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ANALYSIS OF THE DESIGN OF A TUBE PHOTOBIOREACTOR FOR CARBON CAPTURE OF EXHAUST GAS IN SINGLE-CYLINDER ENGINE VEHICLES USING MICROALGAE

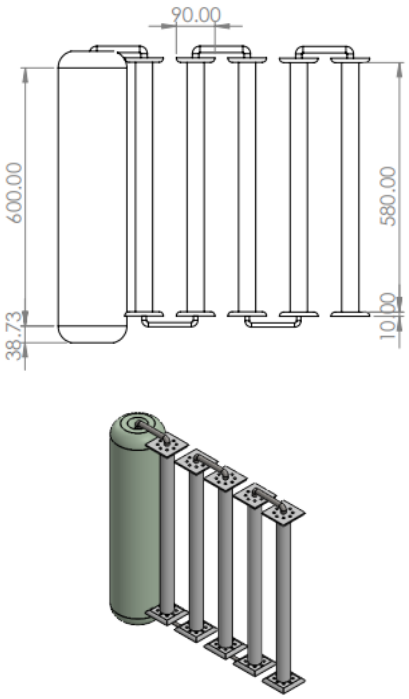
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Graphical abstract



ABSTRACT

The increase in carbon dioxide (CO_2) emissions from transportation significantly contributes to global warming, necessitating innovative carbon capture solutions. This study aims to analyze the exhaust gas characteristics of a single-cylinder Otto cycle engine as a basis for designing a tubular photobioreactor for carbon capture using microalgae. The research method involves stoichiometric analysis of octane (C_8H_{18}) combustion, thermodynamic calculations of exhaust gas flow rate, and mathematical modeling of photobioreactor design parameters, including volume, illumination surface area, hydraulic retention time (HRT), Reynolds number, and CO_2 mass transfer rate. The stoichiometric combustion analysis shows that 1 mol of C_8H_{18} produces 8 mol of CO_2, which theoretically can be fully utilized in the photosynthesis process to generate 8 mol of biomass (CH_2O). The designed tubular photobioreactor has a total volume of 3.33 liters, an illumination surface area of 0.21 m^2, and an HRT of 300 seconds under a flow rate of 0.67 L/min. The Reynolds number of 392 indicates laminar flow conditions, with a CO_2 transfer capacity of approximately 10.5 g/hour. These results demonstrate the potential integration of internal combustion engine exhaust gas with a tubular photobioreactor system as a small-scale carbon capture approach.

Keywords: Photobioreactor, Exhaust Gas, Microalgae, Carbon Capture, Single-Cylinder Engine.

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1. INTRODUCTION

According to the United Nations (UN), global conditions over the past two years have experienced an increase of 1,55˚C (Ade, 2022). Data from the World Health Organization (WHO) indicate that the global average concentration reached 338.0 pbb in 2024, representing a 25% increase compared to pre-industrial levels (Arif, 2025). This phenomenon refers to the gradual increase in the earth's average surface temperature due to the accumulation of greenhouse gasses in the atmosphere. Global warming is primarily driven by human activities, especially the combustion of fossil fuels, deforestation, industrial activities, and vehicle exhaust emissions.

These factors are the main contributors to the increasing concentration of gasses. According to the Ministry of Transportation of the Republic of Indonesia, Indonesia was recorded as one of the largest contributors to CO_2 emissions in the world in 2022, with approximately 1.3 gigatons of CO_2 emissions. Around 50.6% of these emissions originate from the energy sector, with more than 80% coming from transportation modes (cars and motorcycles). Vehicle exhaust emissions contain chemical compounds such as H_2O, CO_2, Nox, hydrocarbons (HC), and others. Excessive concentrations of these substances can lead to air pollution, which poses serious risk to the environment and human health (Publik, 2024).

