A Simulation for Precision Airflow Control using Multi-Fan in a Plant Factory

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A new airflow system with multi-fan for precise airflow control and its evaluating method were suggested. A computational fluid dynamics (CFD) simulation was employed to analyze airflow. A cultivation space ($1.0 \times 1.0 \times 0.5$ m$^3$) was established in the CFD model, and 12 lettuce models with simplified shapes were set in the space. Six small fans were used for generating airflow in the model. In order to verify the accuracy of the CFD model against the actual situation, the same situation as the CFD model were prepared. Lettuce replicas were made of steel meshes with sealing tapes. The accuracy of the CFD model was enough to investigate performances of the airflow control patterns. We assumed that the net photosynthetic rate per plant can be calculated the summation of the net photosynthetic rate calculated with the air current speed and the leaf area in the cell (the minimum unit of the CFD model) on the surface of the lettuce models which were the adjacent cells to the lettuce models. The suggested airflow control pattern could provide more uniform airflow distribution than the conventional airflow pattern and also enhance the net photosynthetic rate more than that in the conventional airflow pattern with the same energy input.

Keywords: air current speed, CFD lettuce, photosynthetic rate

INTRODUCTION

Risks of decreasing yields in warmer environments and increasing insect outbreaks are virtually certain because of global warming (IPCC, 2007). Against these risks and also other environmental problems, new innovations are required in agricultural industry. The Low-Input Sustainable Agriculture (LISA) program was launched to reduce the use off-farm inputs which the greatest potential to harm the environment or the health of farmers and consumers. However, LISA has not gained appreciable support from the agricultural sector, since the nature of LISA decreases profits. On the other hand, the implementation of Precision Agriculture (PA) which uses the extensive application of information and mechanical technology has been embraced. The difference between PA and LISA is that PA requires technological innovation, whereas LISA always involves revising or improving traditional practices. There are some plant factories operating commercially in Japan. The fully controlled environment of a plant factory can be considered as an ideal cultivation system in which most of the environmental factors are observable and controllable. This means more in-

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tensive PA, we called Micro-Precision Agriculture (MPA), can be attained by using plant factories to realize profitable alternative agriculture (Murase, 2000).

In this study, we focused on an airflow control as one of techniques for MPA in a plant factory. It is much easier to design an airflow control system that provides an adequate airflow to plants in a plant factory than in an open system such as a greenhouse. The photosynthesis of a leaf is not only depend on the light intensity, but also both relative humidity and air velocity (Yabuki and Miyagawa, 1970). Therefore, the air circulation method is essential to control the micrometeorological environment around plants (Shibuya et al., 2006). Some studies show the importance of airflow control for plant growth. The net photosynthetic rate of tomato seedlings at the air current speed of 0.6 m s\(^{-1}\) was 1.9 times that at the air current speed of 0.1 m s\(^{-1}\) (Shibuya and Kozai, 1998). And the net photosynthetic rate of sweet potato leaves increased significantly as the air current speed increased from 0.01 to 0.2 m s\(^{-1}\) and the net photosynthetic rate of tomato seedling canopy was doubled by increased air current speed from 0.1 to 1.0 m s\(^{-1}\) above the plant canopy (Kitaya et al., 2003). Soybean plants in the air current speed of 0.8 m s\(^{-1}\) was 14% more massive (shoots) than plants in the air current speed of 0.4 m s\(^{-1}\) (Korthals et al., 1994). Shibuya et al. (2006) reported that the effects of airflow directions on the CO\(_2\) exchange rate of the tomato seedling canopy and the growth of the seedling using the upward and downward airflow system were compared with those observed using the conventional horizontal airflow system. The suggested airflow system enhanced the CO\(_2\) exchange rate of the canopy and the dry masses of the seedling by 1.4–1.5 and 1.2–1.3 times, respectively, as compared to the conventional horizontal airflow. These results indicate that airflow direction is also important for plant growth.

