International Journal of Smart Home
Vol. 10, No. 2, (2016), pp. 63-74
http://dx.doi.org/10.14257/ijsh.2016.10.2.07

Improvement of the Crop Growth Rate in Plant Factory by Promoting Air Flow inside the Cultivation

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Abstract

Temperature increases and air flow stagnation caused by the large temperature variation between the cultivation beds and the close irradiation by artificial lightings in a vertical type plant factory serve as chief factors in the deterioration of crop quality and growth. In preceding researches, the methods to resolve these problems and to improve air flow rate were applied by utilizing air flow devices such as air conditioning devices and external fans. However, enhancing the air flow by an external fan reduces the temperature deviation in the entire area of the facility. To maintain a uniform growth environment, there is a limit in improving air flow, which is locally stagnant. Therefore, the factors that hinder the growth of the crops need to be removed by promoting air flow stagnation near the crops with a simultaneous operation of the inner fans at each cultivation bed. Firstly, CFD simulation process is required because a lot of time and cost are involved to establish a testing environment and cultivation experiment in order to investigate improvement effect of the cultivation environment according to the operation mode of air flow device. Experiment and analysis have to be carried out based on these simulation results. This study attempts a CFD simulation, and compares and analyzes the improvement effect on the growth environment according to the operation mode of air flow devices for the vertical type plant factory. By measuring cultivation environment under the smart environment based on the sensor network, accuracy of simulation result is verified, and effect on the improvement of growth rate is investigated through crop cultivation experiment. Experiment results showed that control condition of Case H wherein internal fans are additionally operated was the most suitable in maintaining set temperature, improving air flow, and growth rate of the crops.

***Keywords**: Improvement of the Crop Growth Rate, Control of Air Flow Devices, CFD Simulation, Plant Factory*

1. Introduction

It is essential to provide an environment suiting the growth of the subject crops in order to produce crops with high quality and to save energy consumption in the plant factory[1]. A vertical plant factory has different growth environmental factors such as temperature, humidity, and CO_2 depending on the installation location of cultivation bed, normally resulting in a large deviation in the crops[2]. Further, air flow is not smooth due to a physical structure isolated from the external environment, and stagnant air current in a certain zone. Close illumination by artificial lighting installed in each cultivation bed causes temperature increases and reduction in the air current velocity inside cultivation beds and spurs quality, as well as growth rate, among the deteriorating crops[3].

In the preceding researches, Air flow devices such as Air conditioning and Circulation fans were adopted to improve the growth rate of the crops[4-6]. Circulation fans are categorized into external fans and internal fans depending on the installation position[7]. External fans reduce the temperature deviation between zones at the upper layer and the

ISSN: 1975-4094 IJSH

lower layer and are effective in maintaining an even growth environment. However, it tends to hamper air flow inside a cultivation bed. It has been reported that operating inner fans installed above the crop populations reduces the resistance at the boundary layer of the leaf surface, and improves the flow of energy, water vapor pressure, and CO_2 concentration between the leaves and surrounding air[8]. Therefore, to address air flow stagnation locally inside a cultivation bed, External fans and Inner fans have to be simultaneously operated by additionally installing Inner fans at each cultivation bed. Since gas cannot be checked by eyes and it is difficult to measure its minute changes unlike solid or liquid, there is a limit in validating the effect of the inner fan only by experiment at the site. A simulation to analyze the growth environment, which keeps on changing depending on the operation mode of each air flow device, has to be preceded before commencing an experiment at the site. Computational fluid dynamic (CFD) simulation can artificially control various Environments and conditions, and search the optimum values[9] such as a structure, shape, and operation plan by way of a numerical analysis computational fluid dynamics, thereby saving time, cost, and labor[10]. In a plant factory which is constructed with complicated structures and components, if installation location and operation mode of the air flow devices are to be decided, this CFD simulation technique can be utilized beneficially.