Various previous studies have examined the utilization of microalgae as carbon capture agents in climate change mitigation through the integration of photobioreactor technology. Research by Debowski et al., 2025 shows that real exhaust gas can be effectively utilized, particularly in the co-combustion of coal and biomass, resulting in the highest biomass growth and biohydrogen production. In addition, the highest CO_2 reduction efficiency was achieved using biogas combustion exhaust, indicating that system has strong potential to support emission reduction and sustainable renewable energy production.

Furthermore, Falah, Abdi, & Arnadia, 2025 investigated the potential of microalgae as feedstock in carbon capture technology integrated with Carbon Capture and Storage (CCS) system. The study found that microalgae can absorb CO_2 with an efficiency ranging from 40% to 93.7%, depending on the species and operational conditions while requiring relatively low resources. However, large-scale implementation still faces challenges such as high operational costs, energy consumption, and regulatory constraints.

Kentji, Azzahra, & Kuswowo, 2025, demonstrated that photobioreactor can support optimal microalgae growth and enhance photosynthetic activity, making them a promising environmentally friendly carbon capture solution in urban areas. Nevertheless, the system still faces limitations in environmental control and large-scale application.

Research conducted by (Nirmawan, Kussuryani, & Hanupurti, 2014) showed that the addition of 10% CO_2 resulted in the best performance, characterized by the highest cell density and optimal CO_2 reduction rate. This finding indicates that moderate CO_2 injection can enhance both microalgae growth and carbon absorption effectiveness.

Meanwhile, Debowski et al., 2021 developed a photobioreactor based on immbolizied biomass (IMC-CO_2PBR) as an alternative carbon capture system that is more efficient than conventional photobioreactors. This technology is capable of producing high biomass concentrations and achieving CO_2 absorption efficiency of up to 40% under low gas flow rate conditions, indicating significant potential as a high-performance carbon capture solution.

In addition to design and system aspects, reaction kinetics have also been studied by Purba & Khairunisa, 2012 the study showed that the CO_2 absorption process follows a zero-order reaction, where temperature plays a significant role in increasing the reaction rate constant, while variations in CO_2 feed concentration have no significant effect. This highlights the importance of the thermal parameter control in photobioreactor operation.

Based on the review of previous studies, the utilization of microalgae in photobioreactor as a Carbon Capture and Storage (CCS) system Falah, Abdi, & Arnadia, 2025 and at laboratory and pilot scales (Nirmawan, Kussuryani, & Hanupurti, 2014). However, most studies still focus on experimental aspects of microalgae growth and variations in operational parameters such as CO_2 concentration, light intensity, and temperature, with limited attention to reactor design analysis and mathematical modeling of system performance (Purba & Khairunisa, 2012).

Moreover, studies specifically utilizing exhaust gas from single-cylinder Otto cycle engines as a CO_2 source in tubular photobioreactor are still very limited (Debowski et al., 2021). Therefore, this study aims to analyze the characteristic of exhaust gas from a single-cylinder Otto cycle engine as a basis for designing a tubular photobioreactor for carbon capture using microalgae. This research is expected to provide a foundation for designing a more optimal tubular photobioreactor system in utilizing vehicle exhaust emmisions as a CO_2 source.

2. METHOD

Research Flow

To ensure that the research is conducted in a systematic and well-structured manner, as illustrated in (Figure 1). The study begins with an initial stage (start), followed by a literature review to gather references related to photobioreactors, microalgae, and out to define the focus and scope of the analysis. The next stage involves determining the parameters used in data processing, including the photobioreactor design diameter, light intensity, seawater characteristic (pH), temperature, CO_2 concentration, microalgae growth rate, and mass transfer coefficient as the basis for evaluating system performance.

