Numerical simulation of detailed airflow distribution in newly developed photosynthesis chamber

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Abstract. Predictive numerical simulation of airflow uniformity in canopy plants could provide a suitable environment for plant growth. A numerical investigation of airflow in a photosynthesis chamber was conducted using the Computational Fluid Dynamics (CFD) model. This research-validated the numerical model with measurements performed in a bare bottom open chamber. The chamber has bottom openings with three exhaust fans on the roof. After model validation, airflow patterns and their uniformity were evaluated in different fan arrangements and doubled air volume rates. The obtained results showed that a more uniform airflow distribution was observed with increasing the fan's air volume rate (0.0187, 0.0172, and 0.0177 m$^3$s$^{-1}$), particularly fan in the middle position and diagonally position inside the plant with coefficients of variation of 14.36%, 9.3% and 10%, respectively. Moreover, increasing the fan's air volume rate and moving the fan positions to the middle and diagonally can significantly help produce uniform air velocity distribution inside the plant.

1. Introduction
The response of net photosynthesis to air velocity has become vital in increasing and maintaining airflow uniformity in the plant canopy. Many researchers have conducted air velocity studies in the plant canopy to investigate its influence on plants. For example, Shibuya et al. (2006) experimentally clarified that upward and downward airflows enhanced the CO$_2$ exchange rate of the canopy and dry masses of the seedlings from 1.4–1.5 and 1.2–1.3 times, respectively, compared with a conventional horizontal airflow [1]. Okayama et al. (2008) reported (that fans set on both sides of the space and opposed fans not set coaxially) could provide more uniform airflow distribution than the conventional airflow pattern (fans set on one side of the room) [2]. It also enhanced the net photosynthetic rate more than that in the traditional airflow pattern with the same energy input. Furukawa (1975) showed that changing the air temperature did not significantly affect airflow rate efficiency on photosynthesis but increasing the light intensity enhanced it significantly [3].

Primary data on adequate air circulation to enhance plant growth in a closed plant culture system (chamber) were obtained by investigating the effects of the current airspeed ranging from 0.01–1.0 ms$^{-1}$. Researchers also found that the plant canopy's net photosynthetic rate doubled with increased air
current speed above the plant canopy [4]. The net photosynthetic rate at an air velocity of 0.4 m s\(^{-1}\) was 1.3 more times than 0.1 m s\(^{-1}\) under CO\(_2\) concentrations of 0.4–0.8 mmol [5].

Shibuya et al. (2006) reported that a recently developed closed-type transplant production system could produce high-quality transplants, regardless of the weather [1]. It is easier to design a ventilation system that provides the required air circulation in a closed-type system than in a greenhouse. In previous studies, the chamber had openings on both sidewalls, and outside air entered the chamber through these openings [1,4,5]. The chamber's length and width are more significant than its height. In this study, we focused on a newly developed bottom opened chamber with three exhaust fans on top of the chamber. Shimomoto et al. (2020) successfully traced the time courses of the net photosynthetic rate, transpiration rate, and total conductance of tomato plants inside the monitoring system using a similar chamber [11]. The new chamber measures the photosynthesis rate and various environmental data around the entire plant. However, the uniformity of airflow and the detailed distribution of air velocity in the chamber is unclear, despite the air movement contributing to gas exchange between the plants and ambient air affecting plant growth.

One method for identifying a detailed airflow pattern is using the Computational Fluid Dynamics (CFD), model. CFD has often been used to evaluate and predict the environment in several greenhouses [7–10] or chambers. CFD can also be used for testing various simulation cases without an experimental approach. This study numerically investigates airflow patterns and their uniformity in the new chamber under different fan arrangements to realize a suitable plant growth environment.

