International Journal of the Physical Sciences Vol. 6(33), pp. 7604 - 7613, 9 December, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS10.315
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Numerical simulation and construction of using indoor plants to improve indoor air quality

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Accepted 14 November, 2011

This study used an indoor plant system to improve the indoor air quality, and discussed the correlation between the CO_2 derived from human breathing and the photosynthesis of plants. This study took peace lily (*Spathiphyllum kochii*) as the experimental target. The absorptivity of peace lily to CO_2 at the CO_2 concentration of 4000 ppm was 2.4847E-5 m^3/h according to the experiment of CO_2 absorptivity of peace lily. The theory and method of computational fluid dynamics were applied for simulating the CO_2 concentration changes in a confined space with and without indoor plants. The constructed experimental environment and numerical simulation were used for validation and comparison. The obtained experimental data matched the CO_2 change curve of the simulation result. Lastly, simulation was conducted using vertical garden to improve the CO_2 concentration in the environment.

Key words: indoor plant, environmental control, computational fluid dynamics.

INTRODUCTION

In order to save energy, the buildings built in the recent two decades are more effective in isolating outdoor air, so as to reduce the energy consumption of buildings. However, this method keeps many organic gases produced by artificial compounds indoors. As the modern life style tends to be indoor oriented, people spend 80 to 90% of time indoors. Thus, the sick building syndrome (SBS) and the sick house syndrome (SHS) have become more prevalent. The World Health Organization (WHO) defined the sick building syndrome in 1984 as "any abnormal symptoms of human body resulting from air pollution inside buildings." It also indicated that the menace of indoor air pollution to human health is worse than that of outdoor pollution, as people contact indoor air pollution for a long time. In order to maintain good indoor air quality, the air conditioning in general buildings adopts ventilation to dilute indoor air, but this would result in high energy consumption by Kuo (2007). It has been specified in the "Indoor Air Quality Recommended" and announced by the Environmental Protection Administration, Executive Yuan, on December 30, 2005 that the recommended carbon dioxide in general public place is 1000 ppm by EPA (2005). Thus, a balance between healthful living conditions and conserving energy should be reached. These problems can be solved by planting indoor plants.

LITERATURE REVIEW

Gan (1995) used the computational fluid dynamics (CFD) to simulate an indoor room to discuss the relation between indoor concentration and human comfort. Chung and Derek (1994) employed the CFD to simulate indoor space and used forced convection to discuss the efficiency of removing indoor pollutant. Hyun and Kleinstreuer (2001) adopted numerical simulation to analyze the diffusion of concentration breathed out by a standing person caused by the gas streaming. Shiu et al., (2005) tested the activated carbon adsorption building material to discuss its influencing factors reducing the toluene concentration. They suggested that when the toluene concentration was reduced, the air exchange rate, product load factor and mass area ratio would influence the experiment. Bartzanas et al. (2002) combined crops with the evapo-transpiration model and

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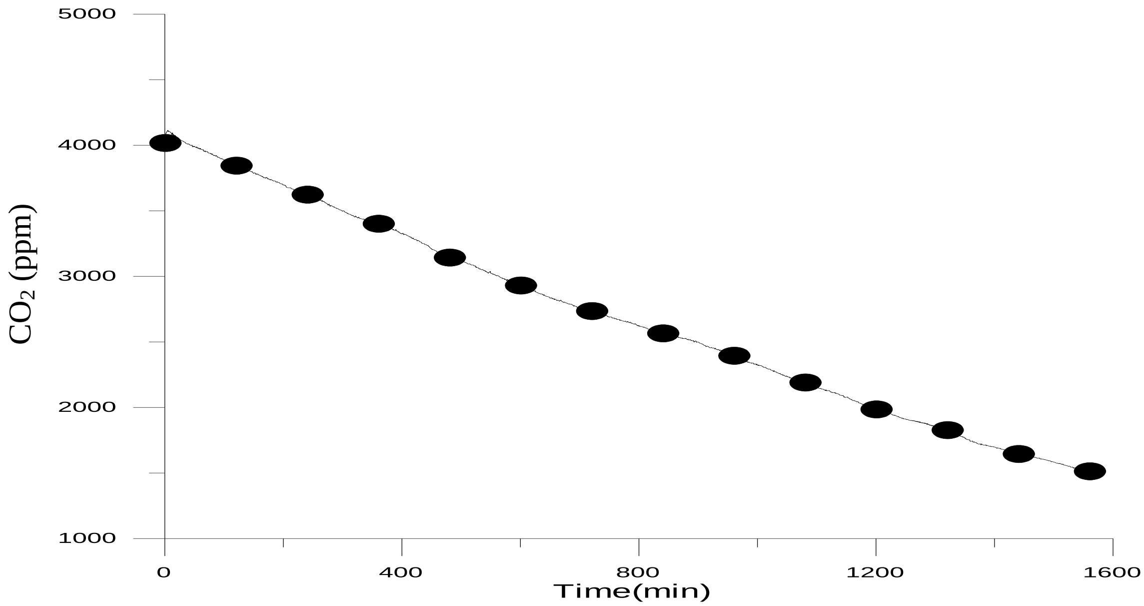

Figure 1. Numerical curve of concentration in box after CO_2 is filled.

drag model, which was consistent consistent with the practical situation. Boulard and Wang (2002) used porous media to calculate the drag effect of crop canopies, and analyzed the insect screen and ventilation rate well.

