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1. RELEVANCE TO GROWERS AND PRACTICAL APPLICATION

1.1 Application

The objectives of the project were:

1. to establish the optimum speed of air movement;
2. to determine the effectiveness of air movement in improving uniformity of the glasshouse environment;
3. to quantify the effects of air movement on plant transpiration and on glasshouse heat requirement;
4. to assess ways of creating air movement;
5. to provide recommendations for practical fan installations.

The key results obtained were:

1. the optimum air speed is in the range 0.2 to 0.4 m s^{-1};
2. persistence of air movement, rather than high air speed, is required to improve uniformity of the environment;
3. a single fan correctly positioned in a 426 m^2 glasshouse can provide the required air speed in 65% of the space below gutter height; this was only increased to 90% by using eight fans;
4. fans should be positioned to create circulatory air movement, so they should reinforce the motion each creates;
5. a floor level ducted air system can create more uniform air flow through a tomato crop than overhead fans;
6. air speeds below 0.4 m s^{-1} increase heat loss by less than 1%; higher speeds increase heat loss proportionally more;
7. air movement can increase the transpiration of young tomato plants by up to 50%, and by up to 20% for mature plants if air movement can be created over all leaves;
8. the potential of computational fluid dynamics to analyse the influence of fan location on air circulation, and enable practical recommendations on fan installations to be made, was identified. However, shortcomings were identified in the specific CFD program used, which limited its practical application;
9. the CFD studies indicate that a single fan should be capable of creating effective air movement in an area of 1000-1500 m^2;
10. the water table provides a simple and easy to use tool to determine the positions and numbers of fans required to create effective air movement in greenhouses having different dimensions.

1.2 Summary

Uniformity of the greenhouse environment is important for two reasons, firstly in order to promote uniform plant growth and development, and secondly, so that the conditions at the site of the aspirated screen, which contains the sensors used to control the environment, are representative of those throughout the glasshouse. Heating and ventilating systems are designed to provide a distribution of heat and air which creates uniform environmental conditions in the region of the crop. However, in practice non-uniform conditions frequently occur. These can be reduced by establishing a persistent circulation of air in the greenhouse. Creating air movement consumes energy and so it is important that the minimum air speed is used which is consistent with producing the required effects; this implies the need for uniformity of air movement.

To obtain definite and persistent movement the air speed needs to be higher than 0.2 m s^{-1}. However, speeds of 0.5 m s^{-1} and above have been found to adversely affect plant growth and development. Consequently the optimum air speed lies in the range 0.2 to 0.4 m s^{-1}.

Creating a recirculating air flow in a greenhouse inevitably results in a region of low air speed in the centre of each recirculation zone. Using a single fan in the optimum position in a 426 m^2 area glasshouse, produced air speeds above 0.2 m s^{-1} in approximately 65% of the space beneath gutter height. Adding a second fan made the situation worse, with only 50% of the space having an air speed above 0.2 m s^{-1}. Even when using eight fans, 10% of the space still had an air speed below 0.2 m s^{-1}.

It was not practicable to measure the effect of air speed on the heat loss from a glasshouse. However, a theoretical assessment made using heat transfer theory showed that the increase in heat loss was less than 1% for air speeds within the optimal range. At higher air speeds the heat loss increased almost in direct proportion to the increase in air speed above 0.4 m s^{-1}. At a speed of 0.5 m s^{-1} the heat loss increased by 2%, and the increase was 8% at an air speed of 1 m s^{-1}.

The uniformity of the spatial distribution of temperature, humidity and carbon dioxide concentration was found to decrease as solar irradiance increased. In 'still-air' conditions in summer maximum horizontal variations of 7°C in temperature, 1 kPa in water vapour pressure and 150 vpm in CO_2 were measured. When air recirculation fans were used these variations were reduced to 1.6 °C, 0.3 kPa and 20 vpm respectively. The growing tomato crop reduced the uniformity of air speed; the ratio of the maximum to minimum speeds was 2 in the empty glasshouse, but rose to 7 when the tomato plants were 2.6 m high. At the bottom of the crop, the fans had a negligible influence; air flow rates similar to those observed in still air occurred in paths without fans and even in many areas of paths with

fans. The air speeds in the space between the crop and the roof increased as the crop grew.