Lettuce which is one of the most popular leafy vegetables in the world was targeted in this study, because lettuce is frequently cultivated in plant factories due to its short cultivation cycle from seed to harvest and low light intensity requirement. Lettuce tip burn is a serious problem when growth speed is promoted. An adequate air supply to the inner leaves was shown to prevent tipburn by increase Ca accumulation in the inner leaves (Goto and Takakura, 1992a, b).

Little air movement induces spatial variations in the air temperature, CO\(_2\) concentration and humidity, and these variations hinder from equalizing qualities of products. It is obvious that the airflow from the one side of a cultivation room can not provide uniform air current between near side of a plant canopy and the far side of that. The airflow should be flexible, because the air velocity which can enhance the rates of net photosynthesis depends on the size of plants (Shibuya and Kozai, 1998).

We suggested an airflow system with multi-fan to control airflow precisely. Takahashi et al. (2002) tried to control local temperature by controlling two fans separately. The airflow control using multi-fan will be able to reduce the variability of environmental condition and to optimize air velocities around plants more easily than a conventional control. These advantages lead to minimize an input energy and maximizing cost-benefit performance.

To control the airflow precisely, the airflow distribution must be recognized precisely. However, it is difficult to measure speed and direction of the air current at multi-point three-dimensionally and simultaneously. Therefore, a computational fluid dynamics (CFD) simulation was employed to analyze airflow. Now CFD simulations are regularly employed to solve environmental problems of greenhouses and animal production facilities (Norton et al., 2007). Boulard and Wang (2002) showed validity of the CFD model for a plastic greenhouse against the experimental results. And Campen and Bot (2003) and Lee and Short (2001) also reported that the good performance of the CFD model to evaluate the natural ventilation system of greenhouses. Kacira et al. (2004) reported that the necessity of analyzing the air current condition in the plant canopy zone using the CFD model.

Objectives of this study were to investigate the performance of the airflow control system with multi-fan in a plant factory, to compare a result of the CFD simulation model to measured data,
and to explore the better airflow control using this system for uniform airflow distribution and enhancement of photosynthesis.

MATERIALS AND METHODS

The CFD model description
In this study, the CFD software (QuickStream Ver. 3.0, Yokogawa Techno-Information Service Inc., Japan) was used for analysis. The QuickStream employs Adams-Bashforth method which improves the time derivative and the following dynamic equations (QuickStream manual, 2006).

\[
\frac{\partial(u)}{\partial t} + \frac{\partial(v^2)}{\partial x} + \frac{\partial(uv)}{\partial y} + \frac{\partial(uw)}{\partial z} = - \frac{\partial P}{\partial y} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]

\[
\frac{\partial(v)}{\partial t} + \frac{\partial(v^2)}{\partial y} + \frac{\partial(vu)}{\partial x} + \frac{\partial(vw)}{\partial z} = - \frac{\partial P}{\partial x} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)
\]

\[
\frac{\partial(w)}{\partial t} + \frac{\partial(w^2)}{\partial z} + \frac{\partial(wu)}{\partial x} + \frac{\partial(wv)}{\partial y} = - \frac{\partial P}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\]

where:
- \( u \): Flow velocity in X direction (m s\(^{-1}\))
- \( v \): Flow velocity in Y direction (m s\(^{-1}\))
- \( w \): Flow velocity in Z direction (m s\(^{-1}\))
- \( P \): Air pressure Pa
- \( \nu \): Dynamic viscosity coefficient (m\(^2\) s\(^{-1}\))

The airflow was considered as laminar airflow in the simulation.

A cultivation space \((1.0 \times 1.0 \times 0.5 \text{ m}^3)\) was established in the CFD model. Due to the software limitation, the maximum number of cells on each side is 100. The maximum length of the side in the model was 1 m. Therefore, the minimum cell size in the model was a cube 10 mm on a side. Lettuce models with simplified shapes were employed, because it is impossible to imitate an actual shape of a lettuce using the cell. Even if actual lettuces are seeded simultaneously and grown in the same environmental condition, they do not have exactly the same shapes. Therefore, two types of the lettuce models were prepared to represent these differences. The size of the lettuce models was explained in Fig. 1. The lettuce model corresponds with an actual lettuce on about 20 days after germination under a conventional environmental condition.