EXPERIMENTAL STRUCTURE AND SIMULATION METHOD

Experiment and simulation of photosynthetic rate of individual plant

When plants carry out photosynthesis, the CO_2 content in the air will influence the absorptivity of photosynthesis to CO_2 directly. The efficiency changes in attenuation curve with the CO_2 concentration in the environment, in order to obtain the net photosynthetic rate of peace lily. This study designed an experimental method which put the selected peace lily, small fan and carbon dioxide recorder in a transparent acrylic box, and then sealed the box with adhesive tape. The illumination on the plant and the temperature inside the box were fixed. Then 4000 ppm CO_2 was filled in the box, and a small fan was used to mix the air in the box. Continuous illumination was provided so that the plant could photosynthesize completely to reduce the CO_2 concentration in the box. The infrared carbon dioxide sensor in the box recorded the numerical values once a minute.

The illuminance was 12000 lux, and the temperature was 30 ± 1°C. The attenuation curve of CO_2 concentration in the box when one peace lily was in photosynthesis is as shown in Figure 1.

The linear regression analysis is used to figure out the trend line of the measured values, the trend line equation is $y = -1.6566x + 3991.5$, R^2 value is 0.9962 and is differentiated to obtain the absorption rate of the peace lily to CO_2 in this CO_2 concentration environment, the absorptivity is 2.4847e-5 m^3/h.

The model was constructed according to the data obtained from the previous experiment and experimental conditions. The computational area was plotted, and the corresponding boundary condition type was designated. The size X × Y × Z of the constructed 3D geometric model was 0.5 × 1 × 0.5 m. The plant pot was 0.1 × 0.1 × 0.1 m and the plant was a porous media area of 0.3 × 0.4 × 0.3 m. A fan with wind direction of positive Y was mounted at the height of 0.7 m inside the box. The geometric graph is as shown in Figure 2.

In this simulation, the assumptions for the flow field and concentration field in the room and the plant box are as follows:

1. Assume that the fluid is incompressible flow and ideal gas.
2. The wall surface inside the box is assumed to be heat insulated.
3. Neglect the lighting equipment and its heat energy.
4. The porous media area is Darcy effect.
5. The operating fluid is set as air and CO_2, the moisture and oxygen generated by the plant are neglected.

The boundary condition setting of CFD simulation is set according to the experimental parameters. This simulation assumed that the initial concentration in the box is 4000 ppm. According to the previous experimental

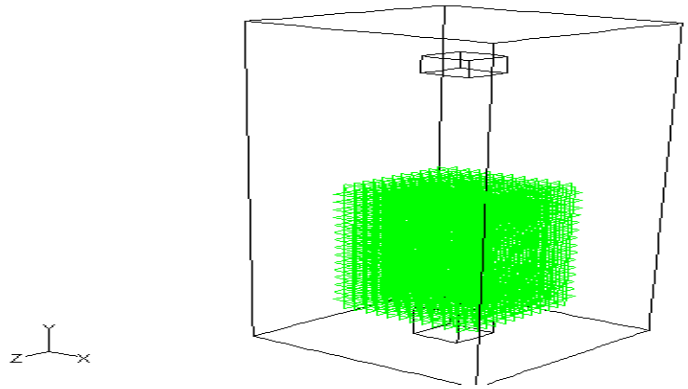

Figure 2. Geometric model of small experiment box.

