ANALYSIS OF AIR CURRENTS IN PHYTOTRONS BY THE FINITE ELEMENT METHOD

Chikushi, Jiro
Biotron Institute Kyushu University

Mori, keiichiro
Biotron Institute Kyushu University

Eguchi, Hiromi
Biotron Institute Kyushu University

出版情報：BIOTRONICS. 18, pp.45-54, 1989-12. Biotron Institute, Kyushu University

BIOTRONICS **18**, 45–54, 1989

ANALYSIS OF AIR CURRENTS IN PHYTOTRONS BY THE FINITE ELEMENT METHOD

J. CHIKUSHI, K. MORI* and H. EGUCHI

Biotron Institute, Kyushu University 12, Fukuoka 812, Japan

(Received September 18, 1989; accepted September 30, 1989)

CHIKUSHI J., MORI K. and EGUCHI H. *Analysis of air currents in phytotrons by the finite element method.* BIOTRONICS **18**, 45–54, 1989. The spatial variability of air current in two types of the phytotron glass room were examined. The hot wire anemometer was used for measurements and the finite element method was employed for the simulations. In one type (Phytotron I) both the air inlet and the air outlet locate in the same wall, and in the other type (Phytotron II) the air inlet coincides with all over the floor and the air outlet locates on the upper part of a wall. In the Phytotron I, the air velocity was relatively high and direction of air current varied in space. In the Phytotron II the air velocity was relatively low and the directions were homogeneous in the region lower than 2 m high where plants are grown. From these results, it was found that the air movement in the Phytotron II is more suitable for plant research than that in the Phytotron I in respects of magnitude of air velocity, flow direction and their homogeneity.

Key words: air velocity; growth room; phytotron; finite element method; three dimensional simulation.

INTRODUCTION

The air current in the phytotron is known to be important for heat and mass transfers between plants and air, and to be responsible for the controls of air temperature and humidity. The air current pattern in the room is not necessarily uniform with respect to magnitude and direction of air velocity. The designs of air inlet and air outlet cause different air current in the room as well as the geometry and size of the room. Inhomogeneity of the air current brings about different micro environments around plants even in the controlled environment (*1*, *2*, *6*, *7*, *10–12*).

The present paper deals with the analyses of the spatial variability of the air current in two phytotron glass rooms.

METHODS

Measurements

Two types of phytotron systems (*4*) were used for examining the air current pattern. In one type (Phytotron I), the packaged air conditioner is used. Con-

* Present address: Oita Junior College, Chiyomachi 3–3–8, Oita 870, Japan.

