from 13.55% to 10.78% indicates less excess air, which occurs in diesel engines as the load increases [20]. Load changes also alter CO and NOx formation [20], and the measured pattern in this study, with  $O_2$  decreasing, NOx increasing, and CO decreasing, is consistent with such a load change. The reductions in corrected CO and NOx reflect concentration changes after the dilution effect is removed, but they cannot yet be separated from the difference in

engine load. Because the load was not recorded and the two tests were performed by different laboratories, the observed changes cannot be attributed to the chamber.

The consistency of the  $O_2$  and  $CO_2$  contents in the May 2026 test was checked with Equation (11). The measured  $O_2$  content of 10.78% gives an expected  $CO_2$  content of 7.3–7.5%, whereas the measured  $CO_2$  was 6.46%, or 12–14% lower than expected. Conversely, the measured  $CO_2$  corresponds to an  $O_2$  content of about 12.0–12.2%. The laboratory correction factors in Equation (13) also correspond to  $O_2$  contents about 0.5–0.6 points below the measured values, namely about 13.0% in November and 10.2% in May. Neither report explains the cause of these inconsistencies, so the corrected values and the  $CO_2$  load in this study carry uncertainty from the  $O_2$  and  $CO_2$  measurements.

These results were compared with the targets of the emission control program [3]. The concentration that would be reached if a target were met was calculated as:

$$\begin{aligned} C_{target} &= C_{before} \times (1 - \eta_{target}) \quad (14) \\ C_{CO,target} &= 151 \times (1 - 0.17) = 125.3 \text{ mg}/Nm^3 \\ C_{NOx,target} &= 586 \times (1 - 0.78) = 128.9 \text{ mg}/Nm^3 \end{aligned}$$

The measured CO concentration after installation ( $121 \text{ mg}/Nm^3$ ) was lower than  $125.3 \text{ mg}/Nm^3$ . The 17% target was derived from  $CO_2$  removal efficiency [3] and was therefore not used as a benchmark for CO removal. The *Chlorella* stage in that document was not targeted to reduce NOx, and the 78% target is associated with the *Scenedesmus obliquus* stage, which has not been built. The increase in measured NOx therefore cannot be judged as a deviation from the design target (Table 3).

**TABLE 3:** Comparison of Observed Reductions with the Emission Control Program Targets.

| Gas | Target                        | Conc. if target met | Observed (meas.)           | Remarks                    |
|-----|-------------------------------|---------------------|----------------------------|----------------------------|
| CO  | 17%<br>( <i>Chlorella</i> )   | 125.3 $mg/Nm^3$     | 121 $mg/Nm^3$ (down 19.9%) | Below the target value     |
| NOx | 0%<br>( <i>Chlorella</i> )    | 586 $mg/Nm^3$       | 695 $mg/Nm^3$ (up 18.6%)   | Not targeted, not assessed |
| NOx | 78%<br>( <i>Scenedesmus</i> ) | 128.9 $mg/Nm^3$     | –                          | Stage not yet built        |

**Source:** targets from the program document [3]; target concentrations calculated with Equation (14); observed values from Table 1.

Both targets were derived from  $CO_2$  and NO removal in other studies and therefore do not yet represent the characteristics of CO and NOx in this pump exhaust. With one sample per condition, different laboratories, different  $O_2$  contents, and unrecorded engine load, these figures are called observed reductions and cannot yet be stated as the removal efficiency of the chamber. Demonstrating the role of the chamber requires simultaneous inlet and outlet measurements at the same engine load.

### Comparison with Similar Technologies

Exhaust emission control using microalgae is a biotechnological approach that combines gas absorption into the liquid phase with the metabolic activity of photosynthetic microorganisms. Compared with conventional emission control systems, such as catalytic oxidation, wet scrubbers, and mechanical filtration, microalgae-based systems use the ability of microalgae to assimilate carbon dioxide ( $CO_2$ ) as a carbon source for biomass growth and to use nitrogen compounds from the exhaust gas.

In this study, the technology developed is a microalgae-based water filter in a single bioremediation chamber shaped as a horizontal cylinder 40 cm in diameter and 80 cm long. The reactor has a total geometric volume of 100.48 L and an effective volume of 80 L and had no baffles during testing.

Assessing the conformity of the chamber design requires comparators expressed in numbers. Table 4 covers the reactor volume, aeration rate (vvm), inlet gas concentration, and removal percentage from microalgal studies.