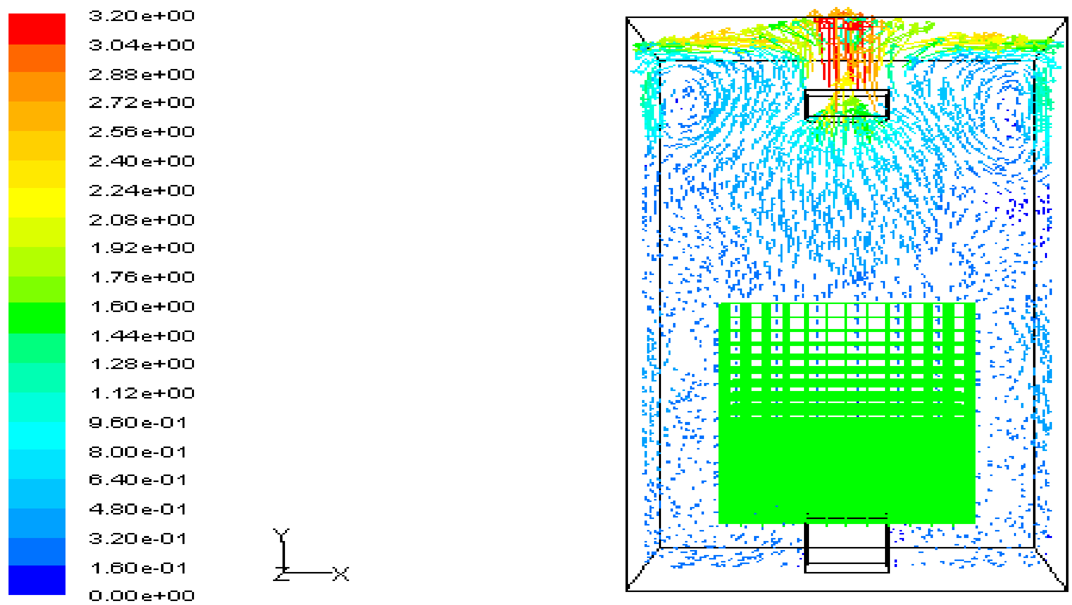

Figure 3. Airflow field inside box simulated by CFD.

result, the absorptivity of the plant to CO_2 under this condition was $1.6566e^{-6}$ ppm/min. If assumed that the plant was 0.036 m^3 porous media, after unit conversion, the absorption rate of the plant to CO_2 was $1.98e^{-7}$ kg/m^3s. The plant part was set as porous media and assumed to be uniform and inelastic. It was assumed that the porosity of the plant model is 0.9, the fan pressure rise is 8 Pascal, the turbulence model is k-ε. The numerical values were calculated by PISO rule. Although, the PISO had more iterations inside the pressure that extend the computing time, the numerical stability was higher than that of SIMPLE.

According to the simulation results obtained from the previous setting, if Z = 0.25 m is inside the box, the airflow field of XY plane is as shown in Figure 3. The effects of a fan on the air inside a box can be observed through a plant body being simulated by porous media, and the airflow nearby the plant is reduced by resistance. This air current velocity was about 0.3 to 1 m/s, which matched the required condition for general plant growth.

The CO_2 concentration in a box decreases with time, and as the fan stirs the air inside the box, the CO_2 is uniformly distributed within the box.

The CFD simulation result of each hour of 24 h was compared with experimental data, as shown in Figure 4. Since the boundary condition in CFD simulation was set as fixed absorbability that does not decrease with time, if the experimental time was extended, the absorbability of plant to CO_2 would decrease gradually and the curve became flatter. The data adopted by this simulation would be inconsistent with the practical situation. Therefore, the boundary condition set as fixed data was only applicable

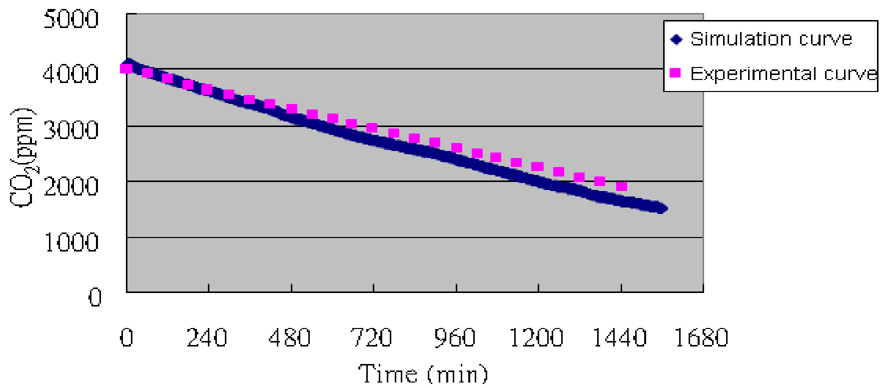

Figure 4. Comparison between experimental results and CFD simulation.