Air speeds of 1 m s^{-1} were shown to increase the transpiration of young tomato plants by 40-50% and it was calculated that the increase for mature plants in summer could be up to 20%. The relative increase in transpiration is highest when the solar irradiance is low, thus air movement would be of the greatest benefit on dull days in winter. If a leaf is transpiring it is not possible for condensation to form on it; thus promoting transpiration is an effective way of preventing condensation and avoiding the consequent danger of fungal diseases developing. In Denmark a recent comparison of the environment in two pot plant houses showed that forced air movement reduced the relative humidity by 7 percentage points.

Fans create very non uniform air movement, with slow air movement approaching the fan and very high speed air leaving it; the latter can be detrimental to the crop and cause local increases in greenhouse heat loss. More uniform air motion can be created using floor level perforated air ducts. The air is discharged vertically upwards and entrains the surrounding greenhouse air, producing a slow vertical circulation of air. As this motion is created from the floor the air is better able to penetrate the crop and thus has a more uniform effect on all plants. However, as the motion is vertical it will not be as effective in reducing horizontal variations in conditions as fans, which create horizontal air recirculation. Such a ducted system might usefully be combined with a CO_2 distribution system uses flue gases as the source of CO_2.

Establishing air speeds in a large space is not easy because of the very large number of measurements which must be made. In this work the air flow patterns were predicted using computational fluid dynamics (CFD), a computer prediction program based on solving the equations of fluid flow. Before using the program its predictions were checked by comparison with a limited number of measurements and shown to be reasonably correct. The CFD program was then used to investigate the influence of fan position on the air flow pattern in the test glasshouse. This showed that in a four span Venlo glasshouse the optimum fan position was close to the first inner gutter and approximately 1/4 the distance from one gable wall, with the fan blowing towards the far gable wall. In principle this program is capable of analysing a specific greenhouse installation and enable the influence of fan number and location to be investigated, and although this was possible in the test glasshouse, the program did not perform satisfactorily when applied to a large commercial glasshouse and the optimum fan position could not be determined.

An alternative technique which would be of value for investigating the effect of fan position and number on air recirculation in different greenhouses is the water table. This will not give any quantified information but will enable the general air motions to be visualised, and as changes in fan position and number can be made very easily, the technique would be of great value in designing systems to provide effective air movement in commercial greenhouses.

1.3 Conclusions

This work has shown that air circulation can give substantial improvements in uniformity of conditions in the greenhouse. This uniformity is likely to be of significant benefit to growers seeking to eliminate problems with condensation and related problems which will be exacerbated by spatial variations in environment. It will also be of significant benefit in ensuring that inputs such as additional CO_2 are available to the whole crop. The evaluation of air flow engineering options and of different approaches to analysing flow using models has provided the essential basis for designing effective air movement systems for commercial greenhouses.

2. EXPERIMENTAL SECTION

2.1 What is the most effective air speed?

There have been few studies reported which seek to establish the minimum air speed required in greenhouses. Walker (1967) suggested that the minimum speed should be 0.2 m s^{-1}. Below that value, the air flow could be highly erratic and mixing throughout the space could not be assured. Koths and Bartok (1985) used a value of 0.25 m s^{-1}, but gave no reasons for doing so. In the air conditioning industry, it is considered the minimum speed is that which will give persistence of air movement and prevent the flow from exhibiting random fluctuations. The air speeds measured in the Venlo glasshouse at SRI, when the house was neither being heated nor ventilated, were in the range 0.06 to 0.12 m s^{-1}. Consequently a minimum air speed of 0.2 m s^{-1} seems reasonable.