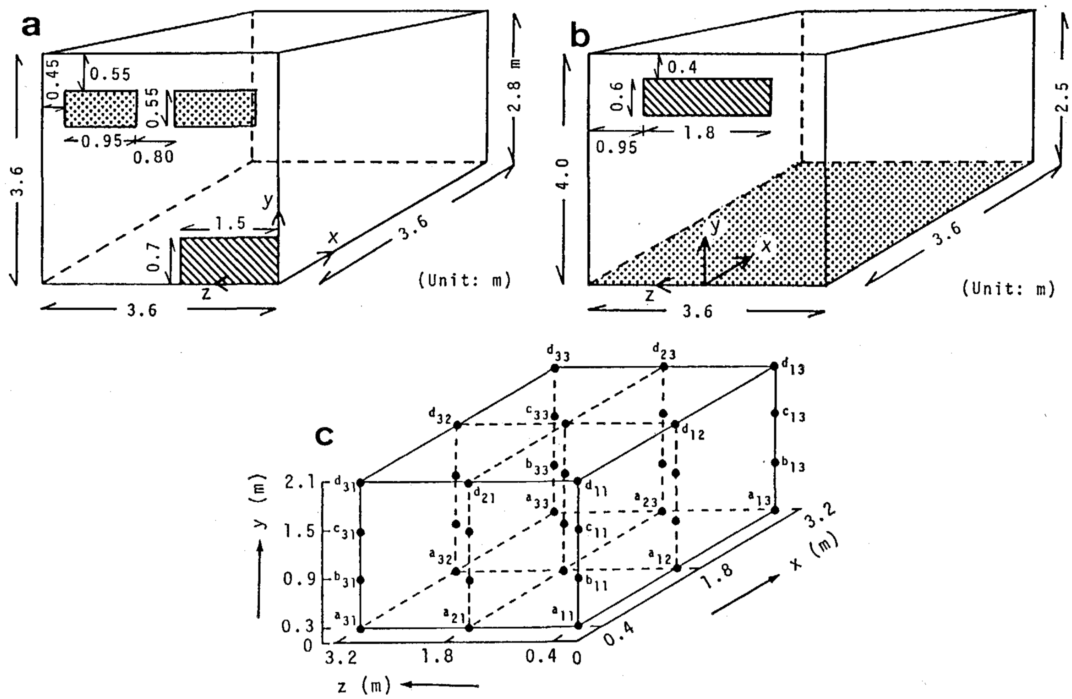

Fig. 1. Schematic diagram of growth rooms: a, Phytotron I; b, Phytotron II; c, measuring points in the Phytotron I and II. Dotted and hatched areas in (a) and (b) indicate the air inlet and the air outlet respectively. Coordinates in (a) and (b) were used for the simulations.

trolled air is supplied to the room from the two air inlets locating at upper part of the wall and the air flows down from the air inlet into the air outlet locating at lower part of the same wall (Fig. 1a). In another type (Phytotron II), air conditioning unit is used. The air flows up through perforated floor into the room and flows into an air outlet attached at upper part of a wall (Fig. 1b). There is a mixing chamber under the floor.

Air velocities were measured for ten minutes by using hot wire anemometer (Kanomax 6141, Nihon Kagaku Kogyo Co., Ltd.), and the mean values were used. Measured points in both the Phytotron I and II are shown in Fig. 1c. In this measurement, only vertical component of air velocity was obtained.

Simulation

A simulation was tried to obtain the information more in details on air velocity distribution in the growth room. Air velocity in the room is designed to be lower than about 0.5 m s^{-1}. In such lower velocity, it could be assumed that the air movement can be regarded as the three dimensional, incompressible and irrotational flow in spite of actually compressible fluid. In this case, the Laplace equation can be employed to express the air current field. That is,

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}=0 \tag{1}$$

where x, y and z are the Cartesian coordinates, and ϕ is velocity potential. If these phytotrons are closed completely, the following conditions are satisfied,

$$\frac{\partial \phi}{\partial n} = -v_i \,, \qquad \text{in air inlet;}$$

$$\frac{\partial \phi}{\partial n} = v_o \,, \qquad \text{in air outlet;}$$

$$\frac{\partial \phi}{\partial n} = 0 \,, \qquad \text{in wall or window}$$

where v is air velocity, n is normal direction to air inlet, air outlet, wall or window. Subscripts 'i' and 'o' indicate the air inlet and the air outlet respectively. According to the conservative law of fluid, following equation can be obtained,

$$v_i A_i = v_o A_o \tag{2}$$

where A is area. If either v_i or v_o is known, then the other velocity can be calculated from Eq. (2). In the Phytotron I v_i was measured and in the Phytotron II v_o was measured.

Equation (1) can be solved by using the finite element method (*8*, *9*). The air current region is divided automatically into many elements of trigonal pyramid according to a computer program (*8*), if only triangular elements in one x-y cross-section and other cross section z coordinates are given.

In the Phytotron II, only a half region was computed owing to the symmetry of the room configuration. The numbers of the node and the element were 912 and 3960 in the Phytotron I, and were 240 and 855 in the Phytotron II, respectively. The velocity in each triangular element of the cross-sections can be calculated from the velocity potential values and coordinates of three nodes constructing the element as follows (*8*),

$$\left.\begin{aligned} u &= \frac{1}{2A}(a_1\phi_1 + a_2\phi_2 + a_3\phi_3) \\ v &= \frac{1}{2A}(b_1\phi_1 + b_2\phi_2 + b_3\phi_3) \end{aligned}\right\} \tag{3}$$

where, $a_k = y_i - y_j$, $b_k = x_j - x_i$ and $A = \{x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2)\}/2$.

RESULTS

Measurements

Figure 2 shows the air velocity distribution from left to right in the air inlet opening of the Phytotron I. Air velocity varied with the distance from a edge of the air inlet; the variation ranged from 1.0 to 6.5 m s^{-1}. This deviated pattern of velocity distribution in the air inlet might be brought by curvature of the duct and promote the locally higher velocities.