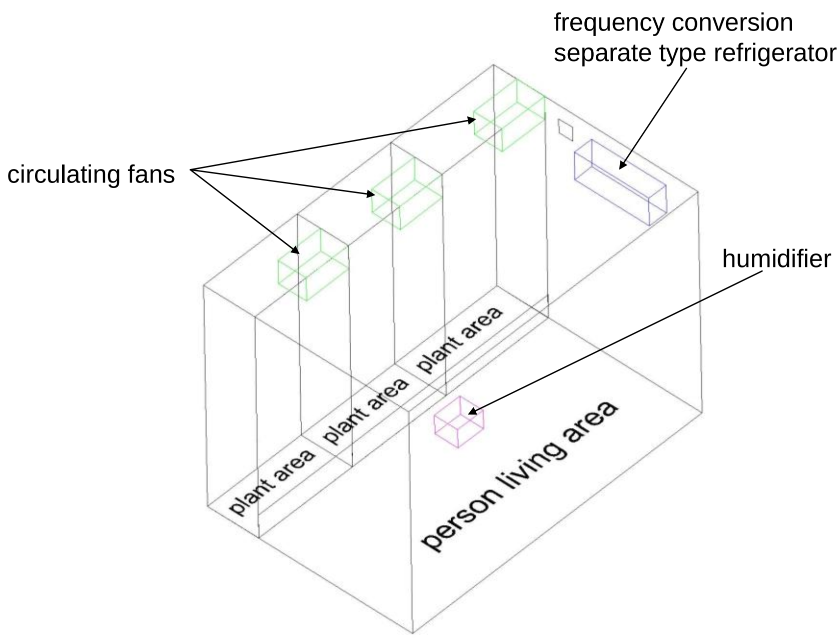

Figure 5. Schematic diagram of experimental space.

to short-term simulation, so as to coincide with the practical situation.

EXPERIMENT CONSTRUCTION AND SIMULATION IMPROVEMENT OF PLANT ABSORBING CO_2 EXHALED BY HUMAN

In order to find out the photosynthesis of indoor plants on purifying the indoor air, this study designed an environmental control space in which the plant and person coexist. The plant culture area and the person living area were separated by a transparent glass, and three indoor circulating fans were mounted on the top of the glass. The return air inlets are mounted at the lower part, so that the air could circulate between the two areas. A split air conditioning was mounted in the person living area to control the room temperature as required by the experiment accurately. The plant area and the person living area had a hygrothermograph and a CO_2 concentration meter, respectively to record the environmental changes in the experimental space and feed back control. Freezer plates were used as the walls of the upper, lower and middle sides of the experimental space. The impact of the external temperature change on the room was minimized. The other side was mounted with an airtight and soundproof glass door for the personnel to pass in and out and observe the experiment, as shown in Figures 5 and 6.

The airtight glass door was kept open for 10 min to

Figure 6. Photo of experimental space.

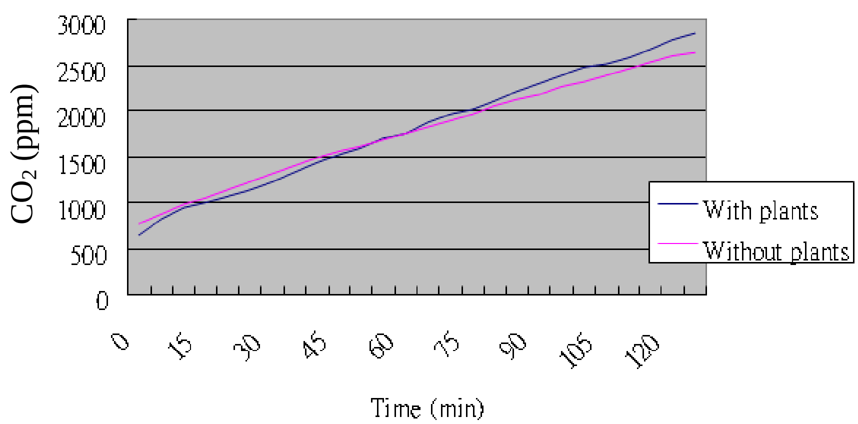

Figure 7. Curve diagram of CO_2 concentration changes in experimental space with and without plants.

make the indoor CO_2 concentration identical with the outdoor one. Then, a person entered the experimental space, and sat down to read. The airtight glass door was closed to compare the CO_2 concentration change in the room with plants with that in the room without plants. A CO_2 sensing recorder was mounted in the person living area and the plant culture area, respectively. The CO_2 sensing recorder recorded data on an interval of 5 min. The experimental time was 2 h.

The data of the experimental space with plants and without plants are as shown in Figure 7. According to the CO_2 concentration curve changes, when the person was in the experimental space without plants, the CO_2 concentration increased quickly, whereas in the experimental space with plants, the rise of CO_2 was inhibited by the plants slightly.