This study attempts the improvement of the growth rate of the crops by promoting the air flow inside cultivation beds by simultaneously operating Air conditioning, External fan, and Inner fan for the vertical plant factories. First of all, Air flow devices were categorized into eight control conditions depending on the operation mode of the air flow device, and then the temperature and air current distribution that were changing according to each control condition were compared and analyzed through CFD simulation. After that, by measuring temperature of entire space of facility as well as inside of each cultivation bed and air flow distribution, with the integrated sensor and 3D anemometer, effective operation mode of air flow device is investigated. Lastly, a leafy vegetable (Jeokchukmyeon lettuce) was chosen as a subject crop, and changes in the growth of the crops by operation mode of air flow devices are analyzed through cultivation experiments for two rounds conducted for a period of 21 days.

2. Materials and Methods

2.1. Modeling of Subjected Space and Boundary Conditions

A vertical plant factory 3.47m in width, 4.35m in length, and 2.97m in height, located in the basement was used as a subject space to perform the CFD simulation. Four sets of plant cultivation devices (1,315mm×1,635mm×605mm) having two layers and one row were placed inside the facility and six sets of bar type LED lightings were installed on the top of each cultivation bed. As for air flow devices, one set of air conditioning device was installed at an around 2.54m height from the ground with an angle of 45°, and four sets of external fan with a coverage area of 10 m^2 and a power consumption of 21W were attached at the bottom center of the facility. Furthermore, six sets of fans were attached on each cultivation bed to activate the air current stagnant inside the cultivation bed.

Table 1 shows the control conditions according to the operation status of the air conditioning device, external fan, and inner fan for CFD simulation. Case A is the control condition for the basic environment, in which air flow device was not operated, while Case B is a condition in which only the inner fan was solely operated. The control condition of Case C composes only external fan, while Case D comprises only air conditioner operation. Case E is a condition wherein both external fan and internal fan are operated, while Case F and Case G are conditions wherein external fans or internal fans are additionally operated along with air conditioners. Lastly, Case H is a condition wherein all the air flow devices are simultaneously operated.

Table 1. Control Condition by Operation Status of the Air Flow Devices

Control condition	Air conditioning	External fan	Inner fan
Case A	Off	Off	Off
Case B	Off	Off	On
Case C	Off	On	Off
Case D	On	Off	Off
Case E	Off	On	On
Case F	On	Off	On
Case G	On	On	Off
Case H	On	On	On

In this Chapter, Fluent (ver. 6.3) and Gambit (ver. 2.4) programs were used for the numerical analysis of CFD simulation. Fluent provides some of the turbulence models such as Spalart-Allmaras, Reynolds Stress, and k-Ɛ as options during an operation of the model. Among the above turbulence models, k-Ɛ, which is the most universally used in air flow analysis and especially known for its high accuracy in the agricultural facilities, was adopted[11].

Figure 1 shows the 3D modeling of the plant factory using Gambit. The measurement data from the site were used as the input data to improve the accuracy of the simulation results, while the complicated and geometric shape was simplified to save the analysis time. The modeling procedure followed each control condition as listed in Table 1. Mesh was split around 73×104 segments. Crops, though they are the subject of the plant factory since the shapes are irregular and they grow minutely, they are subjects which are not easy for modeling. Therefore, the scope of this study was set to preforming a simulation process devoid of the crops.

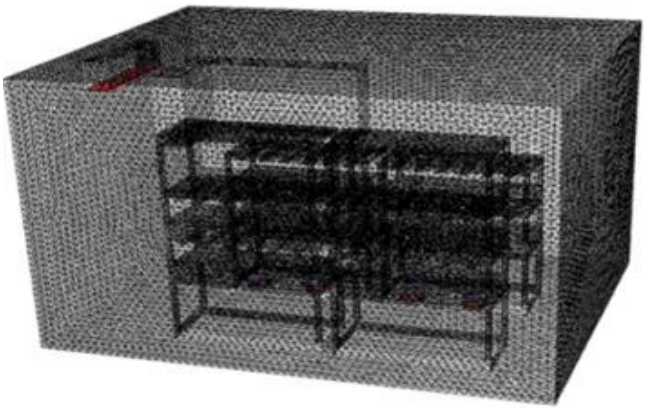


Figure 1. 3D Modeling and Meshing of Plant Factory

The boundary condition for CFD analysis was input based on the preceding research data and measurement data as listed in Table 2.