2. Methodology

2.1. Description of the chamber

The chamber used for monitoring real-time photosynthesis is set in a north-south oriented Venlo type greenhouse. The newly developed bottom opened chamber measurements were 1.05 m in length × 0.52 m in width × 2.15 m in height. It was made of transparent film (vinyl sheet; SUS. Co., Ltd. Japan) and provided by PLANT DATA Co., Ltd. The chamber contained two tomato plants and three fans as outlets with air volume rates of 0.0094, 0.0086, and 0.0089 m\(^3\) s\(^{-1}\) were set on the chamber's roof. The planting density was 2.5 plant m\(^{-2}\). The plant height was ~1.6 m, and the LAI was 4 m\(^2\) m\(^{-2}\) when measurements were conducted inside the chamber.

2.2. Brief description of airflow measurement in the chamber

The air velocity was measured using an anemometer (Climomaster Model 6501-B0, Kanomax, Japan), which can examine wind speeds ranging from 0.05 to 30 m s\(^{-1}\). In this study, horizontal and vertical air velocities were measured inside the empty chamber on 162 points (figures 1 and 2). Air velocities were measured until the anemometer reached a stable value.

![Figure 1. Horizontal measurement points A, B, C (top-view).](image1)

![Figure 2. Vertical measurement point no.1–6, points 2–6 are 0.175 m apart (front-view).](image2)
2.3. Numerical model description
Figure 2 shows the 3D domain used for simulating airspeed by using a foliage object inside the chamber as a plant, 0.6 m in length, 0.4 m in width, and 1.6 m in height. Numerical simulation was performed using commercial CFD software (PHOENICS Ver. 2018), which solves the balance equation by a finite volume method. It is a discretization method well suited for numerical simulation of several types of conservation laws [6]. The basic equation model adopted in this research is shown below. Variable \( \phi \) represents either transport variables for transportation of mass, airspeed, or carbon dioxide concentrations in the domain and is ruled by the governing equation.

\[
\frac{\partial \phi}{\partial t} + \text{div}(u \phi) = \text{div}(\hat{\Gamma}_\phi \text{grad} \phi) + S_\phi
\]

(1)

Where \( u \) is the directional air velocity; \( \hat{\Gamma}_\phi \) is the diffusivity for \( \phi \), and \( S_\phi \) is the source term. In this study, the Chen-Kim modification k-\( \varepsilon \) model was used to compute the turbulent effect of airflow.

2.4. Simulation cases
Three fans were placed at the top of the chamber as outflow with a few designated positions. The fan position was designed to investigate the airflow pattern and airspeed within the chamber. The net photosynthesis in the plant canopy was also calculated for each way. Figure 3 shows three fan arrangements. Pattern (a) was in the default system, set in the real chamber, with the fans placed on one side. Patterns (b) and (c) put the fans in the middle and diagonally.

![Figure 3. Arrangement position of fans.](image)

2.5. Boundary conditions
A constant input value was selected to set the CFD simulation's boundary conditions and validate the photosynthesis model results (table 1).

| Parameter          | Momentum        |
|--------------------|-----------------|
| Flow rate of fan   | 0.0094, 0.0086, and 0.0089 m\(^3\) s\(^{-1}\) |
| Chamber walls      | no slip         |
| Chamber top        | no slip         |
| Bottom opening     | fixed pressure  |

3. Results and discussion
3.1. Model validation
Figures 4A and 4B compare the vertical airspeed between measurement and simulation. The measurement points for the comparison figure 4A are 1B (figure 3 and 4), close to the chamber's left wall, whereas figure 4B is 4B, which shows the measurement points in the middle of the chamber. Figure 4A shows that the observed air velocity rapidly decreased by increasing the fans (2.12 m
height). In the middle of the chamber, the air velocity is almost constant with the altitude (figure 4B). The measurement points in figures 4A and 4B were 0.087 m and 0.525 m from the left wall (figures 3 and 4). The simulation results were plotted in cross-section (B line in figure 1) in the middle of the chamber, showing a good correlation between the measurement data and simulated airflow inside the bottom open chamber (figure 4). The simulation results, especially near the fan, showed good agreement with the measurement results, whereas the simulation results under 1.5 m of the chamber height were slightly overestimated. However, the CFD model's accuracy seemed sufficient to investigate the velocity because the difference between the measurement and simulation data was with RMSE 0.02 ms$^{-1}$ (4A) and 0.03 ms$^{-1}$ (4B).