CFD numerical simulation was carried out based on the aforementioned conditions. The overall space $X \times Y \times Z$ of the simulated physical dimension was $3.4 \times 2.4 \times 2.2$ m, $X \times Y \times Z$ in this space was designed as a plant area of $3.4 \times 2.4 \times 0.5$ m, and the rest was the person living area. The plant area was separated into three compartments, in each compartment there were two layers of supports of 1.13×0.4 m which were 0.85 m apart on the circulating water tank ($0.8 \times 0.25 \times 0.45$ m). It was assumed there were plant pots in the physical dimension of $0.75 \times 0.35 \times 0.3$ m on the supports. There were 30 plants in the plant pots, and each plant pot contained 5 plants in the physical dimension of $0.2 \times 0.4 \times 0.45$ m (porous media area). The plant culture area

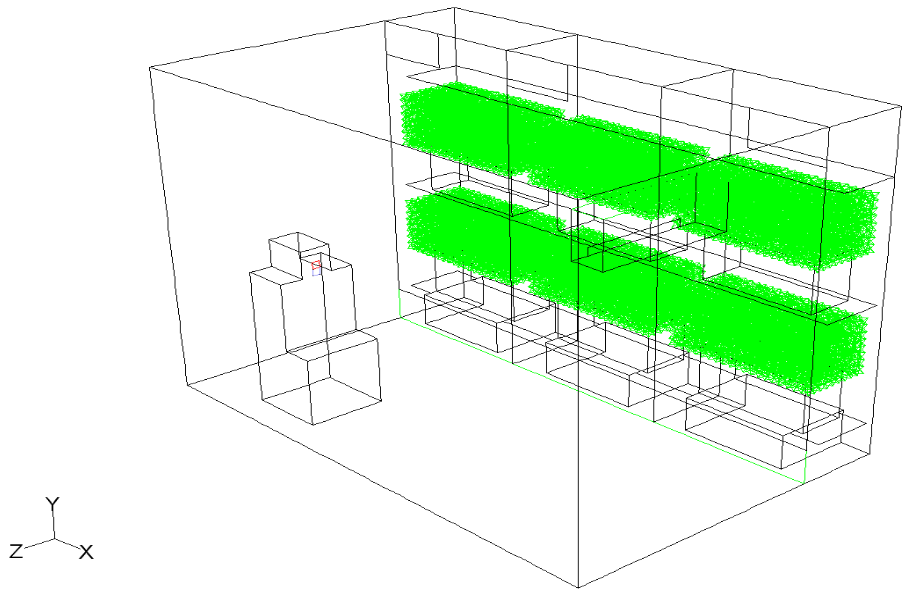

Figure 8. Geometric shape of the architecture space.

was separated from the person living area by glass, and three 0.5 × 0.25 m air-out fans and 1 × 0.25 m return air inlets were mounted at the upper end and the lower end of the glass, respectively. A 0.8 × 0.3 × 0.2 m split air conditioning was mounted on the wall of the person living area, and a 0.8 × 0.2 m return air inlet and a 0.6 × 0.05 m air outlet were mounted above and beside the split air conditioning, respectively. Finally a sitting human model was placed in the space. A 0.05 × 0.05 m outlet for exhaled air is opened at the mouth and nose to simulate the physiological behavior of a human breathing out CO_2. The physical model is as shown in Figure 8.

The fundamental assumption of simulation and the plant model parameter settings were identical with those given previously. The CO_2 exhalation outlet at the human mouth position in the boundary condition setting was set as the velocity-inlet. According to the data provided by ASHEA Standard 62 (1990), the human exhaled CO_2 was 0.3 L/min, and the turbulence intensity of mouth when breathing was 0.036. The breathing air speed was set as 0.17617 m/s, as suggested by Hyun and Kleinstreuer (2001). Since this simulation only discussed indoor CO_2 concentration change, the operating fluid was only set as air and CO_2. The mass fraction of CO_2 was set as 0.01135267; the pressure rise of the circulating fans in the plant area was set as 8 Pascal; the pressure rise of the air outlet of the refrigerator was set as 20 Pascal; the initial concentration of CO_2 in the box was set as 500 ppm and the condition of convergence of iteration was 10^{-4}.

This study employed CFD to simulate indoor flow field and the uniformity of CO_2 concentration distribution in numerical value mode, so as to discuss whether the CO_2 exhaled by human in a closed indoor environment could be absorbed by indoor plants. According to the designed environment in this study, the airflow field distribution in the human living space of the human and plant coexisting space is as shown in Figure 9. As seen, the cold air from the refrigerator formed a large vortex in the simulated space, the velocity of the air flow by the human model was about 0.8 to 1.4 m/s, human may be discomforted at this air speed, and the position under the cold air may be suitable for human.

According to the airflow field pattern in Figure 10, the large vortex in the person living space generated by the circulating fans may detain CO_2 in this area for a long time.

The air flow distribution in the plant area is as shown in the airflow field pattern of Figure 11. Due to the positions of the spatial supports in the plant area, the top airflow formed a vortex, and the airflow in the middle of plant area was about 0.3 to 0.8 m/s when flowing across the porous cube of the simulated plants. It conformed to the growth conditions required by general plants.

