Tracer study of CO₂ enrichment for shallot growth in mini plant factory with CFD approach

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Abstract. It has been proven that the effect of CO₂ enrichment leads to faster growth and higher yields. Using environmental parameters controlling based on needs, responses, and performance of crops, CO₂ level from 800 to 1500 ppm were able to accelerate the growth of shallot in mini plant factory. Therefore, CFD simulation was conducted to simulate and trace the distribution of CO₂ with varying airflow inlet. Airflow inlet is two wall air conditioners (ACs) with the 2 pk specification. Both of ACs was attached at opposite walls. There were two combinations of ACs position, which are top-top (both of ACs were positioned approximately 10 cm below the ceiling) and top-center (an AC positioned approximately 10 cm below the ceiling and another positioned 60 cm below the ceiling). In the simulation, CO₂ gas was injected into the inlet from 0.5 l min⁻¹ to 2 l min⁻¹. The simulation was used for tracing CO₂ injection and position that has the highest uniformity coefficient at the CO₂ levels of around 800 ppm. It is proven through a numerical approach, the best ACs position is a top-top combination, with CO₂ injected, is 2 l min⁻¹.

Keywords: CO₂ level, combination of ACs position, simulation, uniformity coefficient.

1. Introduction

The value of CO₂ gas concentration has an important role in understanding the behavior of plant growth, where the value of CO₂ gas concentration can be used as a key parameter in the photosynthesis so that the physiology of leaves can be monitored periodically [1]. The positive effects of the increase of CO₂ gas in the Earth’s atmosphere are the increase of plant biomass production [2]. Therefore, it can be said that the phenomenon of CO₂ gas exchange on leaves can describe a variety of parameters on the ecophysiological of the plant [3]–[7], both at the molecular level, biochemistry, leaf tissue and canopy [7]–[9].

The effectiveness of CO₂ gas exchange on the leaves is very influential on plant photosynthesis rate which is a key factor of plant growth activity [10], so the effort to increase crop productivity can be done by enriching CO₂ gas in plant canopy [11]. By enriching the carbon dioxide gas concentration of about 1000 ppm, the cumulative biomass of tomato plants can increase by about 30-60% per plant [3]. But when the light intake conditions are small (like during the winter season), the recommended CO₂ concentration for
tomato plants is around 700-900 ppm [4], [12], while for Chrysanthemum and Saintpaulia ionantha flowers, CO₂ enrichment is 900 ppm apparently able to reduce flowering time and increase the number of flowers significantly [12]. This proves that environmental control grows in the form of enrichment of CO₂ is capable of increasing plant growth, both in its vegetative and generative stages. It shows that this method has an important role in environmental engineering efforts to plant growth.

The shallot seed production system in Indonesia, in general, is still dependent on climate and topographic conditions [13], so the alternative production with environmental control efforts on the growth of shallots is a promising expansion of production sources. The alternative recommended in this article is the development of a mini plant factory technology package for shallots production in a controlled environment. One important parameter in the design of the technology package is the distribution model of CO₂ concentration in the growing environment. This parameter is necessary to ensure the supply of CO₂ to cultivated plants. A design tool that can describe and visualize the distribution of CO₂ gas concentrations in 3D is by CFD simulation approach.

CFD simulation approach proved to be able to visualize some physical parameters of plant growth environment such as temperature distribution in the root area [14], [15] to design the root-zone cooling system, the distribution of temperature and relative humidity on the leaf surface [16], air flow through the canopy a plant [17], [18], assessment of the application of natural ventilation [19], [20][21], and mechanical ventilation [22]–[24], the study of quality and concentration of air in a room [25]–[28], even assessment for sprayer applications on plants [29], [30]. Therefore, this article focuses on the tracer study of CO₂ enrichment for shallot growth in a mini plant factory with CFD approach.