High air speeds can have detrimental effects on plant growth. Morse and Evans (1962) showed that an air speed above 0.5 m s^{-1} reduced the relative growth rate of tomato leaves and the rate of dry weight accumulation. This study indicated these quantities reached a maximum at an air speed of 0.25 m s^{-1}. Kalma and Kuiper (1966) reported a reduction in the growth rate of *Phaseolus vulgaris L.* when grown at an air speed of 1 m s^{-1}. Effects on the morphology, anatomy and water relations in grasses grown at an air speed of 1 m s^{-1} compared to plants grown in calm conditions were observed by Grace and Russell (1977). Air speeds which create movement of young plants has been shown to produce more compact plants (Latimer, 1990). Andersson (1990) reported a trial in which air speeds of 0.6-0.7 m s^{-1} were created by ceiling fans mounted 2 m above the canopy of pot plants on benches. Increases in plant height and dry matter content was found with *Ficus benjamina*, and with *Fuschia x hybrida* air movement increased fresh weight and lengthened the time to flowering. Reductions were found in size and quality of *Begonia x hiemalis*. In studies carried out at SRI air speeds higher than 1 m s^{-1} were measured in the upper portion of the crop, particularly within 8 m of the fans. In these regions, leaves with scorched tips and margins were observed, and some flowers showed wilted petals and scorched tips. There was some blackening of the surfaces of developing fruits, probably due to rubbing against leaves and stems. Interveinal scorch was observed in mature leaves further from the fans. The extent of this damage, however, was limited to a relatively small number of plants. The percentage of leaves affected was small, the number of damaged fruits was negligible and the trusses with affected flowers did not show higher levels of aborted fruit than normal.

These results lead to the conclusion that the air speed should be greater than 0.2 m s^{-1} but not exceed 0.4 m s^{-1}.

2.2 Effect of air movement on environmental uniformity

The use of fans, installed over the crop, to create horizontal air flow in greenhouses has been practised for years, however, detailed information about the actual influence on the uniformity of environmental conditions has not been reported. There are differences in the recommended fan capacities[6,7] and the influence of crop resistance on the air flow is mentioned but not well defined[6,17,18]. In this study, the fan installation was based on that used in the USA (Koths and Bartok, 1985), which required eight fans to be installed in the 4 span, 425 m^2 Venlo greenhouse. This is a larger number than is currently used in Europe, but would enable the effects of the number and position of the fans to be studied.

The eight fans were mounted on frames attached to the transverse lattice beams which supported alternate gutters of the glasshouse (Fig. 1). The tops of the fans were at the same height as the tops of the fully grown plants. As there was an even number of beams there was a slight asymmetry in fan position along the house. The four bladed propeller fans, 355 mm in diameter, were mounted on plates with polystyrene bellmouth inlets so the fan axes were horizontal. A stepped speed controller was used to vary the speed of the fans, and when running at maximum speed (1380 rpm), the air flow from each fan was, according to the manufacturers' data, 0.87 $m^3 s^{-1}$.

2.2.1 Horizontal uniformity

2.2.1.1 Air speed

Figure 2 shows the air speeds measured 1.8 m above the ground at the sampling points A to F (Fig. 1), with no crop in the glasshouse. It can be seen that eight fans running at maximum speed (1380 rpm) provided a more uniform distribution of air flow in the glasshouse with a minimum air speed (0.48 $m\ s^{-1}$) significantly higher than measured in still air conditions (0.11 $m\ s^{-1}$).

With the fully developed crop in the glasshouse, the average coefficient of variation between experiments for the measured speeds was 11% for still air conditions and 6% when using maximum fan capacity. For still air conditions (fans off and glasshouse ventilators closed), the average air speed measured during the day at the top of the canopy was 0.12 $m\ s^{-1}$. The air speed was observed to decrease with reducing height to 0.08 $m\ s^{-1}$ at the bottom of the canopy. Lower air speeds were usually observed at night (0.06 $m\ s^{-1}$ at the top of the canopy).

When the fans were running, a considerable air speed was measured in the space between the top of the fully developed crop and the glasshouse roof. With maximum fan capacity, the average air speed measured in this region was 1.02 m s^{-1} (maximum = 1.34 m s^{-1}; minimum = 0.72 m s^{-1}). Even with four fans running, the average air speed was more than five times greater than under still air conditions (Fans 1, 2, 7, 8: average = 0.71 m s^{-1}; maximum = 1.11 m s^{-1}; minimum = 0.49 m s^{-1}. Fans 3, 4, 5, 6: average = 0.66 m s^{-1}; maximum = 1.08 m s^{-1}; minimum = 0.31 m s^{-1}).

The influence of crop height on the air speed is given in Table 1. This shows the crop had little influence on the mean air speed 1 m above the ground. However, the fully developed crop caused a large decrease in the uniformity of air speed in the glasshouse. The ratio of the maximum to minimum speeds rose from 2.0, with the short and medium crops, to 7.2 with the tall crop. At the bottom of the crop, the fans had a negligible influence in many areas, even when using the maximum fan capacity; air flow rates similar to those observed in still air were measured in the paths without fans and even in many areas of the paths with fans.