In order to discuss the correlation of CO_2 concentration change between plants and person in the simulated space, this study conducted numerical simulation to compare the CO_2 concentration in the room with plants and without plants. The changes in CO_2 concentration in the person living area within 2 h are represented as curves, as shown in Figure 12.

The transient simulation found that the concentration of CO_2 exhaled by human in the space after 2 h of simulation exceeded 2000 ppm, regardless of the presence of plants. This CO_2 concentration exceeded the standard of 1000 ppm specified in the indoor air quality law. However, the rising rate of CO_2 concentration in the space with plants was 7.57% better than that in the space

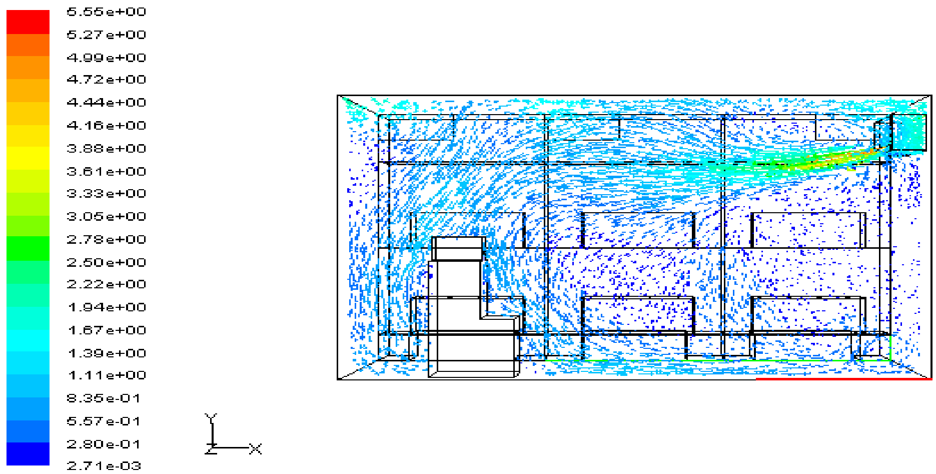

Figure 9. Z= 1.8 m, airflow field pattern of XY plane.

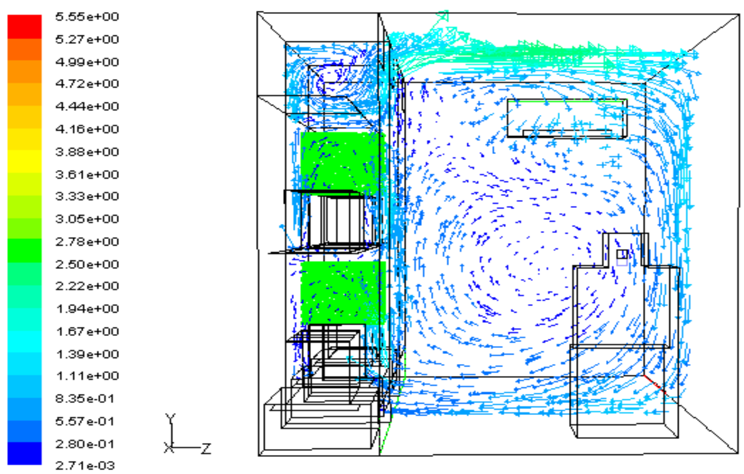

Figure 10. X= 1.4 m, airflow field pattern of YZ plane.

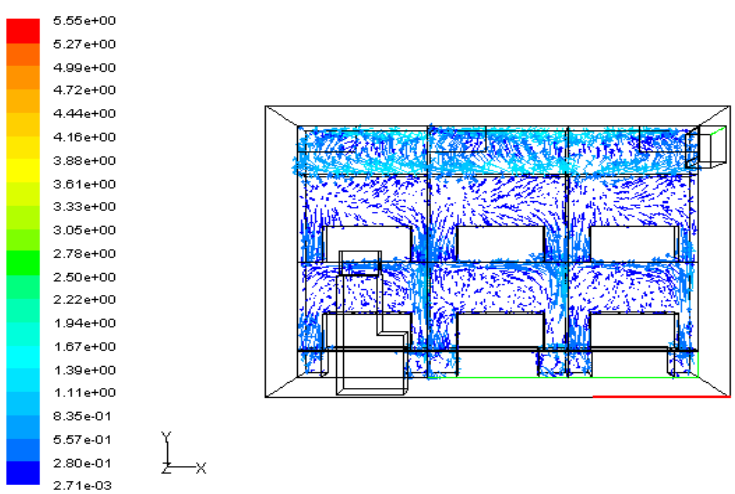

Figure 11. Z = 0.275 m, airflow field pattern of XY plane.

