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Evaluation Indicator for Greenhouse Air Circulator Performances*

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Abstract

Although air circulators are commonly used in agricultural buildings, it is difficult to evaluate the practical performance of many such air circulators currently available in Japan. This study compares the air circulation performances of six commercial air circulators and demonstrates that the distribution of air velocity generation varied among them. Although the power consumption significantly correlated with the range of air circulation observed, the airflow rate listed in the specifications did not. Therefore, power consumption is a better evaluation indicator for the performance of air circulators under the limitation that exceedingly inefficient products are hardly distinguishable. In addition, the energy efficiency in the usage of air circulators is discussed.

[Keywords] airflow, circulation, environment control, greenhouse, power consumption

I Introduction

Air circulators are used to provide uniform air temperature, humidity, and carbon dioxide concentration inside greenhouses (Fernandez and Bailey, 1994; Polycarpou, 2005). Air circulation enhances the photosynthesis rate and promotes the growth of plant seedlings by decreasing the boundary-layer resistances of leaves (Kitaya *et al*., 2005; Shibuya *et al*., 2006). Moreover, air circulation also provides greenhouse laborers with relief from heat by promoting evaporation of sweat from the body (Tsurusaki, 2005); an air velocity of more than 2 m s^{-1} decreases the wet-bulb glove temperature by a maximum of 5 °C (Shimazu *et al*., 2008). In addition, moderate airflow assists in removing dew from leaves and fruit and could suppress incidence of *Botrytis cinerea* (Matsuura *et al*., 2004; Sekine *et al*., 2007). However, according to the results of a previous study, air circulation does not increase the yield of tomatoes under conditions of elevated CO_2 concentration (Elings *et al*, 2007). In Japan, various types of air circulators have been installed in large greenhouses with CO_2 enrichment facilities and in plastic tunnels not equipped with dehumidifiers, heaters, or automatic ventilation systems in various areas including mountainous regions and surrounding areas.

Nearly all air circulators used in greenhouses or plastic tunnels are axial fans and are installed to generate horizontal airflow. However, various types of air circulators of different shapes, designs, and sizes are available commercially. Some have an elaborate flow guide vane at the outlet and optional fogging nozzles fixed at the front or the rim. Although the airflow rate and coverage are generally listed in the specifications, the measurement procedure is generally unclear. It is difficult for cultivators and agricultural extension workers to compare the performance or cost effectiveness of various products. Therefore, the objective of this study is to determine a better evaluation indicator of air circulator performance.

II Materials and Methods

1. Measurement procedure for determining air circulation

Airflow from an air circulator was measured in a closed and empty garage with an opaque roof and walls and a plain concrete floor (8.5 m in width, 33.6 m depth, and 6.1 m in height). A 6 m × 25 m horizontal grid pattern with 1 m spacing was marked on the floor. The grid coincided with the x-y plane in the Cartesian coordinate system from (x, y) = (0, 0) to (6, 25). The central line of the grid (x = 3) was the same as that of the garage.

Air velocities were measured at each point by using a movable pole upon which hot-wire anemometers (Climomaster 6533 and 6542, Kanomax Japan, Inc., Osaka, Japan) were mounted at z = 0.5, 1.0, 2.0, and 3.0 in the Cartesian coordinate system; that is, air velocities were measured at 728 points within the rectangular space from (x, y, z) = (0, 0, 0.5) to (6, 25, 3.0). The pole at (x, y) = (0, 0) was moved horizontally by a 1.75 m tall observer at intervals of 1 m up to x = 6 along the x axis. The observer then stepped back from (x, y) = (6, 0) to (6,

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1) and reversed along the x axis. The series of movement was repeated along with the y axis up to (x, y) = (0, 25). Probes of the anemometers were fixed to the pole via clamps with a 0.22 m long arm. During the measurement, the probes remained facing the circulator and the observer was behind the pole. Air velocities were recorded by two data loggers (Thermic 2300A, Eto Denki Co., Tokyo, Japan) at intervals of 0.1 s for a period of 10 s at each measurement point. The minimum interval of pole movement was 5 s. Averaged air velocities between the periods of 7.5 to 9.5 s in the recordings were used for interpretation. The detection limit of this method was examined by measuring air velocities over the grid without air circulation.