Table 2. The Boundary Condition of Each Device for CFD Analysis

Devices	Boundary Conditions	Value
LED Lighting	Temperature	300K
	Area	1.08m^2
Air conditioning	Velocity	5m/s
	Temperature	296K
	Area	0.04m^2
External fan	Intake Velocity	3.6m/s
	Exhaust Velocity	4.7m/s
	Temperature	296K
Inner fan	Velocity	0.9m/s
	Temperature	299K

According to the preceding researches, the optimum temperature for the growth of the leafy vegetables was known to be in the range of 293.15-298.15K (20~25°C) in terms of absolute temperature[12], while the optimum air current speed is in the range of 200-300mm/s. Keeping the research outcome as above, the initial temperature inside the facility during analysis was set to 297K (23.85°C).

The heating area and the generated temperature from the LED lighting, which were the main load for the room cooling, were 1.08m^2 and 300K (26.85°C), respectively. The air conditioning produced an air flow of 5m/s, outlet port temperature of 296K (22.85°C), and had an outlet port area of 0.04m^2. The air current discharge was perpendicular to the outlet port. The intake and exhaust air velocities of external circulation fan were at 3.6 m/s and at 4.7m/s, respectively. Only the air flow passage was used for the modeling as a cylindrical column while excluding the shape of auxiliary structure for fast and accurate analysis. The inner fans having an air flow of 0.9 m/s and temperature at the outlet port at 299K (25.85°C) were simplified as a rectangle with a size of 7×7cm. Also, analysis was performed as an unsteady state to check the changes in the temperature and air current by time. The heat loss from the space was not considered during the analysis[13].

2.2. Measurement and Analysis

In this study, three types of control conditions were set and growth characteristics of crops which are kept on changing according to each control condition are analyzed. The three types of control conditions implemented in the present experiments are as follows; Case D wherein only air conditioner was operated same as the cultivation environment of general plant factories, Case G (both air conditioner and external fan are operated) which showed an excellent analysis result in the simulation and measurement experiment (Figs. 3 and 6, Table 4), and Case H (air conditioner as well as internal fans are operated).

In the present experiment, air flow device was linked to power sensor in order to improve efficiency of each control condition and then air flow control cooperation algorithm as in Table 3 was developed and implemented in the system in order to operate each air flow device based on the average temperature collected from three sets of integrated sensors [which were located (attached)] at the top, center, and bottom of the facility. Case H was set as an experimental group, while Case D and Case G were set as control groups.

Table 3. Control Condition of Air Flow Device for the Cultivation Experiment

Control Cases	Devices	Control condition
Case D	Air Conditioning	(Control of air conditioning device according to set temperature input by users)

Case G	Air Conditioning, External fan	if (avg temp<=22 or avg temp >=24) operate air conditioning;
		else if (avg temp>=23.5) operate external fan;
		else air conditioning is off, external fan is off
		(Mixed control of air conditioning and external fan based on the air flow control cooperation algorithm)

Case H (Proposed Case)	Air Conditioning, External fan, Internal fan	if (avg temp<=22 or avg temp >=24) operate air conditioning and inner fan; else if (avg temp>=23.5) operate external fan and inner fan; else operate inner fan (Mixed control of air conditioning , external fan and inner fan based on the air flow control cooperation algorithm)

Case D is a control mode wherein either air conditioner is autonomously operated according to the set temperature by user's input, or these were not operated. Case G is a control condition wherein both air conditioning device and external fan are operated according to air flow control algorithm. The process is as follows.

When the average temperature exceeded ±1°C from the target temperature, the system operated only air conditioning, while if average temperature was higher than 0.5°C from the target temperature, only the external fan was operated. Further, if average temperature was not in the range above, all the air flow devices were stopped. Case H had a condition similar to Case G, except operating the inner fan all the time.

3D ultrasonic wave anemometer (Model: WA-790, SONIC Co., Japan)was used in this experiment in order to measure air flow distribution inside each cultivation bed, which is changed according to the control mode as in Table 3. Since geometric shape of subjected crop population was complicated and irregular, the results were compared and analyzed as in Figure 2 in order to minimize errors in the measurement data.