Twelve lettuce models were located on a board \((450 \times 600 \text{ mm}^2)\) and two types of the lettuce models were set alternately (Fig. 2).

Fig. 1 Two types of lettuce models consist of cubes with 10 mm on a side.
Figure 3 (left) shows the schematic view of the cultivation space represented with polygons and meshed for calculation. The space consisted of 50456 (54 × 68 × 14) cells. The region near lettuces for analysis was especially segmented finely (Fig. 3 right).

Airflow on the surface of lettuce leaves is important for photosynthesis. Therefore, the air current speeds of the cells which contact with lettuce models were evaluated. The cells were shown as translucent cells in Fig. 4. An air current speed \( (s_{ijk} \text{ m s}^{-1}) \) used for evaluation was calculated by this equation:

\[
s_{ijk} = \sqrt{u_i^2 + v_j^2 + w_k^2}
\]

(4)

Where, \( i, j, \) and \( k \) indicate the position of the cell on the x-axis, the y-axis, and the z-axis, respectively.

*The considered airflow control pattern*

Three airflow patterns were investigated in this study. Six small fans were used for generating airflow. The pattern 1 was often employed in a conventional system. Airflow was generated by fans placed on the one-side (Fig. 5). In the pattern 2, airflow was generated by fans placed on the both-side (Fig. 6). In the pattern 3, airflow was generated by fans placed also on the both-side, but the opposed fans were not set coaxially (Fig. 7).

In order to verify the accuracy of the CFD model against the actual situation, the same situation as the CFD model were prepared. A chamber \( (1.0 \times 1.0 \times 0.5 \text{ m}^3) \) was made of acrylic boards as the cultivation space in the CFD model. Lettuce replicas were made of steel meshes with sealing tapes (Fig. 8). Six DC Fans (E232190, DC12V-0.2A, Shicho Engineering co., Ltd, Japan) (Fig.

![Fig. 2](image)

**Fig. 2** Top view of the planting panel \( (450 \times 600 \text{ mm}^2) \) with 12 lettuce models.

![Fig. 3](image)

**Fig. 3** Schematic view of the cultivation space represented with polygons (left) and segmented into cells (right).
PRECISION AIRFLOW CONTROL

Fig. 4 The air current speeds of translucent cells which contact with lettuce models were evaluated.

Fig. 5 Pattern 1: Fans set on the one-side of the space.

Fig. 6 Pattern 2: Fans set on the both-side of the space.

Fig. 7 Pattern 3: Fans set on the both-side of the space and opposed fans were not set coaxially. Verification of the CFD model.

8) were used for generating airflow and controlled with a variable electric power source (Kinoshita Electronics, Japan). Then, air current speeds on line A, B, C, D, E, F, and G (Fig. 9) at a height of 30 mm were measured using an anemometer (V-01-AND2N, Denshi Giken Co., Ltd., Japan) 10 times. The result of the pattern 1 with the airflow of 1.0 m s⁻¹ from fans was used for the comparison.

Kitaya et al. (2003) reported relationship between airflow and the net photosynthetic rate of Sweetpotato leaves. The net photosynthetic rate increased significantly as the air current speeds
increased from 0.01 to 0.2 m s\(^{-1}\). However, the net photosynthetic rate was almost constant at air current speeds ranging from 0.5 to 1.0 m s\(^{-1}\). It means that the excessive airflow does not promote the photosynthetic rate and could be waste of energy. The definition of the “optimum control” in this study is to establish the system which can supply necessary and sufficient airflow to each leaf for growth. We assumed that the net photosynthetic rate per plant can be calculated the summation of the product of the air current speed and the leaf area in the cell (the minimum unit of the CFD model) on the surface of the lettuce models which were the adjacent cells explained previously. The air current speeds in the cells in the CFD model can be identified. A leaf area of each cell can be calculated as follows. Total leaf area of the lettuce model corresponds 20000 mm\(^2\) of which the same size of the actual lettuce. The number of the adjacent cells to the lettuce was about 100. Therefore, the leaf area of each cell is approximately equivalent to 200 mm\(^2\). The simulated relationship between the net photosynthetic rate and an air current speed was referred to the result of Kitaya et al. (2003). The net photosynthetic rate of each cell (P: \(\mu\)mol s\(^{-1}\) plant\(^{-1}\)) was calculated using the following equation.