**TABLE 4:** Quantitative Comparison of Microalgae-Based Exhaust Gas Treatment Technologies.

| Study                        | Microalgae                      | Reactor volume    | vvm                 | Inlet concentration                                                                       | Removal (%)                                                               |
|------------------------------|---------------------------------|-------------------|---------------------|-------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Chiu et al. (2011) [7]       | <i>Chlorella</i> sp. MTF-7      | 50 L              | 0.05 (2–22 h)       | CO <sub>2</sub> 25%; NO ≈80 ppm                                                           | CO <sub>2</sub> 60%; NO 70%                                               |
| Duarte et al. (2016) [21]    | <i>C. fusca</i> LEB 111         | 1.8 L             | 0.05; mean 0.00125  | CO <sub>2</sub> 10%; SO <sub>2</sub> 60–200 ppm; NO 100–400 ppm                           | CO <sub>2</sub> 45.6–63.4%; NO not reported                               |
| Kuo et al. (2016) [22]       | <i>Chlorella</i> sp. GD         | 1 L               | 0.05; 0.1; 0.2; 0.3 | CO <sub>2</sub> 8%; NO 57 ppm                                                             | CO <sub>2</sub> 30–53%; NO not reported                                   |
| Jiang et al. (2013) [23]     | <i>S. dimorphus</i>             | ≈700 mL           | 0.25                | CO <sub>2</sub> 15%; SO <sub>2</sub> 400 ppm; NO 300 ppm                                  | CO <sub>2</sub> 1.6% (continuous); 65.3–75.6% (intermittent)              |
| Cheng et al. (2013a) [24]    | <i>Chlorella</i> PY-ZU1         | 0.6 L; 0.6 L × 3  | 0.05; 0.01; 0.011   | CO <sub>2</sub> 15%                                                                       | 15.7% (single); 32.3% (series)                                            |
| Cheng et al. (2013b) [25]    | <i>Chlorella</i> PY-ZU1         | 0.3; 2.7; 4.2 L   | 0.1; 0.011; 0.0071  | CO <sub>2</sub> 15%                                                                       | Mean 7.6%; 50.3%; 70.5%                                                   |
| Anbalagan et al. (2017) [26] | Microalgae–bacteria consortium  | 39 L + 2 L        | 52 mL/min; 0.0013   | CO <sub>2</sub> 24%; toluene 498 mg/m <sup>3</sup>                                        | CO <sub>2</sub> 76 ± 7%; toluene 89 ± 5%                                  |
| Khoo et al. (2016) [15]      | <i>C. vulgaris</i>              | 56 L              | 0.12–0.19           | Compressed air without added CO <sub>2</sub>                                              | Not reported                                                              |
| Uyar et al. (2024) [27]      | <i>C. sorokiniana</i>           | 2 L               | 0.45; 0.6; 0.75     | Air                                                                                       | Productivity 0.097 g/L/day                                                |
| Fernández et al. (2025) [28] | Biofilm ( <i>Chlorella</i> sp.) | 250 L + 15 panels | Not applicable      | CO <sub>2</sub> ≈15%; indoor exhaust gas                                                  | Carbon reduction 41.7%                                                    |
| Anjos et al. (2013) [17]     | <i>C. vulgaris</i> P12          | 0.09 L            | 0.1–0.7             | CO <sub>2</sub> 2–10%                                                                     | Not reported                                                              |
| Al Ketife et al. (2017) [18] | <i>C. vulgaris</i> CCAP 211/11B | 0.25 L            | ≈0.2                | CO <sub>2</sub> 0.03–22%                                                                  | Not reported                                                              |
| This study                   | <i>Chlorella</i> sp.            | 80 L              | 14.6–123.8          | CO <sub>2</sub> 6.46%; CO 121 mg/Nm <sup>3</sup> ; NO <sub>x</sub> 695 mg/Nm <sup>3</sup> | CO 19.9% (measured), 40.7% (corrected); NO <sub>x</sub> –18.6% (measured) |

**Source:** compiled from [7], [15], [17], [18], [21]–[28], emission test results [2], [6], and the program document [3].