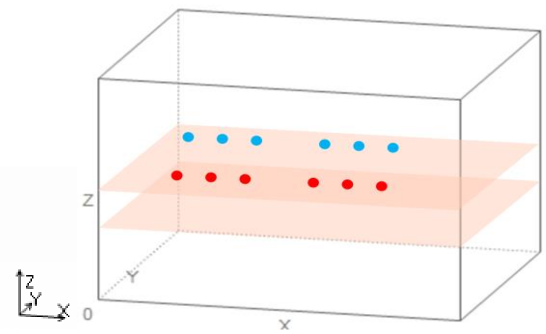


Figure 2. Air Flow Measurement Layer and Definite Points

Lastly, Jeokchukmyeon (Lactuca sativa L, Juk chuk myeon, ASIA SEED Co.,) lettuce was chosen as a subjected crop to investigate growth characteristics which are changed according to each control mode. Set temperature of 23°C was chosen and growth experiment was conducted for two rounds for a period of 21 days.

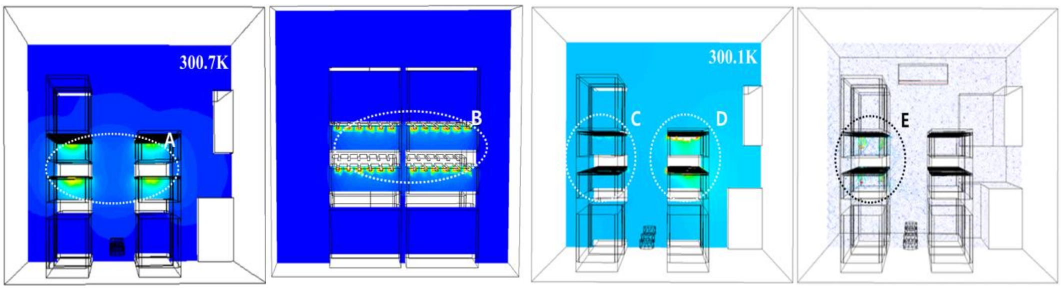
Average quantum of LED lighting during cultivation period was set at 140 $\mu mol\cdot m^{-2}\cdot s^{-1}$[14], and cultivation was executed under the basic environment without separate devices for humidity control and CO_2. Yamazaki composition exclusively for leafy vegetables was used as a nutrient solution at a frequency of 1~2 times a week, and EC concentration was maintained at $1.0 dS\cdot m^{1}$. The seedlings grown for 14days were transplanted as a subject crop. The average number of leaves at the time of transplanting was around four. The fresh weight for root and shoot, leaf length, and leaf width were set as evaluation items. Measurement data were analyzed by using SPSS and R statistics processing tool. Significance analysis for the experiment results was set at 0.05 for one-way ANOVA.

3. Results and Discussion

3.1. CFD Simulation

In this chapter, the simulation results after ten minutes elapsing according to the boundary conditions as in Table 2 are presented. The simulation results under Case A, which is a basic environment wherein air flow device was not operated, showed that the average temperature inside the facility was 300.7K (27.55°C), higher by around 3.7K (3.7°C) than the target temperature of 297K (23.85°C). The reason for the higher temperature was the smooth air flow disturbed by the environmental characteristic with the air-tight structure and not operating the air flow devices. During experiment, internal temperature of cultivation beds were locally increased far higher at point A and point B due to heating of LED lightings that were attached at the cultivation beds.

The Case B condition as in Figure 3 yielded an average temperature of 300.1K (26.95°C) for the entire space with only the inner fan operated. When compared with Case A, the average temperature under the condition Case B decreased on a meager level with an increment of around 3.1 K as compared with the target temperature. As exhibited in Point (C), air flow was promoted inside the cultivation bed with the inner fan operated and the temperatures outside and inside the cultivation beds became uniform. In case of the cultivation bed where the inner fan was not operated (Point D), the air flow was stagnant, forming higher temperature distribution as compared with that of the outer area from the cultivation bed. The active air flow was also confirmed from the graph at the right side which presents the air flow analysis results as observed from Point E. This means that the operation of the inner fan promoted the air flow inside the cultivation bed and provided the beneficial effect to reduce the temperature distribution from the outer space.