\[
P = \sum P_{\text{cell}}
\]

\[
P_{\text{cell}} = 1.4 \times (1 - e^{-12v}) + 1.52
\]

**RESULTS AND DISCUSSION**

*Verification of the CFD model*

Figure 11 shows the measured and the simulated air current speeds on each line. Generally the measured air current speeds were fitted well against the simulated air current speeds. Some simulated air current speeds were underestimated (on line D and G) due to the difference of...
Fig. 10 The assumed relationship between air current speeds and net photosynthetic rates.

Fig. 11 Measured and simulated air current speeds on each line. The horizontal axis indicated the distance (mm) from the fans. Vertical bars indicate standard deviations.

complexity between the lettuce in the CFD model and the lettuce replica. The lettuce replica had only three leaves. On the other hand, an actual lettuce with the similar size has about six leaves. Because of fewer leaves of the lettuce replicas, air currents went through under or between leaves of the replica lettuces. Then, the measured air current speeds were little bit higher than the simulated air current speeds. The lettuce replicas should have more leaves. Then, the error between simulated and measured air current speeds may become less. However, the accuracy of the CFD
Fig. 12  The contour plots of the air current speeds at each height in the pattern 1.

Fig. 13  The contour plots of the air current speeds at each height in the pattern 2.

Fig. 14  The contour plots of the air current speeds at each height in the pattern 3.
model was thought to be enough to investigate approximate performances of the airflow control patterns.

*Airflow analysis of each pattern*

Figures 12, 13 and 14 show contour plots of air current speeds at each height in the pattern 1, 2 and 3, respectively. In the pattern 1, the airflows were blocked with the nearest lettuces from fans. The farther lettuces from the fans received the weaker air current, especially on inner lines.

In the pattern 2, air currents were blocked with six lettuces in front of the fans. Inner lettuces received weak airflow.

In the pattern 3, the airflow passed through between the lettuces. And the air currents crushed at center of the space. Then the air currents spread around the inner lettuces.

Figure 15 and 16 show that the mean air current speeds of the adjacent cells to each lettuce in the pattern 1, 2, and 3 with airflow of 1.0, and 0.5 m s\(^{-1}\) from fans, respectively. In the pattern 1, the mean air current speeds decreased with increasing the distance from the fans. The mean air current speeds around lettuces in the front of the fans (No. 1, 5, and 9) with airflow of 1.0 and 0.5 m s\(^{-1}\) were 0.33 and 0.16 m s\(^{-1}\), respectively. On the other hand, the air current speeds around the

<table>
<thead>
<tr>
<th>Air current speed from the fan</th>
<th>Airflow control pattern</th>
<th>Mean air current speed of the cells in each lettuce (m s(^{-1}))</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 m s(^{-1})</td>
<td>1</td>
<td>0.197</td>
<td>0.090</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.190</td>
<td>0.082</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.198</td>
<td>0.047</td>
</tr>
<tr>
<td>0.5 m s(^{-1})</td>
<td>1</td>
<td>0.076</td>
<td>0.058</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.089</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.099</td>
<td>0.023</td>
</tr>
</tbody>
</table>
Fig. 17  The simulated mean net photosynthetic rate of each plant in the pattern 1 (left), 2 (center), and 3 (right) with airflow of 1.0 m s$^{-1}$ from fans.