Table 4 shows that CO<sub>2</sub> removal efficiency is determined mainly by the aeration rate (vvm) and the gas supply mode, not by the inlet concentration. For boiler flue gas with CO<sub>2</sub> ≈ 8%, efficiency fell from 53% to 30% as aeration increased from 0.05 to 0.3 vvm [22]. A single 0.3 L culture with 15% CO<sub>2</sub> gas at 0.1 vvm removed only 7.6% CO<sub>2</sub> on average, whereas a series of 9 and 14 reactors, at 0.011 and 0.0071 vvm relative to the whole series, raised the average removal to 50.3% and 70.5%, with a peak of 85.6% [25]. The gas supply mode also had a large

effect: at 0.25 vvm and 15% CO<sub>2</sub>, continuous aeration used only 1.6% of the CO<sub>2</sub>, whereas intermittent injection based on pH feedback raised it to 65.3–75.6% [23].

This chamber has a volume of 80 L, comparable to pilot reactors of 39–56 L [15, 26], but operates at 14.6–123.8 vvm. This is about 19–165 times the aeration in a bubble column for growth (0.75 vvm [27]), 49–413 times the highest vvm with efficiency data (0.3 vvm [22]), about 2,000–17,400 times the

vvm of the 14-stage series [25], and about 11,700–99,000 times the time-averaged vvm of intermittent injection [21]. The CO<sub>2</sub> concentration entering the chamber (6.46%) lies within the concentration range in Table 4, 0.03–25%, so the CO<sub>2</sub> concentration is not the main difference between the chamber and the comparison studies, whereas their aeration rates differ by several orders of magnitude. At 0.19 vvm, *C. vulgaris* cells already experienced shear-induced death [15], so the effect of aeration rates as high as 14.6–123.8 vvm on cells needs to be tested.

Of the 12 comparison studies, none reported CO removal. NO removal was reported by only one study, at about 70% [7]. Other studies only tested tolerance to NO up to 400–500 ppm [21, 23] or used synthetic gas without CO and NO<sub>x</sub> [26].

The corrected NO<sub>x</sub> reduction of 12.3% is below the range of NO and NO<sub>x</sub> removal in microalgal studies on exhaust gas, 33–71% [7–9]. These studies used photobioreactors designed for cultivation with gas flow matched to the culture volume, whereas the chamber in this study receives the entire pump exhaust flow.

### Conventional Comparator: Diesel Oxidation Catalyst (DOC)

As a conventional comparator for CO, a diesel oxidation catalyst (DOC) oxidizes CO to CO<sub>2</sub> directly on the catalyst surface [14], so its performance does not depend on CO solubility in water or on cell metabolism. In diesel engines, DOCs remove 90–95% of CO in dynamometer tests with diesel and B20 [29] and up to 100% under steady-state conditions with DOC inlet temperatures of 200–300 °C [30] (Table 5).

DOC efficiency depends strongly on temperature. A calibrated DOC simulation for low-load dual-fuel diesel exhaust showed CO conversion increasing from 20% to 70% as the temperature rose from 122 °C to 173 °C, and the 90% conversion target at 6,200 ppm CO was reached only at 200 °C with a flow of 25 kg/h [31]. Engine tests from cold start showed a DOC light-off temperature of about 200 °C, and CO conversion remained close to 100% throughout the cycle except at the beginning and end of each step [30]. Hydrocarbon conversion was lower, at 85–95%, and hydrocarbon levels downstream of the DOC still exceeded the Euro VI limit at 10–25% load [30]. Thus, CO is more easily removed by a DOC than hydrocarbons are. A summary of CO removal efficiency by DOCs is presented in Table 5.

**TABLE 5:** CO Removal Efficiency of Diesel Oxidation Catalysts (DOC) in Diesel Engines.

| Study                           | Test Conditions                                                                                                                             | DOC inlet temperature                                           | CO removal (%)                                                                                                       |
|---------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| Shi et al. (2012) [29]          | Diesel engine on a dynamometer; diesel and B20                                                                                              | Not reported                                                    | 90–95                                                                                                                |
| Benajes et al. (2018) [30]      | 8 L diesel engine (235 kW), RCCI mode; DOC 5.7 L, 400 cpsi; steady-state tests (1800 rpm; 10, 25, 50% load) and transient tests (WHVC, SET) | 200–300 °C (steady-state exhaust temperatures 203, 311, 318 °C) | 100 (steady-state and transient); light-off 200 °C                                                                   |
| Suthiprasert et al. (2017) [31] | DOC simulation (AVL-BOOST) calibrated with synthetic exhaust gas; low-load dual-fuel conditions; DOC 3.4 L, 300 cpsi                        | 122 → 173 °C; 200 °C                                            | 20 → 70 (flow 58.5 kg/h, O <sub>2</sub> 12.5%, CO 3,155 ppm); 90 (200 °C, 25 kg/h, O <sub>2</sub> 16%, CO 6,200 ppm) |