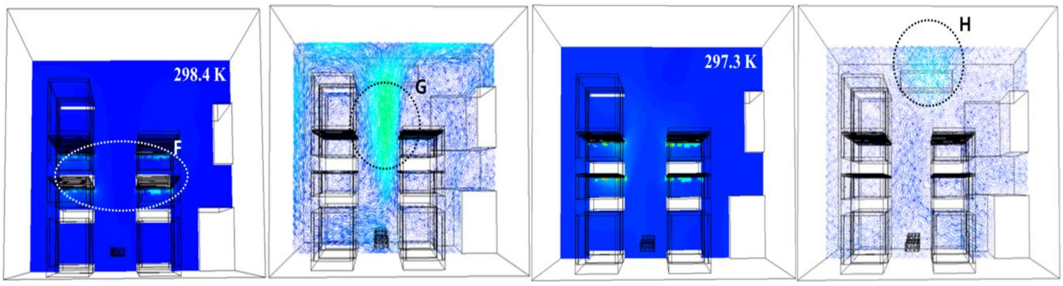


(a) Case A (b) Case B

Figure 3. Temperature and Air Flow Distribution under Case A and Case B Condition

Case C condition is a control condition wherein LED lighting and external fans were operated with four sets of external fans attached at the lower areas of cultivation beds located at 0.07m from the ground and air was discharged upwards. Average temperature inside the facility was 298.4K (25.26℃) which implied that temperature was more or less reduced as compared with that under Case B condition. Further, more uniform air flow was obtained as at point F as compared with those under Case A and Case B. Air flow analysis showed that a strong air flow was generated from the air discharge direction (point G) of external fan. Therefore, overall air flow was promoted, but air flow was stagnant in some areas such as corners in the facility.

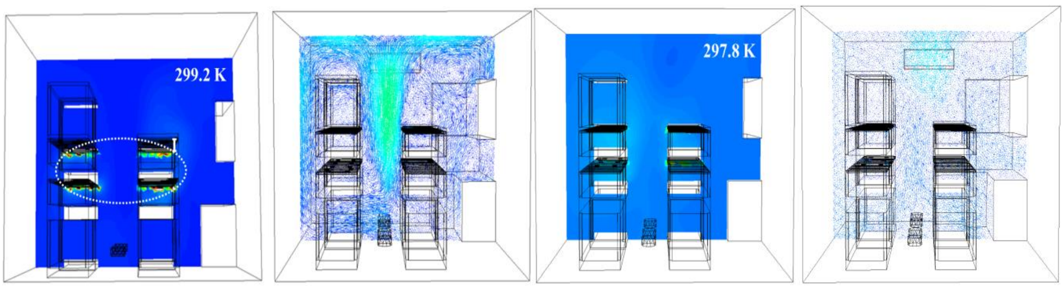
Case D comprises an environment of general plant factories where only LED lighting and air conditioning are operated. Average temperature under Case D was found as 297.3K (24.13℃), which was pretty closer to the set temperature 297K. However, temperature in the internal area of cultivation beds was little bit higher than that of outer area (point H) due to discharge direction (90°) of air conditioner.



(c) Case C (d) Case D

Figure 4. Temperature and Air Flow Distribution under Case C and Case D Condition

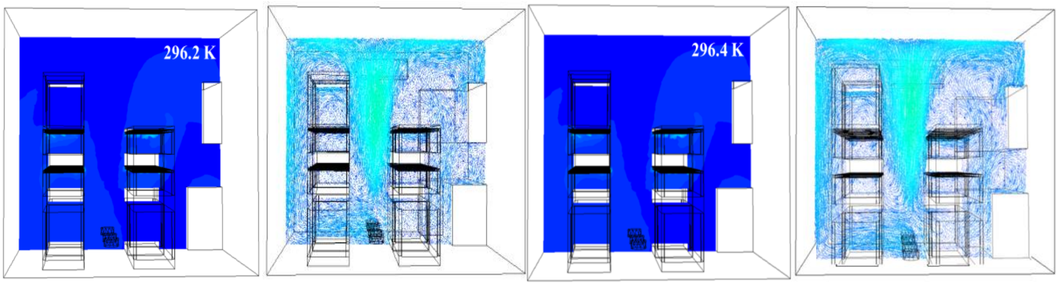
Case E condition as in Table 4 is a condition wherein both external fan and internal fan were simultaneously operated. While, Case F is a control wherein air conditioner and internal fan are operated. Under the condition of Case E, average temperature inside the facility was 299.2K (26.01℃) which was higher by more than 2°C than set temperature (24°C). Average temperature under Case F was 297.8K(24°C), while average temperatures under Case G and Case H were 296.2K(23.05℃) and 296.4 K(23.25℃), respectively as shown in Figure 5.