Subsequently, data processing is carried out through stoichiometric analysis to examine the relationship between exhaust gas composition and carbon absorption capability, as well as photobioreactor (PBR) design analysis to determine the required reactor dimensions. The processed results are then evaluated and iterated until they meet the established criteria. Once the data are deemed satisfactory, the study proceeds to the design stage of the tubular photobioreactor based on the analysis results and concludes with the formulation of conclusions that summarize the entire process, thereby producing an optimal and measurable system design for carbon capture

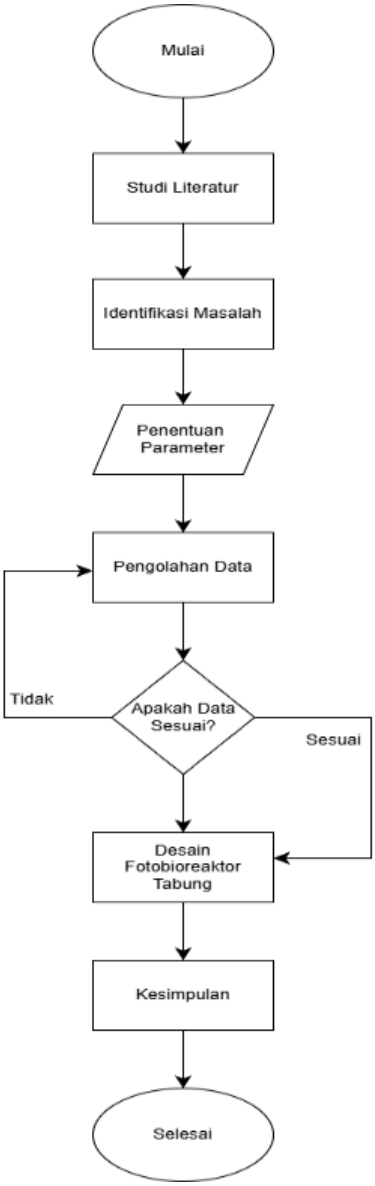


Figure 1. Research Flowchart

Exhaust Gas

Vehicle emissions are by-products of fuel combustion within the engine that are released through the exhaust system. Under complete combustion conditions, exhaust gases generally consist of CO_2, H_2O, O_2, and N_2, whereas incomplete combustion can produce harmful compounds such as Co, hydrocarbons (HC), Nox, and particulate matter. The CO_2 produced has the potential to be reutilized through carbon capture system using photobioreactors, considering its relatively stable nature and its ability to be transported through pressurized piping system.

In a single-cylinder engine, the entire process of air-fuel mixture intake, combustion, and exhaust occurs within a single-cylinder chamber, featuring simpler construction and limited power output. In this study, pertalite (RON 90) is analytically represented as the complete combustion as the complete combustion of octane (C_8H_{18}) to simplify the stoichiometric calculations of exhaust gas composition.

Combustion performance is influenced by factors such as cylinder dimensions, compression ratio, combustion chamber materials, and air temperature intake, which determine emission efficiency and composition. Therefore, measurable design parameters are established to support exhaust gas analysis and the optimal design of a tubular photobioreactor for carbon capture, as systematically presented in Tables 1 and 2.

Table 1 Single Cylinder Engine Parameters

Parameters	Symbol	Value	Unit	Source
Cylinder diameter	D	0,0524	m	Manual service honda
Piston stroke	S	0,0579	m	Manual service honda
Compression ratio	CR	9,3:1	-	Heywood
Maximum pressure	Pmax	3,5	MPa	Heywood, Khurni, & Gupta
Piston allowable stress	σ	0.10	MPa	Bhandari

Table 2 Determination of Design Parameters

Parameters	Symbol	Value	Unit
AFR	AFR	14,7	-
Intake air temperature	T	300	K
Fuel consumption	BSFC	75,7	g.kWh
Volume clearance	Vc	15,05	cm^3
Stroke volume	Vd	124,9	cm^3

Fotobireaktor

A photobioreactor (PBR) is a transparent reactor made of materials such as glass, acrylic, or plastic, designed to support the growth of microalgae. This system is equipped with a medium supply unit and a CO_2 gas delivery unit. Photobioreactors operate as closed systems, allowing the cultivation environment to be optimally controlled.