**Source:** compiled from studies [29]–[31].

The observed CO reduction in the chamber (19.9% measured and 40.7% corrected) is below half of the lower bound of the DOC range (90%) and cannot yet be attributed to the chamber (Tables 1–3). As an indicative illustration, an efficiency of 90–95% applied to the corrected pre-installation CO (113 mg/Nm<sup>3</sup>) would leave about 6–11 mg/Nm<sup>3</sup>, or 3–7% of the 170 mg/Nm<sup>3</sup> standard. The measured CO of 121 mg/Nm<sup>3</sup> (106 ppm) is also far below the 530–5,780 ppm range in [31], and lower CO concentrations actually increase conversion. Oxidizing this CO would add only about 190 mg/Nm<sup>3</sup> of CO<sub>2</sub> ( $121 \times 44.01/28.01$ ), or about 0.16% of the CO<sub>2</sub> already in the exhaust ( $6.46\% \approx 1.16 \times 10^5$  mg/Nm<sup>3</sup>), so a DOC upstream of the chamber would not add a meaningful CO<sub>2</sub> load.

### Role of Microalgae in CO and NO<sub>x</sub> Control

CO is not a carbon source for cell growth and is not part of the main photosynthetic mechanism of microalgae [13], so it is controlled by oxidation to CO<sub>2</sub>, for example through catalytic oxidation [14]. The CO<sub>2</sub> produced by oxidation can be used by microalgae, so the role of microalgae in CO control is better placed within a hybrid system with a CO oxidation stage. Nitrogen from NO<sub>x</sub> can be used by microalgae as a nutrient only after NO transfers to the liquid phase, and NO<sub>2</sub> reacts with water to form nitrate and nitrite [7, 14].

The results show the limited role of microalgae in CO removal. The Henry's law constant of CO (0.00098 mol/L·atm) is about 34 times smaller than that of

CO<sub>2</sub> (0.033 mol/L·atm). Theoretically, the CO dissolution capacity of 80 L of water is only about 0.23 mg, far below the incoming load of 74–142 mg/min at the calculated flow rate and 623–1,198 mg/min at the reported flow rate (Table 7). This comparison shows the limited absorption of CO through the liquid phase, although the actual saturation time depends on mass transfer conditions. The 19.9% reduction in measured CO is presumably related more to differences in engine operating conditions, as indicated by the decrease in O<sub>2</sub> from 13.55% to 10.78%, than to microalgal activity. In addition, none of the 12 studies in Table 4 reported CO removal. The contribution of microalgae to CO control is indirect, through the use of CO<sub>2</sub> produced by oxidation, which at a CO concentration of 121 mg/Nm<sup>3</sup> is equivalent to only about 0.16% of the exhaust CO<sub>2</sub>. Therefore, a diesel oxidation catalyst (DOC) is more suitable for CO control.

NO<sub>x</sub> utilization by microalgae requires gas transfer to the liquid phase and the formation of biologically available nitrogen. However, the Henry's law constant of NO (0.0019 mol/L·atm) is about 17 times smaller than that of CO<sub>2</sub>, so the theoretical dissolution capacity of 80 L of water is only about 1.7 mg, compared with an incoming NO load of 276–531 mg/min at the calculated flow rate and 2,335–4,488 mg/min at the reported flow rate (Table 7). If all NO<sub>x</sub> is assumed to be NO, the nitrogen load is estimated

at 7.7–14.9 g N/h at the calculated flow rate and 65–126 g N/h at the reported flow rate. As an order-of-magnitude comparison, an 80 L culture with a biomass productivity of 0.52 g/L/day [7] produces about 1.7 g of biomass per hour. Assuming a nitrogen content of 5–10%, the nitrogen demand of the biomass is only 0.09–0.17 g N/h, about 45–170 times lower than the incoming nitrogen load at the calculated flow rate and 380–1,450 times lower at the reported flow rate. This assumption tends to be high compared with the nitrogen content of *Chlorella* of 2.3–4.2% [25] and 2.7% [17] at high CO<sub>2</sub>, and 7.3% under air [25]. The NO<sub>x</sub> concentration in the chamber of 695 mg/Nm<sup>3</sup> (≈370 ppm as NO<sub>2</sub> or ≈570 ppm as NO at 25 °C) is close to the exposure levels reported for *C. fusca* (400 ppm) [21] and *S. dimorphus* (500 ppm) [23], so toxicity cannot yet be established as the main limiting factor. The NO and NO<sub>x</sub> removal efficiencies of 33–71% in previous studies [7–9] were presumably also influenced by gas flow-to-culture volume ratios lower than that of the chamber in this study (Table 4). Given that NO<sub>x</sub> concentrations reached only 11–13% of the standard (Table 1), NO<sub>x</sub> removal serves more as an additional environmental benefit than as a determinant of compliance.