2. Performance test

Six types of air circulators commonly used for environment control in greenhouses were tested (Table 1). All the circulators were axial fans designed to generate horizontal airflow and were powered by 100 VAC at a frequency of 60 Hz. Each propeller, except for that in circulator D, contained three blades; circulator D had five blades. All the circulators were equipped with a protective mesh or wall around the propeller, and some types had an additional airflow guide in front of the outlet. Circulator D had 16 streamlined vanes, and circulator E had 16 flat vanes fixed in its front.

Table 1 Tested commercial air circulators

	A	B	C	D	E	F
Diameter (cm)	45	42	35	35	39	35
Airflow rate* (m^3 min^{-1})	87	81	78	105	60	88
Number of propeller wings	3	3	3	5	3	3
Number of flow guide vane	-	-	-	16	16	-

* When powered by 100VAC at 60Hz

Cited from the specifications on the circulators

Air circulators were placed at the edge of the grid (x, y, z) = (3, 0, 2.0). The propeller axis was at z = 2.0 for all types of circulators. The outlet direction was confirmed by manually sighting a pole of 30 mm diameter placed at (x, y) = (3, 10) by using laser light from an oscillator attached to the circulator. The measurements of airflow distribution were started after the circulator had been running for 10 min.

The active power consumptions were measured using a digital electronic watt-hour meter (SHW3A, System Artware, Inc., Hiroshima, Japan). Its accuracy was equivalent to JIS class 2.5 (JIS C 1102-1, 2007), which implies that the sensor error was 2.5 %. The measured electric power was recorded on a PC every 1 min and then averaged over 30 min for interpretation. Neither static nor dynamic pressure was applied to the circulators during the measurements.

III Results and Discussion

A disturbance originating from the movement of the pole with the anemometers was clearly observed at heights of z = 0.5 and 1.0 (Fig. 1). In addition, the air velocities were slightly high on both sides of the grid at x = 0, 1, 5, and 6 where the observer moved backward. The probes at z = 0.5 and 1.0 were drawn into the wake of the observer. Therefore, it is clear that the observer caused undesired airflow, which was regarded as a disturbance. However, the highest air velocity did not exceed 0.2 m s^{-1}. Hence, in this study, air velocities of 0.2 m s^{-1} and higher were regarded as airflow caused by the air circulator.

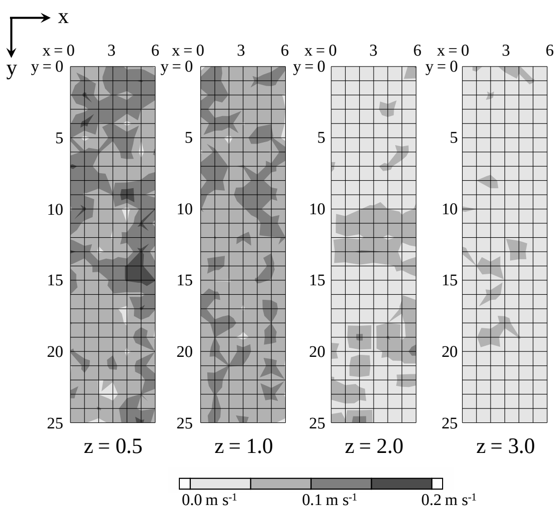

Fig. 1 Horizontal contours of air velocities measured when no air circulator was in operation. z denotes the height above the floor