Fig. 18  The simulated mean net photosynthetic rate of each plant in the pattern 1 (left), 2 (center), and 3 (right) with airflow of 0.5 m s$^{-1}$ from fans.

farthest lettuce from the fans (No. 4, 8, and 12) with airflow of 1.0 and 0.5 m s$^{-1}$ were 0.12 and 0.02 m s$^{-1}$, respectively. In the pattern 2, the mean air current speeds around the lettuces located in the front of fans (No. 1, 5, 6, 8, 9, and 12) with airflow of 1.0 and 0.5 m s$^{-1}$ were 0.27 and 0.13 m s$^{-1}$, respectively. And the mean air current speeds around the lettuces located inside (No. 2, 3, 6, 7, 10, and 11) with airflow of 1.0 and 0.5 m s$^{-1}$ were 0.11 and 0.05 m s$^{-1}$, respectively. In the pattern 3, the variability of air current speeds around each lettuce was smaller than that in the pattern 1 and 2 (Table 1). According these results, the fans should be placed between lettuce plants to provide adequate airflow into the plant canopy.

Simulated net photosynthetic rate

Figure 17 and 18 show the simulated net photosynthetic rate of each plant in the pattern 1, 2, and 3 with the airflow of 1.0 and 0.5 m s$^{-1}$ from the fans, respectively. When the fans generated the airflow of 1.0 m s$^{-1}$, the variability of the simulated net photosynthetic rate was much smaller than that of the airflow distribution. And the mean simulated photosynthetic rates per plant were almost the same in the three airflow control patterns (Table 2). This was because the net photosynthetic rate was almost constant at the air current speeds more than 0.2 m s$^{-1}$. Therefore, the difference of air current speeds over 0.2 m s$^{-1}$ was cancelled when the net photosynthetic rates per plant were calculated. On the contrary, the variability of the net photosynthetic rates per plant in the air-

<table>
<thead>
<tr>
<th>Air velocity from the fan</th>
<th>Airflow control pattern</th>
<th>Mean of the simulated photosynthetic rate (nmol plant$^{-1}$ s$^{-1}$)</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 m s$^{-1}$</td>
<td>1</td>
<td>251.7</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>253.5</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>253.9</td>
<td>11.9</td>
</tr>
<tr>
<td>0.5 ms$^{-1}$</td>
<td>1</td>
<td>215.3</td>
<td>26.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>224.5</td>
<td>23.1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>232.3</td>
<td>11.5</td>
</tr>
</tbody>
</table>
flow of 0.5 m s\(^{-1}\) from the fans was clearer than that in the airflow of 1.0 m s\(^{-1}\). This is because the number of the adjacent cells which had the air current speeds of less than 0.2 m s\(^{-1}\) was larger than that in the airflow of 1.0 m s\(^{-1}\) from the fans. The mean simulated photosynthetic rate per plant in the pattern 3 was about 7.9 and 3.5% higher than that in the pattern 1 and 2, respectively. And also the standard deviation of the simulated net photosynthetic rate per plant in the pattern 3 was less than half of that in the pattern 1 and 2. This means the pattern 3 could distribute the air currents more efficiently and uniformly than the pattern 1 and 2.

In this study, we suggested that the precision airflow control system with multi-fan and the evaluating method for the system using the CFD model. The results indicated that this precision airflow control system had the capability to provide more uniform airflow to plants than the conventional airflow control. It will lead to energy saving and equal quality of products. However, only three airflow control patterns were investigated in this study. Optimal number, directions, and air current speeds of fans should be explored for more efficient airflow controls. At the same time, light intensity, relative humidity, temperature, and CO\(_2\) concentration should be optimized comprehensively, because these factors govern plant growth with complex interactions. It seems impossible to solve this problem with traditional mathematical methods. Probably, neural networks and genetic algorithms can be used for seeking an approximate optimum solution. The neural networks and the genetic algorithms were used to search for the optimal environmental control for plant growth (Morimoto et al., 1995; Morimoto et al., 1996; Morimoto and Hashimoto, 2000). And also Takahashi et al. (2002) suggested that the local temperature control system using two fans with the neural network technique. In future, these algorithms can be used for optimization. In order to install the CFD model into these kinds of systems, more speedy calculation will be required. In addition, to reduce the calculation time, the CFD model-based algorithm using the reduced-order transfer function matrix model suggested by Zerihun Desta et al. (2004) may be useful. If enough quantity and quality data can be collected, this technique is practical. Developments of these techniques will lead to practicing Micro-Precision Agriculture in a plant factory.

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