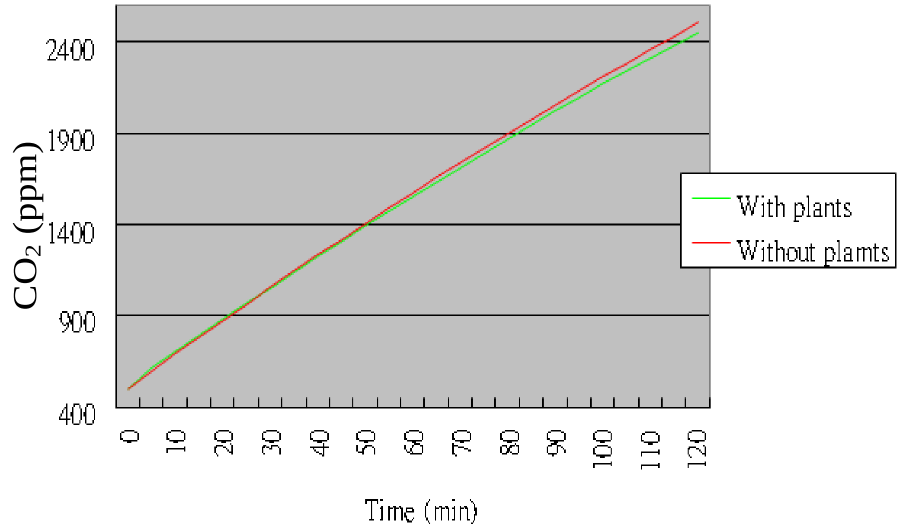

Figure 12. Simulation results curve diagram of CO_2 concentration changes in room with and without plants within 2 h.

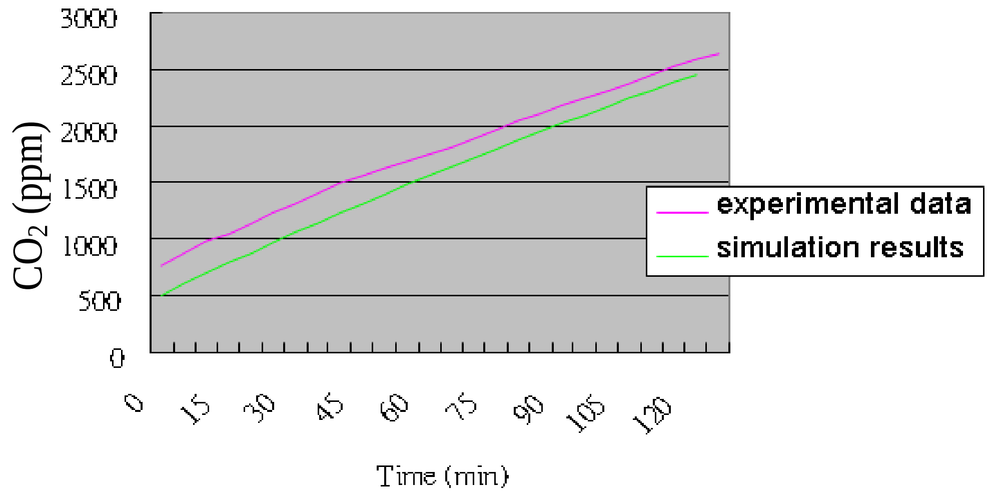

Figure 13. Comparison between experimental data and simulation results with plants.

without plants, indicating that the CO_2 can still be reduced by placing several indoor plants in a closed room. However, the effect of plants on improving indoor CO_2 concentration is not obvious.

The two experiments earlier discussed were compared with the simulation results, as shown in Figures 13 and 14. When there were plants, the CO_2 rate of the experiment and the simulation had a difference of 1.07%. When there were no plants, the CO_2 rate of the experiment and the simulation had a difference of 4.83%. There were few errors between the experimental results and the simulation results of the rising rate of CO_2 in the space with human.

According to the comparative results of the aforesaid experiment and simulation, the effect of a few indoor plants on reducing indoor CO_2 was not obvious. Therefore, this study will replace the vertical garden of plants in order to increase the number of plants. The vertical garden is an entire sheet of plants, with a volume of 3.4 × 1.4 ×0.35 m planted in a 3.4 × 1.4 × 0.5 planting box. When there are 325 plants in the planting area, and the other boundary condition settings are maintained, and the insufficiency of plants is remedied by planting numerous plants in a small area. The three-dimensional geometrical model of the simulation is as shown in Figure 15. According to the curve change in the Figure 16, when the vertical garden with 325 plants is adopted, the climbing rate of CO_2 is improved by 38.44%