The horizontal distribution of airflow at z = 2.0 and the vertical distribution y = 0, 5, 10, 15, 20, and 25 are shown in Figs. 2 and 3, respectively. The airflow in all cases reached the edge of the grid, which was 25 m away from the circulators. The distance to which the airflow reached was not distinguishable in this measurement. The airflow pattern did not show perfect symmetry and linearity for all the circulators. The streamlines assumed by the air velocity distribution in Fig. 2 meandered through the grid for circulators B and E, and the directions of these streamlines were roughly similar to those of the circulators' propeller axes. On the contrary, the main streamlines swerved away from the direction of the propeller axes for circulators A, C, D, and F. An axial fan with three blades generated airflow in a direction oblique to the fan's axis (Momoi *et al*., 2005). Because the size, shape, and rotational frequency of the circulators tested in this study differed, the oblique airflow from the axial fans caused an asymmetric airflow profile, as shown in Figs. 2 and 3. This result suggested that the direction of airflow generated by an air circulator would not always be in the direction of the propeller axis.

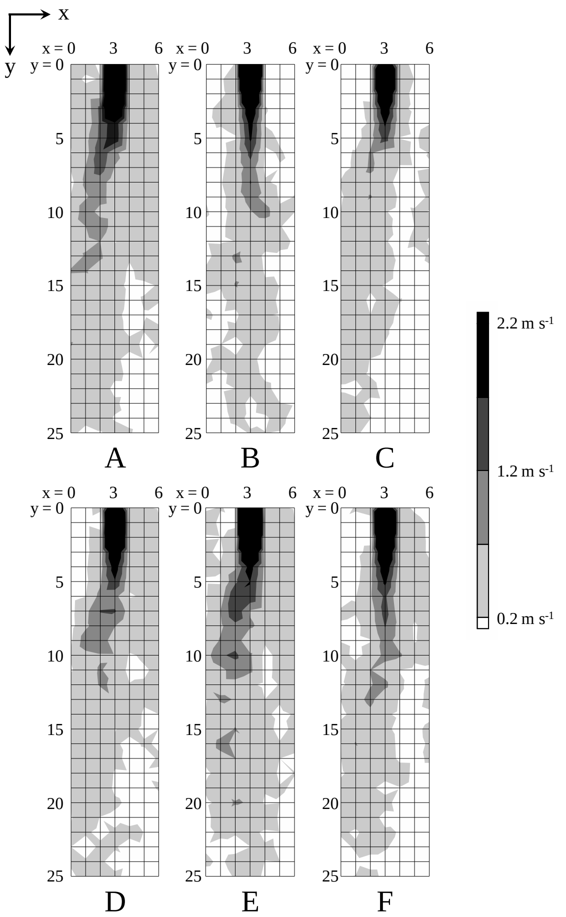

Fig. 2 Horizontal contours (x-y plane) of air velocities at z = 2.0 for various air circulators placed at (x, y, z) = (3, 0, 2.0)

Fig. 4 shows the range of air circulation described by the percentage of the points in which the measured air velocity was greater than 0.2 m s^{-1}. The percentage ranged from 26 % to 58 %, and, accordingly, the air circulators tested in this study were categorized into two groups: powerful, including A, D, and E; and low-powered, including B, C, and F. The airflow rates mentioned in the specifications hardly indicated a clear boundary between powerful and low-powered circulators suggested by the range of air circulation measured in this study (Table 1, Fig. 4), although in principle the airflow rates of circulators should correlate with the range of air circulation.