Figure 3 shows the distributions of vertical air velocities measured in the Phytotron I. Velocities in x-y cross-section at z=1.8 m were higher in the region near the points d_{12}, d_{23}, a_{21} than other regions (Fig. 3a). This seems to be due to the

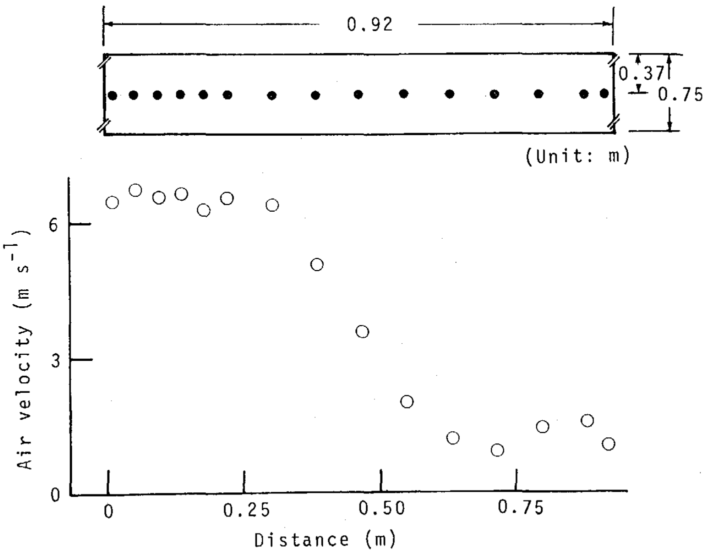

Fig. 2. Distributions of measured air velocities in the air inlet of the Phytotron I.

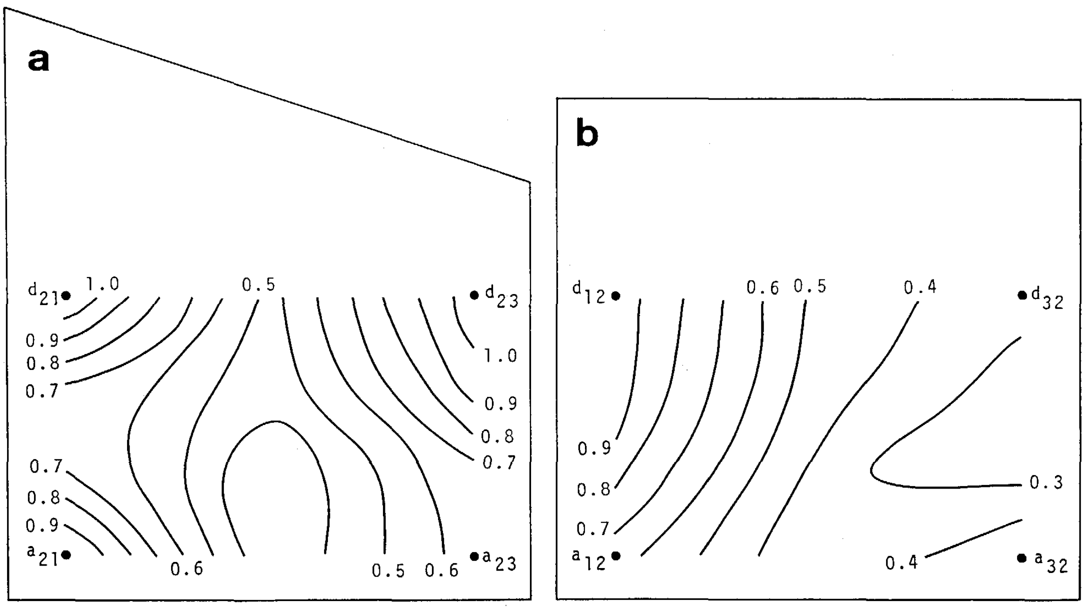

Fig. 3. Distributions of measured air velocities (m s^{-1}) in the cross-sections at z=1.8 m (a) and x=1.8 m (b) in the Phytotron I.

positional effect of the air inlet and the air outlet. The region around d_{21} locates near the air inlet, and the region around d_{23} locates the place which is affected directly by air flow from air inlet. Furthermore, the region around a_{21} locates near the air outlet in which air current contracts. In y-z cross-section at x=1.8 m, the place with higher air velocities was found in the region around a_{12} and d_{12}. These points also locate near the air outlet (Fig. 3b).

The differences in distribution among respective heights are shown in Fig. 4.