2. Description of Mini Plant Factory

The factory with artificial lighting (PFAL) is defined as a closed crop production system with a building structure equipped with thermal insulators that are not translucent, minimal ventilation and a light source for plant growth using artificial light [31], [32]. The concept is based on the concept of a closed plant production system (CPPS) which consists of six important elements [33], namely: 1) impermeable wall structure, 2) multitier system, generally 4-8 layers with a height of about 40 cm between layers, 3) cooling device and dehumidifier as well as air circulator, 4) CO₂ enrichment units, 5) fertilizer system and 6) fertilizer controller.

The developed mini plant factory was made in a 40 ft. container consisting of a control room, chamber room (cultivation room) and nutrient room. The simulated room is only a chamber with a size of 672 x 212 x 261 cm. The room is equipped with 6 planting media shelves in the form of a substrate with a drip irrigation system. Each layer of the plant shelf is equipped with 4 units of lights as a lighting source for the photosynthesis process. The cooling source in the cultivation room comes from 2 AC units with a capacity of 2 pk. The position of the AC is placed on the front and rear walls with two different combinations, namely the top-top and top-center. The top position of the air conditioner is about 10 cm from the ceiling right in the middle of the wall, while the center position is around 60 cm from the ceiling. CO₂ gas with a variety of flow rates is exhaled through the blowing of air from both air conditioners to the chamber using a water pass pipe so that the flow of CO₂ gas will follow the air blowing from the air conditioner. Variations in CO₂ flow rates from 0.5 liters/minute to 2 liters/minute.
3. Numerical simulation

CFD simulation has been done on Flow Simulation Solidworks software (Solidworks inc., 2016). The commonly used mathematical model is the Reynolds Averaged Navier-Stokes (RANS) equation which includes energy conservation, mass and momentum conservation with the finite volume method approach.

The chambers for plants in containers are impermeable, so that the air flow in the room can be laminar or turbulent. Therefore, the Flow Simulation Solidworks software considers laminar and turbulent flow, and to predict turbulent flow, Solidworks uses the Favre-Average Navier-Stokes (FANS) approach. However, for mixing gas concentrations inside the chamber that comes from injection of carbon dioxide gas, the approach taken is diffusion by involving a Lewis number, so that it can describe the concentration of the carrier gas and its essential gas, in this case carbon dioxide gas.

\[
\frac{\partial \rho y}{\partial t} + \frac{\partial}{\partial x_i} \left[ \rho u_i y - \rho \frac{R}{p} \left( \frac{1}{\Pr} \frac{\partial}{\partial x_i} - \frac{k}{\Pr L_e} \frac{\partial y}{\partial x_i} \right) \right] = \frac{\partial}{\partial x_i} \left[ \frac{\rho u_i y - \rho}{p} \left( \frac{1}{\Pr} \frac{\partial}{\partial x_i} + \frac{k}{\Pr \Pr_t L_{et}} \frac{\partial y}{\partial x_i} \right) \right]
\]  

(1)

where, \( \rho \) is the carrier gas and the essential mixture density; \( p \) is the carrier gas static pressure, \( R \) is universal gas constant, \( m \) is carrier gas and the essential mixture molar mass, \( m_1 \) is the essential gas molar mass, \( m_2 \) is the carrier gas molar mass, \( v_i \) is the specific volume of the essential gas, \( \Pr \) and \( \Pr_t \) are laminar and turbulent Prandtl numbers, \( Le \) and \( Le_t \) are laminar and turbulent Lewis numbers, \( x_i \) is the \( i \)-th component of coordinate system, and \( u_i \) is velocity at the \( i \)-th component.