#### Conformity of the Cylindrical Chamber with Design Criteria

The comparison of the cylindrical chamber design parameters with the literature is presented in Table 6.

**TABLE 6:** Comparison of Cylindrical Chamber Design Parameters with Literature References.

| Parameter                  | Cylindrical chamber                      | Literature reference                                                               | Assessment                         |
|----------------------------|------------------------------------------|------------------------------------------------------------------------------------|------------------------------------|
| Aeration rate              | 14.6–123.8 vvm                           | 0.1–1 vvm [10]; optimum 0.16 vvm [15]                                              | Above range (15–124 times)         |
| Water column back pressure | 2.9–3.1 kPa                              | ≤ 7.5 kPa [16]                                                                     | Conforms                           |
| Tube diameter              | 40 cm                                    | Tubular photobioreactor diameter ≤ 0.1 m so that light reaches the center [13, 32] | Exceeds the common limit (4 times) |
| Algal species              | <i>Chlorella</i> sp.                     | <i>Chlorella</i> and <i>Scenedesmus</i> [7–12]                                     | Conforms                           |
| Baffles or compartments    | None during testing                      | Adequate gas–liquid contact time; baffles increase kLa by up to 31% [14, 33]       | Does not yet conform               |
| Dissolution capacity       | Saturated within 0.01–6.4 s              | Henry's law [19]                                                                   | Quickly exceeded                   |
| CO <sub>2</sub> fixation   | 2.3 g/h against a load of 4.25–69.0 kg/h | 0.69 g/L/day [12]; range 0.25–2.22 g/L/day [13, 17, 18]                            | Far below the load                 |

**Source:** calculations and literature [7–19, 32, 33].

The reference temperature of the reported flow rate was not stated in the pre-installation test report [2]. If stated at 25 °C, the reported flow rate is equivalent to 28.7–29.4 m<sup>3</sup>/min at the exhaust temperature of 592–611 °C and lies within the engine datasheet range of 21.7–33.8 m<sup>3</sup>/min [16]. If stated at the exhaust temperature, the reported flow rate of 9.9 m<sup>3</sup>/min is below this range. The calculated flow rate of 1.17 m<sup>3</sup>/min is far below this range, both at the

exhaust temperature and after the datasheet range is converted to 25 °C, 7.3–11.7 m<sup>3</sup>/min. The post-installation test report lists a stack diameter of 0.05 m, equivalent to 2 inches [6], whereas the pump exhaust pipe is 4 inches [16].

The aeration rate of the chamber reached 14.6 vvm based on the calculated flow rate and 123.8 vvm based on the reported flow rate, or 15–124 times the

upper limit of the 0.1–1 vvm range recommended for closed cultivation [10] and 91–773 times the optimum aeration rate of 0.16 vvm [15]. The flow rate in the engine datasheet is equivalent to 91–146 vvm at 25 °C [16], so the aeration rate from the datasheet is of the same order as that based on the reported flow rate. The difference from the literature range is mainly due to the different functions of the two systems. The photobioreactors in those studies were designed for algal cultivation and therefore received only small gas flows relative

to the culture volume, whereas the chamber in this study receives the entire pump exhaust flow directly. The aeration rate of the chamber is determined by the engine flow rate, so it does not change even though the pump operates only briefly. The calculated flow rate of 1.17 m<sup>3</sup>/min and the reported flow rate of 9.9 m<sup>3</sup>/min deliver gas equivalent to the entire chamber water volume about every 4 s and 0.5 s, respectively. This short contact time is consistent with the rapid saturation of the water shown in Table 7.