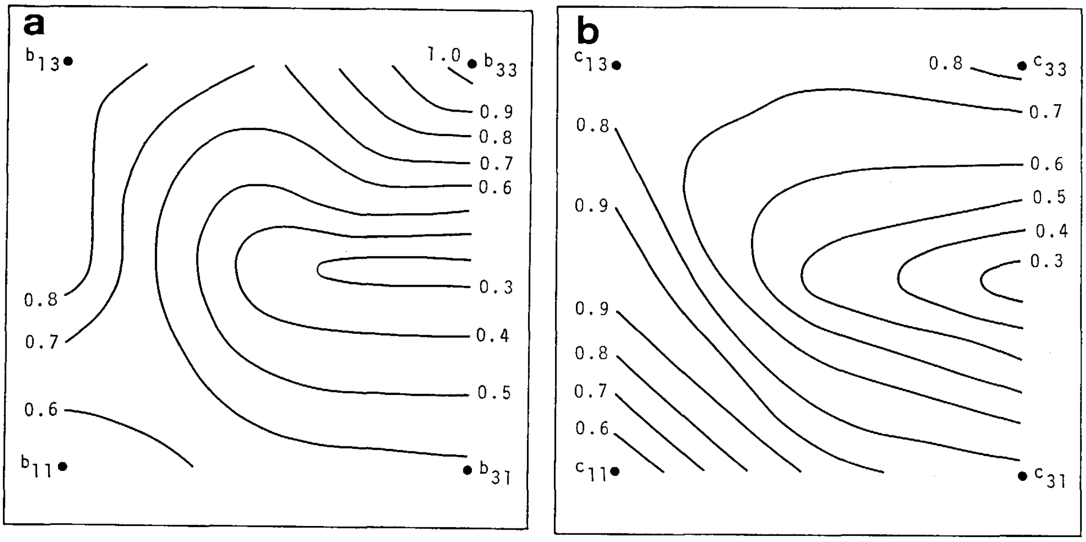

Fig. 4. Distributions of measured air velocities (m s^{-1}) in the cross-sections at y=0.9 m (a) and y=1.5 m (b) in the Phytotron I.

The velocity was highest around the region of b_{33} at y=0.9 m high and around the center region between c_{13} and c_{11} at y=1.5 m high. The region with the lowest velocity was found around the center of the opposite side wall of the air inlet.

Figure 5 shows the distribution of vertical air velocity measured in the Phytotron II. In x-y cross-section at z=0.9 m (Fig. 5a), the velocity was more homogeneous as compared with that in the Phytotron I. However, the velocity near d_{21} was relatively high owing to the fact that d_{21} is close to the air outlet. More homogeneous distribution was found in y-z plane at x=1.8 m as shown in Fig. 5b.

The distribution of vertical air velocity in both 0.9 and 1.5 m high indicated the pattern symmetric to the line perpendicular to the center line (z=1.8 m) of the wall with the air outlet (Fig. 6).

Simulation

Figure 7 shows the distributions of simulated air velocities and directions in the x-y cross-sections at z=0.4, 1.6, 2.6 and 3.6 m in the Phytotron I. From the results, it appears conceivable that air current varies locally in the room as shown in velocities and directions by vector forms. In the cross-section at 0.4 m, air velocity was considerably high in the region of smaller x value, because the air inlet and the air outlet existed at the regions around y=2.7 m and y=0.5 m respectively in the Phytotron I (Fig. 7a). Thus, velocities were also relatively high at larger x values. In the cross-section at z=1.6 m, air flew swiftly because of the region close to the outlet on z axis. In the cross-section of larger z value, velocities in lower region of the room were stably low. In the case of z=2.6 m, the air inflow velocity was high in higher region owing to the fact that the air inlet locates at about y=2.7 m along y axis. In the cross-section at z=3.6 m, velocities were low on the whole.

Figure 8 shows the distributions of simulated air velocities and directions in the x-y cross-sections at z=0.0, 0.6, 1.3 and 1.7 m in the Phytotron II. In the cross-