4. CFD model setup

The air inlet only comes from the AC that is carried with the CO\(_2\) gas inlet. The mass flow rate of air from AC based on its specifications is around 17.7 \( m^3/min \), where by default the CO\(_2\) content in the air is defined as 380 ppm. Then, pure CO\(_2\) gas is injected into both ACs which are applied with the same mass flow rate, starting from 0.5 \( l/min \) to 2 \( l/min \). The combination and input scenario in this CFD simulation can be seen in table 1.
Table 1. The input scenario combination of simulation.

| AC position       | Mass flow rate CO₂ (l min⁻¹) |
|-------------------|-------------------------------|
| top-top           | 0.5, 1, 1.5, 2,               |
| top–center        | 0.5, 1, 1.5, 2,               |

Accuracy in the CFD simulations strongly influenced by the appropriate set of boundary condition exerts. The surface material in the chamber (including the surface of rack materials, side walls, floor, and ceiling) was defined as impermeable no-slip walls or real walls.

Simplifying the model in the simulation is something that cannot be avoided, so that the problems in the iteration can be solved easily. Some of the assumptions in this simulation are: 1), incompressible, 2) steady state, 3) single phase or no chemical reaction between essential gas and carrier gas, 4) CO₂ absorption by plants ignored, and 5) wall temperatures are constant.

5. Result and Discussion

Calculations in this simulation converge at 1.7 million mesh cells. Convergence is obtained by doing a mesh independency study to verify numerical calculation results or in other words reduce the error value of the iteration results and the parameter values obtained have shown a consistent number even though there is an increase in the number of cells. The main parameter of the calculation is the value of the concentration of carbon dioxide. The local domain that is considered is the space where the plant grows or the canopy zone of plant, so that in this case the calculated data that is noticed is in the zone of about 10 cm from the surface of the planting media found on each plant shelf. Plant shelf consists of 3 layers.

Levels of mass fraction of carbon dioxide gradients are presented in 15 levels with a range of values from 400 ppm to 1000 ppm. This is considered to represent the CO₂ enrichment target, ie until the optimum rate of photosynthesis is around 800 ppm until 1000 ppm. In addition to the concentration of CO₂, other parameters also contribute to the process of photosynthesis and respiration, such as temperature and relative humidity. The distribution of CO₂ concentration is presented in figure 2 with a parameter of mass fraction of carbon dioxide with ppm units. The image is a side view with a difference of 2 AC height locations; top-center and top-top.

Figure 2 shows that in general the concentration of CO₂ gas spreads fairly evenly between the plant shelves and moves towards the surface of the floor when the CO₂ gas is injected from the AC unit. This proves that the gravity factor calculated in the simulation works well. In addition, the spread of CO₂ gas to various corners of the room also proves that the fluid moves diffusively in addition to being affected by air blowing from the air conditioner.

The concentration of CO₂ for 0.5 l min⁻¹ input on top-top and top-center layouts is approximately 680 ppm to 742 ppm, and 572 ppm until 618 ppm. In scenario 2 (where CO₂ is injected 1 l min⁻¹) the CO₂ concentration is around 740 ppm until 786 ppm (top-top), and 732 ppm until 780 ppm (top-center). The concentration increase is close to the target value of the optimum CO₂ concentration. In general observations, the distribution of CO₂ that can be categorized as reaching the target value of optimum growing environmental requirements is found in scenarios 3 and 4 (1.5 l min⁻¹ and 2 l min⁻¹) which is around 800 ppm until 910 ppm. But on the other hand, it should also be considered the uniformity factor to ensure that the distribution of CO₂ gas can be accessed by all cultivated plants, so that uniformity of plant growth can be achieved. In general, the coefficient of CO₂ concentration uniformity of the simulation results is very
good, which is above 98%. But the best value of uniformity is found at the value of the flow rate of 2 \( \text{l min}^{-1} \) of carbon dioxide, where the uniformity of the top-top is almost the same as the top-center which is 99.78% and 99.82% respectively. The coefficient of uniformity for each flow rate can be seen in figure 3.

**Figure 2** The distribution of carbon dioxide.

**Figure 3** Coefficient of uniformity for variation of carbon dioxide flow rate.
6. Conclusion
The best scenario in designing the ACs position and carbon dioxide discharge in the mini plant factory respectively is the top-top position and 2 l min⁻¹.

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