**TABLE 7:** Gas Dissolution Capacity of the Chamber Water and Incoming Gas Rates.

| Gas             | KH (mol/L·atm) | Dissolved mass at saturation | Incoming gas rate                                             | Time to saturation                                |
|-----------------|----------------|------------------------------|---------------------------------------------------------------|---------------------------------------------------|
| CO <sub>2</sub> | 0.033          | 7.6 g                        | 70.8–136.2 g/min (calculated);<br>598–1,150 g/min (reported)  | 3.3–6.4 s (calculated);<br>0.4–0.8 s (reported)   |
| CO              | 0.00098        | 0.23 mg                      | 74–142 mg/min (calculated);<br>623–1,198 mg/min (reported)    | 0.1–0.2 s (calculated);<br>0.01–0.02 s (reported) |
| NO              | 0.0019         | 1.7 mg                       | 276–531 mg/min (calculated);<br>2,335–4,488 mg/min (reported) | 0.2–0.4 s (calculated);<br>0.02–0.04 s (reported) |

**Source:** calculated with Henry's law constants at 25 °C [19]; NO<sub>x</sub> assumed to be entirely NO; water volume 80 L; incoming gas rates calculated for the calculated and reported flow rates at 25 °C and 300 °C.

The gas dissolution capacity of the chamber water calculated with Henry's law is presented in Table 7. The 80 L of chamber water is not replaced during pump operation, so it becomes saturated with CO<sub>2</sub> within 3.3–6.4 s at the calculated flow rate and 0.4–0.8 s at the reported flow rate, whereas CO and NO saturate within less than half a second at both flow rates. Gas entering after saturation leaves the chamber undissolved. The mass of CO that can dissolve is about 0.23 mg, far less than the CO entering in one minute, which is 74–142 mg at the calculated flow rate and 623–1,198 mg at the reported flow rate.

The CO<sub>2</sub> fixation rate of the entire culture is about 2.3 g/h, whereas the CO<sub>2</sub> entering the chamber reaches 4.25–8.16 kg/h at the calculated flow rate and 35.9–69.0 kg/h at the reported flow rate. The highest fixation rate of 2.22 g/L/day [17] gives a capacity of only about 7.4 g/h, which remains far below this CO<sub>2</sub> load. The culture volume required to fix all of this CO<sub>2</sub> is about 148–284 m<sup>3</sup> at the calculated flow rate and 1,249–2,401 m<sup>3</sup> at the reported flow rate, or 1,850–30,000 times the chamber water volume of 0.08 m<sup>3</sup>. This volume is the requirement for fixing CO<sub>2</sub> as fast as the gas enters during pump operation. The pump operates only 15–20 min per week [16], so the CO<sub>2</sub> load per running test is about 1.1–2.7 kg at the calculated flow rate and 9.0–23.0 kg at the reported flow rate, whereas the weekly fixation capacity of the culture is about 386 g. The culture volume required to fix the CO<sub>2</sub> from one running test within one week is about 0.22–0.56 m<sup>3</sup> at the calculated flow rate and 1.9–4.8 m<sup>3</sup> at the reported flow rate, or 3–7 and 23–60 times the chamber water volume. Fixation over one week would require CO<sub>2</sub> storage in the water, whereas saturated water holds only about 7.6 g of dissolved

CO<sub>2</sub> (Table 7), and the pH of the chamber water was not monitored, so the bicarbonate contribution cannot be calculated. The dissolution and fixation capacities of the chamber are not commensurate with the exhaust gas load, so the reduction in CO concentration cannot be attributed to dissolution or to gas utilization by microalgae in the chamber.

The hydrostatic pressure of the water column at a depth of 0.30–0.32 m is 2.9–3.1 kPa, below the 7.5 kPa back-pressure limit allowed in the Clarke JU4HNL54 engine datasheet [16]. This value does not yet include pressure losses in the diffuser and piping, so the actual back pressure is higher than calculated. The 4.4–4.6 kPa margin below the limit is the room available for these pressure losses.

The selection of *Chlorella* sp. is consistent with the literature because this genus is widely used and relatively tolerant of exhaust gas [7, 11, 12]. The chamber diameter of 40 cm, or four times the common diameter limit of 0.1 m for tubular photobioreactors, may limit the light reaching cells in the center of the tube because light does not penetrate far into a dense culture [13, 32]. The absence of baffles during testing also allowed gas to flow directly to the outlet without adequate residence time [14]. Horizontal baffles in a panel photobioreactor slow the vertical flow, lengthening the bubble residence time and increasing the mass transfer coefficient by 31% at 0.06 vvm [33].