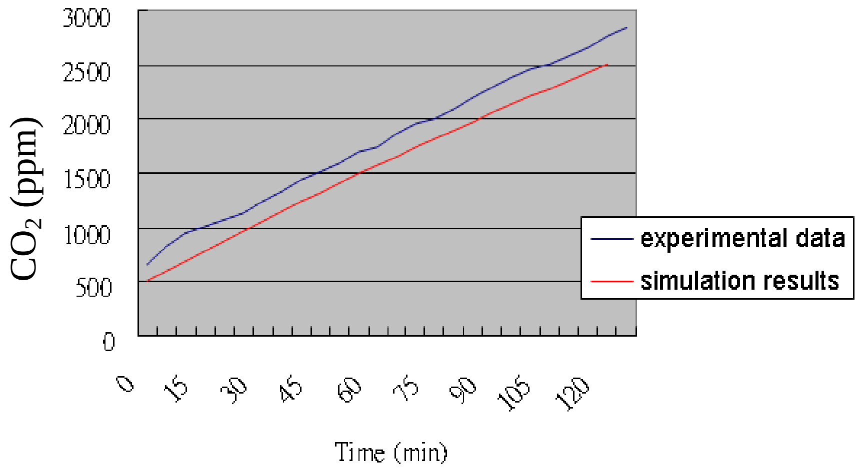

Figure 14. Comparison between experimental data and simulation results without plants.

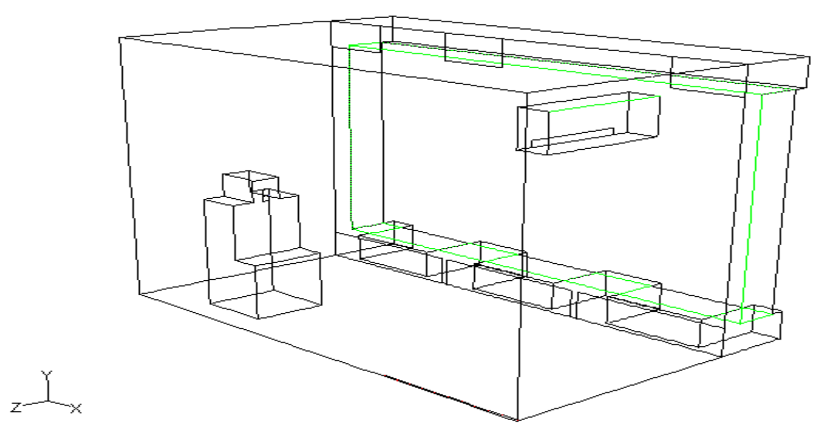

Figure 15. Three-dimensional geometric model of replacing plant supports by vertical garden.

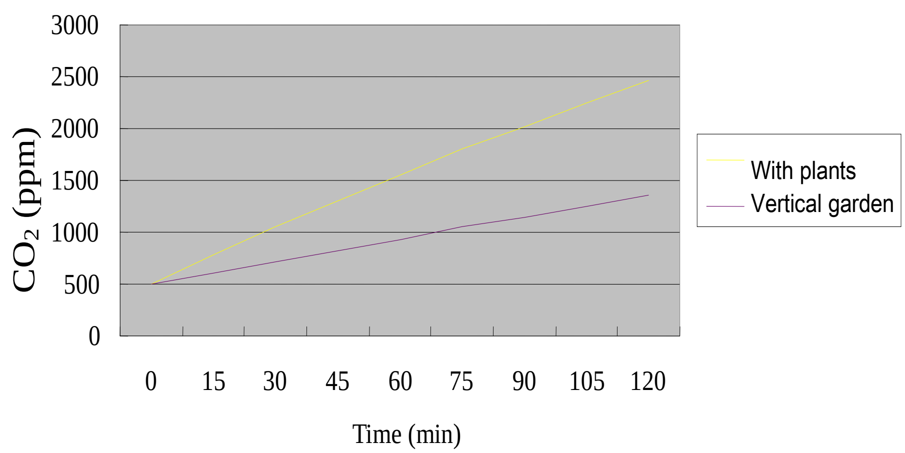

Figure 16. Simulation results comparison diagram of CO_2 concentration change curves of rooms with plants and vertical garden within 2 h.

than that with only 30 plants.

Conclusions

The study is concluded as follows:

1. Each plant has a different absorption efficiency to the CO_2 in the environment, even plants of the same variety would be influenced by environmental factors, leaf area, illumination time and intensity.
2. The peace lily used in this study was taken as an example, the absorptivity of an individual peace lily to CO_2 is only 3.4428e-5 m^3/h at the CO_2 concentration of 5374 ppm. A few indoor plants are not enough to reduce indoor CO_2 to reduce outdoor air intake.
3. Since the absorptivity of individual indoor plants to CO_2 is low, a large amount of plants can be planted in a small area only by tridimensional plant, such as vertical garden, to use the quantity of plants to remedy the deficiency.

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