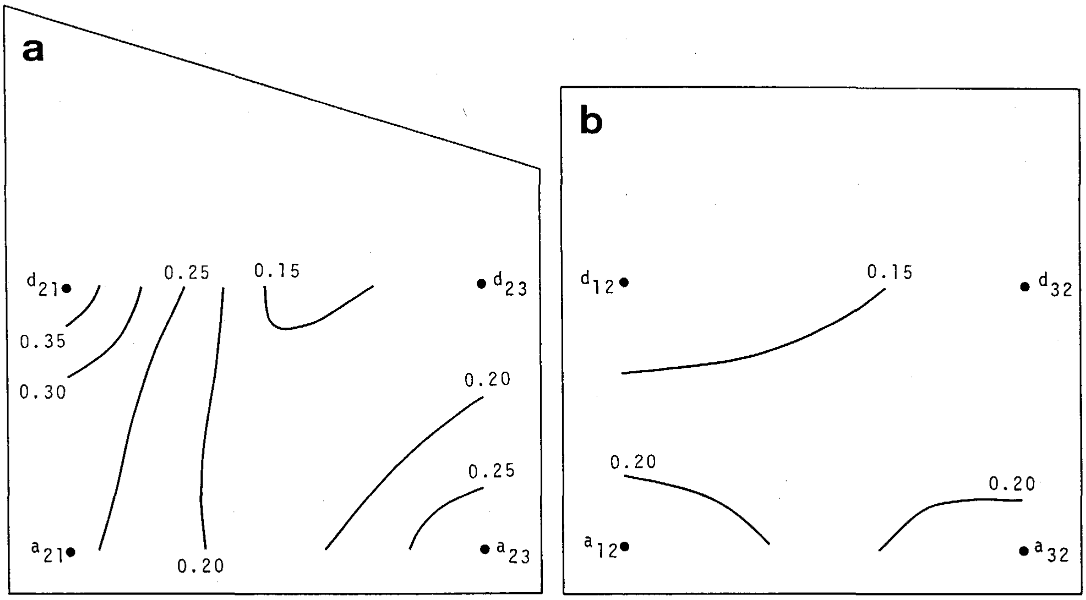

Fig. 5. Distributions of measured air velocities (m s^{-1}) in the cross-sections at z=1.8 m (a) and x=1.8 m (b) in the Phytotron II.

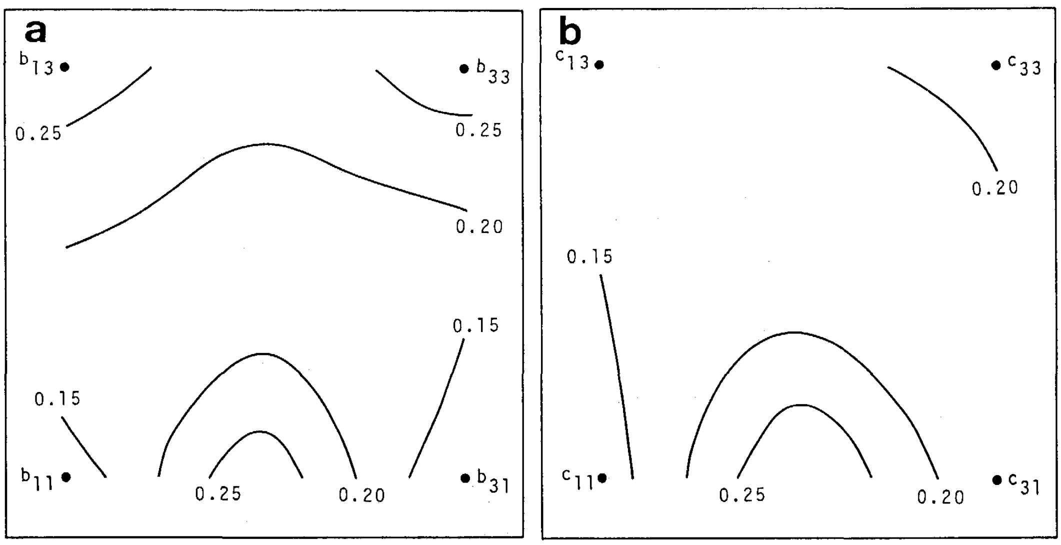

Fig. 6. Distributions of measured air velocities (m s^{-1}) in the cross-sections at y=0.9 m (a) and y=1.5 m (b) in the Phytotron II.

section at z=0.0 m, which is the central plane of symmetry, air velocity at the air outlet was highest among the cross-sections at other z value. However, the higher air velocities in the outlet did not affect the velocities in the region lower than 2 m high, where plants are grown. Furthermore, velocity distribution did not change in any x-y cross-sections except for the region over 2 m high. In the region under 2 m high, spatial variation of air velocity and current direction were relatively low.