Microalgae within the photobioreactor utilize CO_2 as a carbon source through the photosynthetic process. Photosynthesis occurs in two stages, namely the light-dependent stage, in which the reaction is expressed as follows $H_2O + ADP + Pi + NADP^+ \rightarrow O_2 + ATP + NADPH + H^+$ dan $CO_2 + ATP + NADPH \rightarrow (CH_2O) + ADP + Pi + NADP^+$ the light-independent (dark) phase of photosynthesis (Politaeva, 2023).

In the photosynthetic process, microalgae produce oxygen, and the light source can be derived from sunlight, halogen lamps, LEDs, or other artificial lighting sources. The configuration of a tubular photobioreactor is illustrated in (Figure 2).

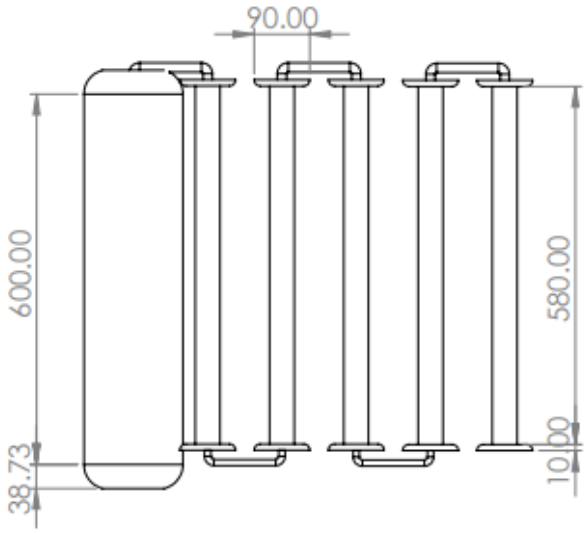


Figure 2. Tubular Photobioreactor

Therefore, in designing a tubular photobioreactor, it is essential to determine a set of relevant parameters to ensure that the proposed system can operate efficiently and optimally under the intended conditions. These parameters serve as fundamental design variables that influence system performance, including mass transfer, light distribution, and microalgae growth dynamics.

A comprehensive set of these parameters is presented in Table 2 below, which is used as a reference for the design process, performance evaluation, and further development of the photobioreactor system.

Table 3 Design Parameters of Tube Photobioreactor

Parameters	Value	Symbol	Source
Inner diameter of the tube	36	mm	(Torzillo, 2015)
Outer diameter of the tube	40	mm	
Tube thickness	2	mm	
Tube length	600	nm	
Inner diameter of storage tube	76	mm	
Outer diameter of storage tube	80	mm	
Thickness of storage tube	2	mm	
Storage tube length	600	mm	
Light intensity	1000	Lux	(Landa, et al., 2021)
Time	300	s	(Depra, 2019)
Temperature	20 -30	˚C	(Torzillo, 2015)

3. RESULTS AND DISCUSSION

Exhaust Gas Analysis

In the internal combustion exhaust process of a single-cylinder engine, the piston moves from Bottom Dead Center (BDC) to Top Dead Center (TDC) in one stroke. In a four-stroke engine, air intake occurs once every two crankshaft revolutions. Therefore, to determine the volumetric flow rate of air entering the cylinder based on engine speed (RPM), the relationship can be expressed as follows:

$$V_{air} = \frac{V_d \cdot RPM}{2} \quad (1)$$

$$V_{air} = \frac{124{,}9 \cdot 10^{-4} \cdot 6000}{2}$$

$$V_{air} = 37{,}47 m^3/menit$$

$$V_{air} = 0{,}6245\ m^3/s$$

Thus, the volumetric flow rate of the incoming air is obtained as 0.6245 m³/s. Furthermore, to determine the mass of air available in the combustion process based on operating pressure and temperature, the ideal gas law approach is applied using the parameters P=101325 Pa, R=287 J/kg·K, dan T=300 K,