(e) Case E (f) Case F

Figure 5. Temperature and Air Flow Distribution under Case E and Case F Condition

Temperature deviation under all three control conditions was below 1°C as compared to the set temperature. However, under Case G and Case H, air flow was promoted more than that under Case F, resulted in lower average temperature distribution that set temperature.



(g) Case G (h) Case H

Figure 6. Temperature and Air Flow Distribution under Case G and Case H Condition

CFD simulation results by each control showed that control conditions of Case G and Case H were the most suitable in maintaining average temperature and average air flow velocity suitable for the growth of leafy vegetable.

3.2. Air Current Velocity inside Cultivation Beds

It was reported in the prior arts that air flow formation at 200~300mm/s[15-16] near the leafy vegetables were effective in improving cultivation environment such as temperature, humidity, and CO_2 by promoting transfer of heat and substances to near the crops[17].

Table 4. Minimum, Maximum, and Average air Velocity Inside the Cultivation by the Operation Mode

Control condition	Minimum air flow velocity (mm/s)	Maximum air flow velocity (mm/s)	Average air flow velocity(mm/s)
Case A	14	59	31.4 ± 4
Case B	48	154	94.0 ± 10
Case C	94	241	151.2 ± 13
Case D	67	217	121.2 ± 11
Case E	92	279	146.3 ± 14
Case F	65	203	128.6 ± 13
Case G	109	387	214.6 ± 26
Case H	121	432	225.1 ± 25

Mean ± SE, n = 12.

Table 4 shows the measurement results of the minimum, maximum and average air velocity, which kept on changing depending on the operation mode of the air flow device.

As indicated in the graph, average measured air flow velocities under Case G and Case H condition were 214.6mm/s and 225.1mm/s, which was proved to be suitable for growth of leafy vegetables. Unlike this result, other control conditions including Case D, which is a control environment of general plant factories was not suitable in providing an adequate air flow.