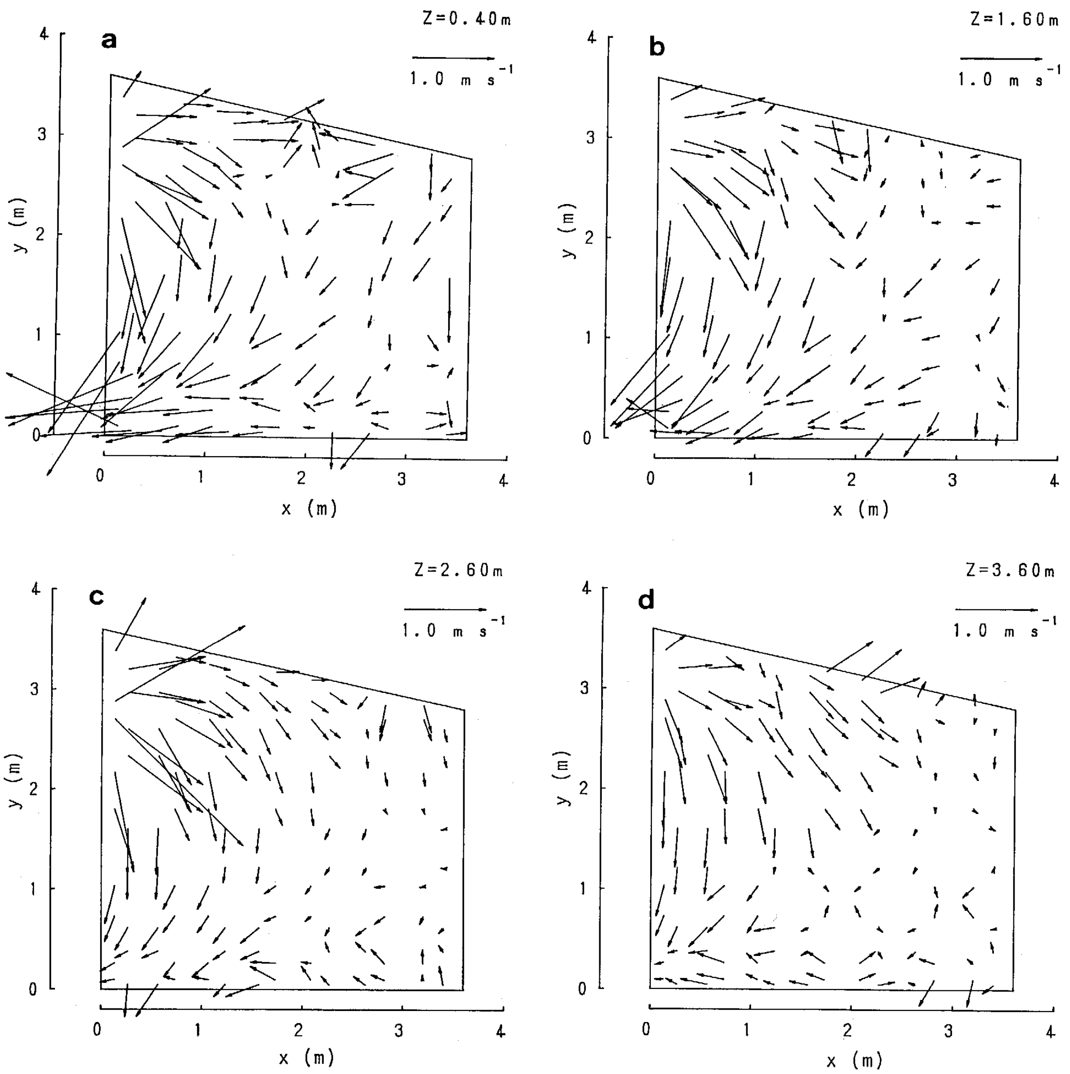

Fig. 7. Distributions of simulated air velocity in the cross-sections at z=0.4 (a), 1.6 (b), 2.6 (c) and 3.6 m (d) in the Phytotron I. Arrows indicate the magnitude of the velocity (length) and air current direction (at the rear of the arrow).

DISCUSSION

In general, environmental factors of air temperature and humidity are controlled in phytotron systems. For such controls, it is necessary to displace the air in the room continuously. If air velocity is high, then heat and gasses exchanges in the room is promoted easily. On the other hand, high air velocity affects plants growth in the room. Thus, air velocity in the room is kept to be within a certain range.