The calculation can therefore be expressed by the following equation:

$$\rho_{air} = \frac{P}{R \cdot T} \quad (2)$$

$$\rho_{air} = \frac{101325}{287 \cdot 300}$$

$$\rho_{air} = 1{,}176 \frac{kg}{m^3}$$

Using the ideal gas law approach, the air density is obtained as 1.176 kg/m³. As a basis for determining fuel consumption and the amount of exhaust gas produced, it is necessary to analyze the air mass flow rate, which can be expressed by the following equation:

$$m_{air} = \rho \cdot V \quad (3)$$

$$m_{air} = 0{,}6245 \cdot 1{,}176$$

$$m_{air} = 0{,}734412\ kg/s$$

From the above calculation, the air mass flow rate has been obtained as 0,734412 kg/s.

Analysis of the Relationship between Single Cylinder Exhaust Gas and Microalgae

In the stoichiometric combustion of gasoline, which is theoretically represented as the complete combustion of octane (C_8H_{18}), the reaction indicates that each 1 mole of octane fuel produces 8 moles of CO_2 under complete combustion conditions.

Therefore, in this study, the combustion reaction is analyzed using 1 mole of C_8H_{18} as the basis. The equation used is as follows:

In the combustion reaction of octane exhaust gas:

$$C_8H_{18} + 12.5(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2$$

Thus, the reaction yields CO_2 =8 mol, H_2O =9, and N_2=47. After obtaining the exhaust gas composition, the next step is to analyze the stoichiometry of photosynthesis in microalgae. In general, the reaction can be expressed as $CO_2 + H_2O \rightarrow CH_2O + O_2$, This indicates that 1 mol of CO_2 produces 1 mol of O_2 and generates 1 mol of biomass in the form of CH_2O. In this study, 8 mol of CO_2 from the engine are used; therefore, the photosynthetic reaction is multiplied by 8, as follows:

$$8CO_2$$

$$8CO_2 + 8H_2O + \rightarrow 8CH_2O + 8O_2$$

Thus, it can be integrated as follows:

$$C_8H_{18} + 12.5O_2 \rightarrow 8CH_2O + 8O_2 + H_2O$$

Thus, the CO_2 produced from the combustion of 1 mol of C_8H_{18} (amounting to 8 mol of CO_2) can be entirely utilized by microalgae in the photosynthetic process to form 8 mol of biomass (CH_2O) and regenerate 8 mol of O_2. From the 9 mol of H_2O generated during combustion, 8 mol are consumed in photosynthesis, leaving 1 mol remaining.

Stoichiometrically, this indicates the potential integration of combustion and photosynthesis within a closed carbon cycle.

Tube Photobioreactor Analysis

In general, photobioreactor equations utilize tubular geometry to determine the volume of the reactor tube and the storage tank, as expressed below:

$$V_1 = \frac{\pi D^2}{4} L \quad (4)$$

$$V_1 = \frac{\pi(0{,}036)^2}{4}(0{,}6)$$

$$V_1 = \frac{\pi(0{,}001296)}{4}(0{,}6)$$

$$V_1 = 0{,}000611 m^3$$

$$V_1 = 0{,}611\ liter$$

$$V_2 = \frac{\pi(0{,}076)^2}{4}(0{,}6) \quad (5)$$

$$V_2 = \frac{\pi(0{,}005776)}{4}(0{,}6)$$

$$V_2 = 0{,}00272 m^3$$

$$V_2 = 2{,}72\ liter$$

$$V_{total} = V_1 + V_2 \quad (6)$$

$$V_{total} = 0{,}611 + 2{,}72$$

$$V_{total} = 3{,}331\ liter$$

Based on the calculation results using the parameters of inner diameter and the length of each tube, the total volume of the tubular photobioreactor system is obtained as 3.33 liters. This volume

falls within the laboratory scale, as most microalgae photobioreactor studies are conducted at the bench scale with relatively small volumes, typically below tens of liters, to maintain controlled conditions (Mondal, et al., 2017). In general, the laboratory scale typically ranges at volumes below 10–20 liters, while larger scales are employed for pilot and industrial applications. (Nirmawan, Kussuryani, & Hanupurti, 2014).