Overall, the parameters related to engine operating safety and algal species selection conformed, whereas the parameters that determine gas contact with the water and culture were not commensurate with the exhaust gas flow rate. The water volume required to reach the upper limit of 1 vvm with the

entire pump exhaust flow passing through the chamber is about 1.2 m<sup>3</sup> at the calculated flow rate and 9.9 m<sup>3</sup> at the reported flow rate. Storing gas upstream of the chamber could lower the aeration rate, but it would only assist CO<sub>2</sub> utilization by microalgae and would not resolve CO removal, the main program target, because CO is not used by microalgae [13] and its solubility is very low (Table 7). Gas storage also requires an additional unit and can therefore be considered only as a development option. The compartments currently being added by the company may extend the contact time but will not increase the dissolution capacity as long as the water volume remains 80 L.

### Limitations

The results of this study should be interpreted in light of several limitations. Measurements before and after installation of the cylindrical chamber were each made only once, by two different laboratories, without records of engine load and speed, so the emission reduction cannot yet be attributed to the performance of the water filter. The gas temperature at the sampling point and the reference temperature of the flow rate were not reported, and the location where the stack diameter was measured was not described in the post-installation report, so the aeration rate, dissolution capacity, and CO<sub>2</sub> load were calculated using two flow rates and two temperatures. The test reports also did not describe the position of the May 2026 sampling point relative to the chamber, the sampling duration, or the measurement uncertainty. Water depth was not measured during testing, so the hydrostatic pressure was calculated for a depth of 0.30–0.32 m. The pH and temperature of the chamber water were not monitored, so the dissolution capacity was calculated at 25 °C without accounting for carbonate equilibrium, assuming that NO<sub>x</sub> was entirely NO. The measured CO<sub>2</sub> content was inconsistent with the measured O<sub>2</sub> content, and the O<sub>2</sub> correction formula used by the laboratories was not given in the reports.

### Validation Plan

Demonstrating the role of the chamber requires retesting with the following design. First, CO, NO<sub>x</sub>, CO<sub>2</sub>, and O<sub>2</sub> concentrations should be measured simultaneously at the inlet (before the gas enters the chamber) and the outlet (after the gas leaves the chamber), using the same test method and laboratory, so that the concentration difference reflects chamber performance rather than differences in engine conditions or laboratories. Second, testing should be conducted at the same engine load and speed, recorded together with the sampling duration. Third, each condition should be repeated at least three times so that the mean and deviation can be calculated. Fourth, the exhaust gas temperature at the inlet and outlet should be recorded to correct the flow rate, CO<sub>2</sub> load, and dissolution capacity. Fifth, the pH and temperature of the chamber water should be measured before and after testing to calculate the carbonate equilibrium and gas solubility at the actual temperature.

### CONCLUSIONS

The cylindrical chamber containing *Chlorella* sp. on the fire pump stack at AFT Husein Sastranegara was followed by observed reductions in corrected CO and NO<sub>x</sub> concentrations of 40.7% and 12.3%, and all values met the standards for the 101–500 kW class. Measured CO decreased by 19.9%, whereas measured NO<sub>x</sub> increased by 18.6%. O<sub>2</sub> correction removes the effect of dilution but not the effect of the different engine loads between the two tests. The chamber water became saturated with CO<sub>2</sub> within 0.4–6.4 s and with CO and NO within less than half a second, whereas microalgal CO<sub>2</sub> fixation was only about 2.3 g/h against a load of 4.25–69.0 kg/h. A single 15–20 min running test delivered 1.1–23.0 kg of CO<sub>2</sub>, whereas the weekly fixation capacity of the culture was about 386 g, so the emission reduction cannot yet be attributed to chamber performance. Microalgae do not use CO directly, so their role in CO control is better placed within a hybrid system with a CO oxidation stage.

In terms of design, the algal species conformed to the literature, and the hydrostatic pressure was below the engine back-pressure limit. The aeration rate was 15–124 times above the upper limit of the literature range; the 40 cm diameter may limit the light reaching the center of the tube, and the chamber had no baffles during testing. Further development could focus on CO<sub>2</sub> utilization by microalgae by matching the gas flow rate to the culture volume, with a water volume of about 1.2–9.9 m<sup>3</sup> to reach an aeration rate of 1 vvm, and by adding compartments, whereas CO control is better achieved through catalytic oxidation. This development should be accompanied by validation through simultaneous inlet and outlet testing at the same engine load, as detailed in the Validation Plan subsection.

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