Air velocity in the room varies according to the geometry and size of the room, and to the attached locations and areas of the air inlet and the air outlet. This fact was demonstrated by measurements and simulation of air velocity and direction in

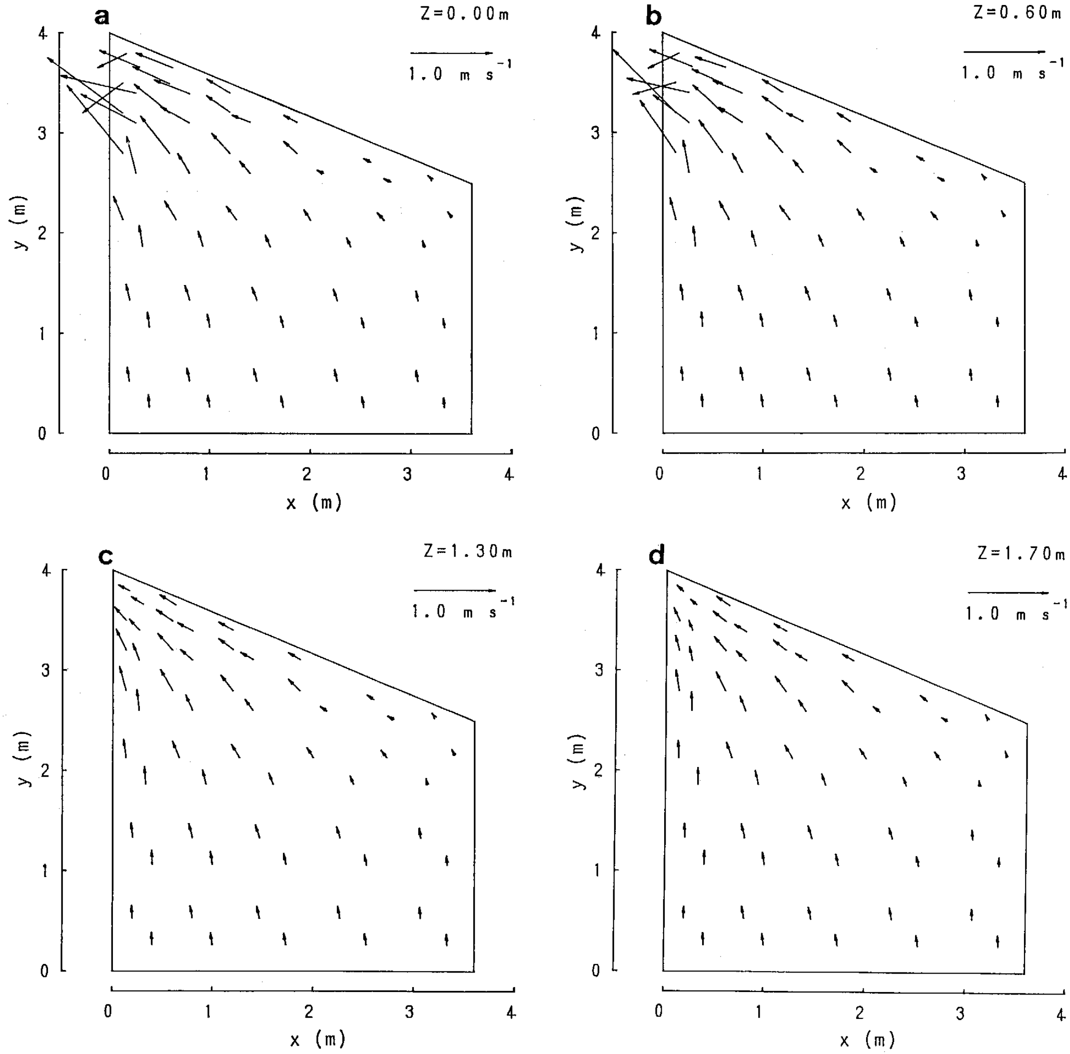

Fig. 8. Distributions of simulated air velocity in the cross-sections at z=0.0 (a), 0.6 (b), 1.3 (c) and 1.7 m (d) in the Phytotron II. Arrows indicate the magnitude of the velocity (length) and air current direction (at the rear of the arrow).

the room. The geometry and size of glass room in the Phytotron I are similar to those in the Phytotron II. The sizes, areas and attached locations of the air inlet and the outlet are, however, fundamentally different between the two types of the phytotrons. This difference caused the clear variation of the air current pattern in the room. In the Phytotron I, air velocity was high near the wall where both the air inlet and the air outlet are attached, and the velocities were lower near the opposite wall. On the other hand, in the Phytotron II the distribution of air velocity was more homogeneous and directions of velocities were almost same in plant region, because the air inlet and the air outlet exist on the walls perpendicular to each other and because the air inlet area is relatively large (about 12 times of the Phytotron I). Furthermore, it could be conceivable that homogeneity of velocity in the Phytotron

II is partially attributed to the smoothing of air velocity by the mixing chamber constructed under the floor.