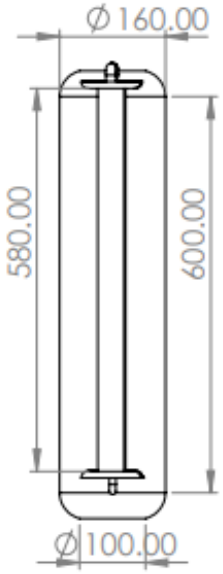


Figure 3. Storage Tube Design

The illumination surface area influences the growth of microalgae within the photobioreactor. Before calculating the total surface area, it is necessary to determine the surface area of both the storage tube and the illumination tube, which can be analyzed using the following equations:

$$A = \pi DL \quad (7)$$

$$A_1 = \pi(0{,}036)(0{,}6)$$

$$A_1 = 0{,}0679m^2$$

$$A_2 = \pi(0{,}076)(0.6)$$

$$A_2 = 0{,}1433m^2$$

$$A_{total} = A_1 + A_2 \quad (8)$$

$$A_{total} = 0{,}0679 + 0{,}1433$$

$$A_{total} = 0{,}2112m^2$$

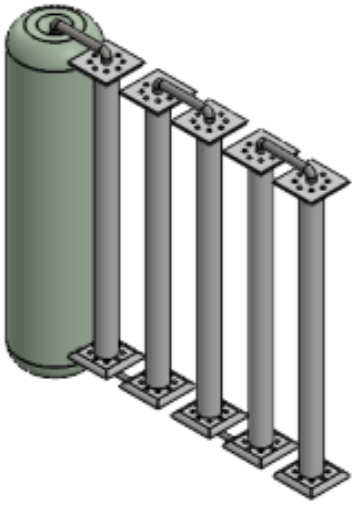


Figure 4. 3D Photobioreactor Tubular

Based on the calculation, the total illumination surface area of the photobioreactor system is 0.21 m². This surface area determines the amount of light energy that can be received by the microalgae culture during the photosynthetic process. It has the potential to enhance light distribution and photosynthetic efficiency, thereby supporting optimal microalgae growth.

Hydraulic Retention Time (HRT) is the residence time of a fluid within a system, which determines the effectiveness of reaction or growth processes in a reactor. Prior to analyzing the HRT, it is necessary to determine the required flow rate, which can be expressed by the following equation:

$$Q = \frac{V}{\tau} \quad (9)$$

$$Q = \frac{0{,}00333}{300}$$
$$Q = 0{,}0000111 m^3/_s$$
$$Q = 0{,}000111 \times 1000$$
$$Q = 0{,}0111\ liter/s$$
$$Q = 0{,}0111 \times 60$$
$$Q = 0{,}666 \frac{liter}{menit}$$

Thus, the required flow rate is 0.666 liters per minute. After obtaining the flow rate value, the next step is to analyze the Hydraulic Retention Time (HRT), which is defined as:

$$\tau = \frac{V}{Q} \quad (10)$$

$$\tau = \frac{0{,}00333}{0{,}0000111}$$
$$\tau = 300\ detik$$

With a system volume of 3.33 liters and a flow rate of 0.67 L/min, the Hydraulic Retention Time (HRT) is obtained as 300 seconds or 5 minutes. This value indicates that each fluid element remains within the system for 5 minutes before recirculating.

Furthermore, to determine the Reynolds number in the tubular photobioreactor system, it is necessary to calculate the cross-sectional area and flow velocity. This can be evaluated using the following equation:

$$A = \frac{\pi D^2}{4} \quad (11)$$

$$A = \frac{\pi(0{,}036)^2}{4}$$

$$A = 0{,}001018 m^2$$

With its flow rate, namely:

$$A = \frac{Q}{A} \quad (12)$$

$$A = \frac{0{,}0000111}{0{,}0109 m/s}$$

$$A = 0{,}0109 m/s$$

After obtaining the values of the cross-sectional area and flow velocity, the Reynolds number can be calculated as follows:

$$Re = \frac{\rho v D}{\mu} \quad (13)$$

$$Re = \frac{(1000)(0{,}0109)(0{,}036)}{(0{,}001)}$$

$$Re = 392$$

Thus, the Reynolds number is 392, indicating a laminar flow regime. Laminar flow suggests that the fluid moves in an orderly manner without significant turbulent mixing.