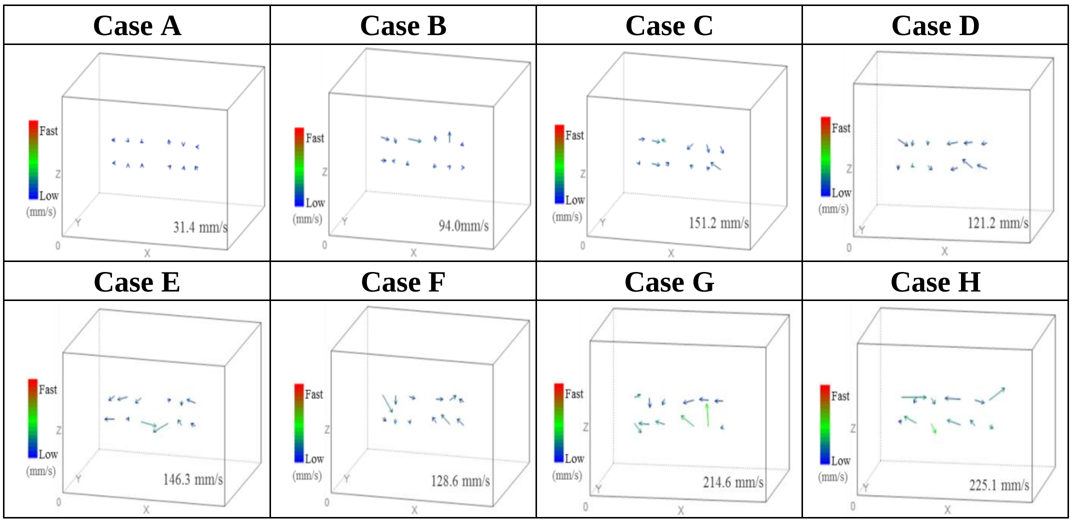


Figure 7. Air Flow Distribution Inside the Cultivation Bed by Each Case

Figure 7 shows the measurement results for the air flow velocity and direction inside the cultivation bed using an ultrasonic anemometer. The arrow in each graph indicates the direction of air flow, and the color of the arrow indicates the velocity. The nearer the arrow is to the blue color, the slower the air velocity is, while the nearer the arrow is to the green color, the faster is the air velocity. The air flow velocity (31.4mm/s) under Case A where the entire air flow device was not operated was significantly slower than that under other conditions. The color and length of arrows under Case G and Case H showed that green arrows are largely distributed as compared with those under other control conditions and those were relatively long. These arrows indicate that air flow velocity was far active and evenly distributed towards all the directions.

3.3. Growth Characteristic of the Crops

Table 5 shows comparison and analysis results of crops cultivated under the various control condition with one-way ANOVA.

ANOVA analysis results showed that significant probability was 0.000 for fresh weight, leaf length, and leaf width, confirming that there are significant differences in three control conditions. That is, under case H wherein all the air flow devices were operated, average fresh weight of the crops was 163.7g which was more by 44.6% and 10.2% than those under Case D wherein only air conditioner was operated and Case G where air conditioner and external fan were operated. As far as leaf length is concerned, leaf length was 219.7mm which was more by 13.2% than that of Case G, while it was shorter as compared with that under Case D. Further, leaf width was 223.4mm which was wider by 23.1% and 20.1% than those under Case D and Case G.

Table 5. Difference in the Growth Characteristics According to Each Control Condition

Variable	MEAN			SD			F	P
	Case D	Case G	Case H	Case D	Case G	Case H		
Fresh weight	113.2	148.5	163.7	9.62	23.89	27.07	14.422	.000*
Leaf length	225.4	194.0	219.7	11.21	20.35	16.59	10.301	.000*
Leaf width	181.5	186.0	223.4	13.29	20.75	16.67	17.936	.000*

Mean separation within columns by Duncan's multiple range test at P=0.05
Mean ± standard deviation [n = 10].

Figure 8 shows growth and red color appearance of crops under each control. As shown in the Figure, growth of the crop under Case H was prominently larger than those under Case D and Case G. Red color was also evenly distributed throughout leaves.

In this study, by implementing air flow control cooperation algorithm inside the plant factory under sealed environment, and by efficiently operating air conditioning device, external fan, and internal fan, air flow which was stagnant near the crop population was improved and grow rate of the crops was promoted. We aim to increase overall crop production by implementing the proposed system in the site and to reduce energy consumption by shortening the cultivation period in the future.

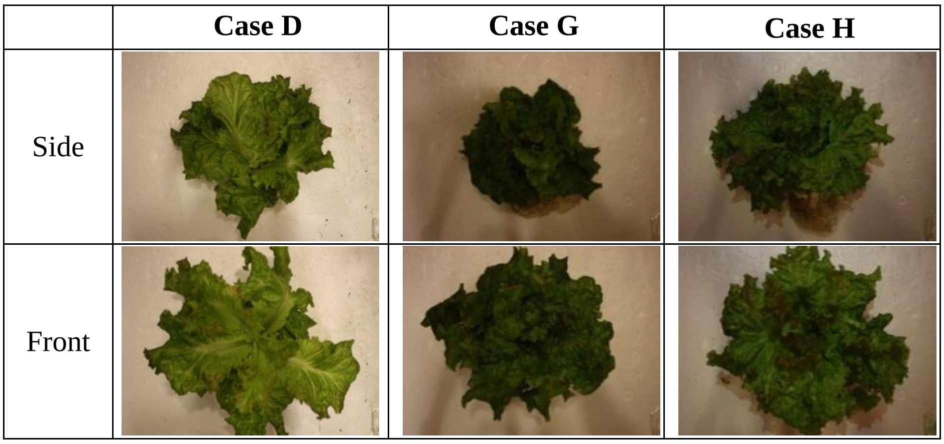


Figure 8. Comparison of Crop Growth under Each Control Condition

Acknowledgments

This work was supported by the research grant of the Kongju National University in 2013.

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