The critical factor influencing on the air velocity could be the air flow rate. It was also obvious from the results of measurements and simulation that velocities in the Phytotron I were higher than those in the Phytotron II in general. That is, the measured values of vertical velocity distributed about 0.3 to 1.0 m s^{-1} in the Phytotron I, whereas they were less than 0.3 m s^{-1} in most of the regions in the Phytotron II. Simulated data also indicated that extremely high velocities appear near the air inlet and the air outlet in the Phytotron I, whereas low velocity prevailed all over the room in the Phytotron II. It could be considered that these results are generally attributed to the difference of the air flow rate, which values were 3.9 and 1.8 m^3 s^{-1} in the Phytotron I and II respectively.

Air velocity influences on plant growth through gaseous exchange, leaf temperature and transpiration (*1*, *3*), and permissible air velocity in the room without any plant should be 1 or 2 mile h^{-1} (0.44 or 0.88 m s^{-1}) (*3*). Krizek (*5*) has reported that the optimal air velocity is about 0.5 m s^{-1} for vegetative growth of plant. In the Phytotron I, there were the regions where air velocity exceeds 0.88 m s^{-1}.

Thus, it became clear that the Phytotron II is superior to the Phytotron I in respects of magnitude of air velocity, flow direction and their homogeneity in the room.

REFERENCES

1. Day W. and Parkinson R. J. (1979) Importance to gas exchange of mass flow of air through leaves. *Plant Physiol.* **64**, 340–346.

2. Drakes B. K., Raschke K. and Salisbury F. B. (1970) Temperatures and transpiration resistances of *Xanthium* leaves as affected by air temperature, humidity and wind speed. *Plant Physiol.* **46**, 324–330.

3. Duysen M. (1979) Air movement: Guideline. Pages 381–390 *in* Tibbitts T. W. and Kozlowski T. T. (eds) *Controlled Environment Guideline for Plant Research.* Academic Press, New York.

4. Eguchi H. (1988) *Biotron Institute, Kyushu University*. Pages 2–7, Biotron Institute, Kyushu University, Fukuoka.

5. Krizek D. T. (1978) Air movement. Pages 107–116 *in* Landhhans R. W. (ed) *A Growth Chamber Manual.* Cornell Univ. Press, Ithaca.

6. Matsui T. and Eguchi H. (1972) Effects of environmental factors on leaf temperature in a temperature controlled room. II. Effect of air movement. *Environ. Control in Biol.* **10**, 105–108.

7. Matsui T., Eguchi H., Mori K., Tateishi J. and Nonami H. (1980) Humidity distribution in plant population under different air currents. *Environ. Control in Biol.* **18**, 29–37.

8. Mizumoto H. and Hara H. (1983) Finite Element Method for Engineering Science, Program. (Enjiniaringu saiensu no tameno yugen yoso ho, puroguramu hen) 1st ed. Pages 117–131 Morikita, Tokyo (in Japanese).

9. Segerlind L. J. (1976) *Applied Finite Element Analysis.* John Wiley and Sons, Inc. Japanese Translation, 1978, by Kawai T. Pages 51–55, 133–166, Maruzen Co., Ltd., Tokyo.

10. Yabuki K. and Kiyota M. (1978) Studies on the effect of wind speed upon photosynthesis. (6) Relation between wind speed and diffusive resistance of cucumber leaves. *J. Agr. Met.* **26**, 65–70 (in Japanese with English summary).

11. Yabuki K., Miyagawa H. (1970) Studies on the effect of wind speed upon photosynthesis. (2)

The relation between wind speed and photosynthesis. *J. Agr. Met.* **26**, 137–144 (in Japanese with English summary).
12. Yabuki K., Miyagawa H. and Ishibashi A. (1970) Studies on the effect of wind speed upon photosynthesis. (1) Boundary layer near leaf surface. *J. Agr. Met.* **26**, 65–70 (in Japanese with English summary).