Due to the laminar flow condition (Re = 392), the volumetric mass transfer coefficient is 0.02 s^{-1}. Furthermore, gasoline engine exhaust gas generally contains approximately 10% CO_2, with a CO_2 solubility in water (at 25°C) of 1.2 mol/m^3, while the actual concentration in the culture is 0.2 mol/m^3.

Thus, the CO_2 transfer rate Microalgae, can be determined as follows:

$$N_{CO2} = 0{,}02(1{,}2 - 0{,}2) \quad (14)$$

$$N_{CO2} = 0{,}02\ (1)$$

$$N_{CO2} = 0{,}02\ mol/m^3.s$$

With a total system volume of 0.00333 m^3, the total transfer within the system is expressed as follows:

$$\dot{n}_{CO2} = N_{CO2} \times V \quad (15)$$

$$\dot{n}_{CO2} = 0{,}2 \times 0{,}00333$$

$$\dot{n}_{CO2} = 0{,}0000666 mol/s$$

1 mol CO2=44g, so (16)

$$m_{CO2} = 0{,}0000666 \times 44$$

$$m_{CO2} = 0{,}00293 g/s$$

Per-hour:

$$= 0{,}00293 \times 3600$$

=10,5 gram/hour

Under laminar flow conditions and a system volume of 3.33 liters, the system can transfer approximately 10 grams of CO_2 per hour into the culture. The CO_2 transfer rate in this system is relatively low due to the laminar flow regime and the small reactor volume.

4. CONCLUSION

Based on the analysis of exhaust gas from a single-cylinder Otto cycle engine and the design of a tubular photobioreactor, it can be concluded that the stoichiometric combustion of octane (C_8H_{18}) produces 8 mol of CO_2 per mole of fuel, which can theoretically be fully utilized in the photosynthetic process of microalgae to form biomass (CH_2O). This demonstrates the potential integration of combustion systems and photobioreactors within a closed carbon cycle.

The resulting photobioreactor design has a volume of 3.33 liters, an illumination surface area of 0.21 m², a Hydraulic Retention Time (HRT) of 300 seconds, and operates under laminar flow conditions with a Reynolds number of 392, achieving a CO_2 transfer capacity of approximately ±10.5 grams per hour, which falls within the laboratory scale. These results indicate that the system can operate in a measurable and controlled manner; however, the CO_2 transfer capacity remains relatively low due to the limited volume and flow characteristics.

Therefore, future research is recommended to conduct direct experimental validation, scale up the reactor system, optimize lighting and mixing conditions to approach transitional or controlled turbulent flow, and evaluate energy efficiency and economic aspects to support the development of a more practical and sustainable carbon capture system.

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Table 4 Glosarium

Symbol	Information
P	Air pressure
R	Air gas constant
T	Temperature
ρ	Air density
Q	Debit
m	Air mass rate
RPM	Engine speed
Di	Inner diameter of the tube
Do	Outer diameter of the tube
L	Tube length
V	Reactor volume
A	Surface area
HRT	Hydraulic residence time
D	Diameter
Re	Reynolds number
ρ	Fluid density
v	Flow rate
μ	Dynamic viscosity
τ	Fluid residence time (HTR)
$\dot{n}$	Molar flow rate
n	Number of moles
C_8H1_8	Octane (gasoline fuel)
O_2	Oxygen
N_2	Nitrogen
CO_2	Carbon dioxide
H_2O	Water vapor
CH_2O	Representation of microalgae