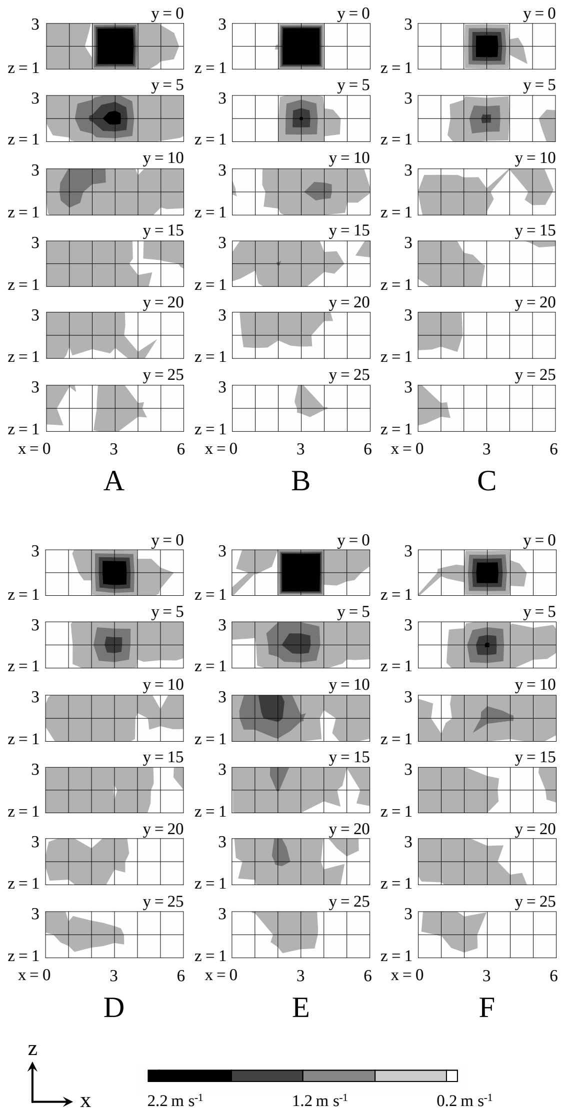

Fig. 3 Vertical contours (z-x plane) of air velocities at y = 0, 5, 10, 15, 20, and 25 for different air circulators. Air circulators were placed at (x, y, z) = (3, 0, 2.0).

In principle, the output of a circulator should reflect its input. In this study, the range of air circulation correlated significantly ($R = 0.84$, $p < 0.05$) with the power consumption of each circulator according to the t-test (Fig. 5). In contrast, the airflow rate cited in the specifications did not correlate with the power consumption (R = 0.36, N.S.). In addition, the airflow rate and the range of air circulation were not at all correlated (R = -0.08, N.S.).

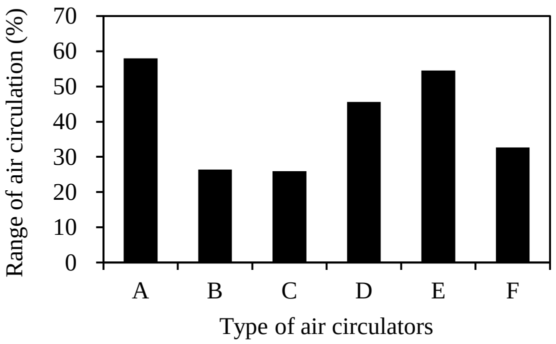

Fig. 4 Percentage of points from a total of 728 measured in which air velocity greater than 0.2 m s^{-1} was measured at heights of z = 3.0, 2.0, 1.0, and 0.5 m above the floor

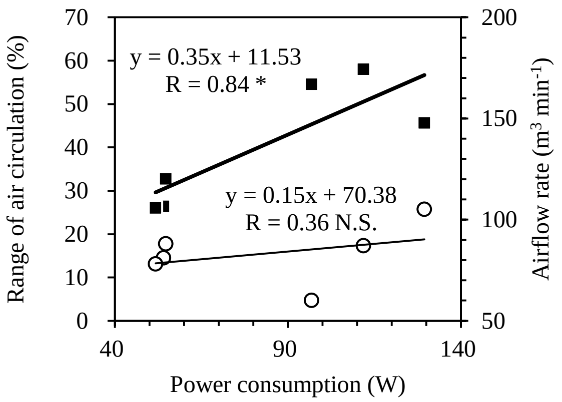

Fig. 5 Relationship of power consumption and ranges of air circulation (■) and airflow rates (○) cited in the specifications. The asterisk (*) indicates significance at the 0.05 level, and N.S. indicates no significant correlation according to the t-test