![Figure 4A](image_url) ![Figure 4B](image_url)

**Figure 4.** Simulated and measured air velocity profile.

3.2. Airflow through the plant

Figure 5 shows the simulated airflow distribution inside the chamber with the plant. Outside air has entered the room through the bottom opening. The air velocity was almost uniformly, with an average value of 0.05 ms$^{-1}$ inside the chamber and the plant. Although it is not shown in figure 5, there was a slight discrepancy in air velocity between inside and outside the plant because of the tomato plant's drag effect.

![Figure 5](image_url)

**Figure 5.** The simulated airflow at the horizontal cross-section B inside the chamber. The rectangular box represents a tomato plant.

3.3. Airflow change in different air volume rates

Figures 6 and 7 show the distribution of air velocity at controlled and double air volume rates, respectively. When the fan's air volume is 0.0094, 0.0086, and 0.0089 m$^3$s$^{-1}$, the chamber's average air velocity is 0.05 ms$^{-1}$. 


However, in the case of a doubled air volume rate (0.0187, 0.0172, and 0.0177 m$^3$s$^{-1}$), air velocity inside the chamber increases and, consequently, the average speed becomes 0.09 m$s^{-1}$ (figure 7). Air velocity near the fans was higher than the opposite side (the right side of the wall, near the border). In both cases, the distribution of airflow seems almost uniform inside the plant. Figure 7 shows that the air velocity inside the plant reached $\sim$ 0.11 m$s^{-1}$, triggering the increase in net photosynthesis. This increase can also be because the increased air current speed doubled the plant canopy's net photosynthesis rate from 0.1–1.0 m$s^{-1}$ [4].

![Figure 6](image6.png)  
**Figure 6.** The airflow distribution inside the chamber for control air volume rate. The rectangular box represents a tomato plant.

![Figure 7](image7.png)  
**Figure 7.** The airflow distribution inside the chamber for a double air volume rate. The rectangular box represents a tomato plant.

3.4. *Airflow change in different fans positions*

Figure 8 shows the distribution patterns of air velocity at different fan positions. In the prints (a), (b), and (c), the average air velocity inside the plant was 0.05 m$s^{-1}$ with almost equal distribution. In pattern (b), the variability of air velocity inside the chamber was relatively high. The airflow passed through the bottom opening as an inlet and spread to the entire chamber, including the plant's inner portion. In pattern (c), the air velocity inside the chamber has high variation because the side near the outlet had a higher air velocity. The mean air velocity inside the chamber with different fan positions ((a), (b), (c)) was the same at 0.05, m$s^{-1}$. The simulation results show in detail the airflow distribution inside the chamber. As shown in table 2, a more uniform airflow distribution was observed with a fan in the middle position (pattern (b)) and diagonally position (pattern (c)) inside the plant with coefficients of variation of 9.3% and 10%, respectively. According to these results, fan positions influence the uniform provision of airflow into the plant canopy. Like Okayama [2], the airflow from one side of a cultivation room cannot provide a constant air current between the near side and the far side of a plant canopy.

![Table 2](image2.png)  
**Table 2.** Summary of air velocity for each model in the uniformity of airflow.
4. Conclusion
A CFD model simulates airflow in the newly developed photosynthesis chamber and design and proposes an improved air velocity uniformity in the canopy plant. With a doubled air volume rate, the airflow design improved the air movement uniformity in the plant canopy compared to the default air volume rate. Changing the fan position to the middle and diagonally for enhancing the uniformity of air velocity in the canopy plant was better than placing it at the side (default).

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