The airflow rate was estimated by using the JIS C 9601 standard (1990) for one of the tested circulators; however, the procedure to measure airflow rate was not mentioned in the specifications of other tested circulators. Accordingly, it was difficult to perform a fair comparison of the performance of the air circulators in terms of specified airflow rates. In addition, the airflow rate provided by the JIS C 9601 standard (1990) is based on the measurement of horizontal distribution of air velocity at three times the distance of the fan diameter away from the outlet. However, the streamline is not parallel to the direction of the propeller axis (Momoi *et al*., 2005), and the intensity of airflow can be partly increased by converging the streamline with the vane fixed at the front of the circulator (Baba, 2010). These facts suggest that an airflow rate measured with the JIS C 9601 standard (1990) consists of air velocities in the conditions of swirls or multiple interferences. Such results may be the reason for the inability of airflow rates in the specifications to reflect the range of air circulation or the power consumption.

Although the JIS B 8330 (2000), JIS C 9603 (1988), and ANSI/AMCA 230-99 (2000) standards are available for measurement of the airflow rates of air circulators, uniform methods have not been authorized for testing air circulators used in agricultural buildings. Therefore, the power consumption would be available for evaluation indicator rather than the airflow rate for the performance of a circulator in the present situation. The power provided to a circulator is used for air circulation in a greenhouse in addition to mechanical and other losses such as mechanical friction between a propeller axis and bearings, friction between air and propeller surface, protective cover and airflow guide, and internal and external leakage (JSME, 2007). Evaluation based on power consumption has a limitation such that powerful and inefficient circulators can be misidentified.

From the perspective of energy efficiency which can be defined as the ratio of the range of air circulation to the power consumption, the measurement results suggest that the greenhouse air could be circulated larger by two low-powered circulators than by one powerful unit. However, the airflow generated by air circulators is considerably attenuated by drag effect of tall crops such as tomato (Ishii *et al*., 2012). Therefore, it remains unclear whether low-powered circulators can circulate air in the presence and absence of crop canopies. Further studies should be performed to determine the number and types of air circulators required to circulate air in greenhouses to sufficiently provide uniform areal conditions and optimal energy efficiency.

IV Summary and Conclusions

The performances of six commercial air circulators were tested in a grid of area of 6 m × 25 m to determine their ranges of air circulation. Among these circulators, the distance of airflow reach could not be determined. The percentage of points from a total of 728, at which the airflow generated by the circulator was observed, ranged from 26 % to 58 %. Although the power consumption was significantly correlated with the range of air circulation, the airflow rate listed in the specifications was not.

The range of air circulation is a valuable factor in the practical use of a circulator; however, direct measurement is cumbersome. Therefore, users must either estimate the performances of a circulator from the specified airflow rate or assume the range or contours of airflow without detailed measurements.

Although the airflow rate is typically listed in the specifications of an air circulator, few products describe the measurement procedure. Those that do, however, fail to provide a valid protocol. Accordingly, it would be inappropriate to evaluate the performance of air circulators on the basis of the airflow rate under such conditions. Conversely, the power consumption can be easily measured with a watt-hour meter. Although the reactive power must be considered for such measurements due to the inductive loads of air circulators, the reliability of the measurement depends on the accuracy of the watt-hour meter. The results in this study showed that power consumption was significantly correlated with the range of air circulation. Therefore, power consumption is a valid evaluation indicator for the performance of air circulators, although exceedingly inefficient circulators are hardly distinguishable in such cases.

For the practical use of air circulators, energy efficiency that relates the range of air circulation to power consumption should be considered. However, the results of this study do not reflect an application to cultivated crops. Therefore, further studies should be conducted to determine the proper number and types of air circulators that can be used in greenhouses.

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