At a height of 1.8 m, the average air speeds over locations A to F (Fig. 1) were greater than those measured at 1 m (Table 1), which was due to the fact that the sensors were closer to the fan axis, where the air speed was highest. The average air speed with no crop (0.64 m s^{-1}) was slightly lower than with the tall crop (0.69 m s^{-1}). This was attributed to the presence of the plants which channelled the air into the paths creating some regions of high flow. At this height also the presence of the plants decreased the uniformity of the air flow. The ratio of the maximum to minimum speeds was 1.7 without a crop and increased to 5.5 with the fully grown crop. The influence of the fans was detected at this height even in paths without fans, where the minimum measured air speed (0.29 m s^{-1}) was significantly higher than the average air speed for still air conditions (0.12 m s^{-1}).

2.2.1.2 Temperature

In practical greenhouse horticulture extremes of climate are important in respect of plant stress and so the improvement in microclimate uniformity produced by the moving air was determined by changes in the maximum differences in temperature, water vapour pressure and CO_2 concentration of the air, measured at the sampling points A to F (Fig. 1). The standard deviation for each distribution was also determined.

In still air conditions, temperature differences were greater on sunny days than on overcast days. At the top of a fully developed crop, the maximum difference in temperature between sampling points (7.9 °C) was measured on sunny and hot days (average values: temperature 36 °C; external radiation 490 W m^{-2}) and the warmest area in the glasshouse was adjacent to the south side. On overcast days during the same period (average values: temperature 25 °C; external radiation 230 W m^{-2}), a maximum difference in temperature between sampling points of 3.2 °C was detected, with the warmest area located at the centre of the glasshouse. On sunny days and when the inside temperature was over 30 °C, differences in temperature between sampling points of up to 6 °C were usually detected. Such high temperatures as these occur frequently even in ventilated greenhouse in Southern Europe when solar radiation is high and wind speed low. Figure 6 shows how the maximum difference between the sampling points increased as the outside solar radiation increased. A reduction in temperature uniformity was detected with increasing height above the ground, for all meteorological conditions. Maximum differences in water vapour pressure of up to 1.06 kPa were measured on sunny, hot days, compared with a maximum of only 0.21 kPa on overcast days. However, these differences may be a reflection of the differences in air temperature.

A big improvement in temperature distribution was obtained when using the fans (Table 2). This was observed especially at the top of the crop, where the air flow was the greatest. The maximum temperature difference at that height was reduced to 1.6 °C, an improvement in uniformity of more than 6 °C with respect to still air conditions. In the paths between crop rows, where the air flow was reduced, the improvement in uniformity was less. Maximum temperature differences of more than 2.2 °C were measured at the middle of the canopy, even when using maximum fan capacity. No significant differences were observed between the different fan capacities. This could be due to the fact that the greatest temperature differences detected in still air were in the upper half of the crop and even with the lower fan capacities, a reasonable air flow was obtained in this region.

2.2.1.3 Humidity

As with temperature, the large differences in water vapour pressure between sampling points detected in still air on sunny days were significantly reduced by the fans as shown in Table 2. A maximum difference of 0.29 kPa between sampling points was measured when using the fans, which was nearly four times smaller than the maximum difference measured in still air.

2.2.1.4 Carbon dioxide

The CO_2 distribution at the top of the crop was also greatly improved when using fans. Table 2 shows data from experiments carried out during periods with an average CO_2 concentration of 630 ml m^{-3}. Differences between sampling points of up to 155 ml m^{-3} were measured in still air, but were reduced to less than 20 ml m^{-3} when the fans were used. When the greenhouse was not ventilated and CO_2 was not provided, an average of 250 ml m^{-3} was measured at the centre of the glasshouse. The depletion in the centre was higher than at the sides of the house. In still air conditions, the concentration of CO_2 in the centre of the glasshouse was 70 ml m^{-3} lower than at the sides; this difference was reduced to 30 ml m^{-3} when the fans were running. Uniformity of CO_2 is particularly important because photosynthesis does not increase linearly with light or CO_2 concentration. Consequently, the overall rate of photosynthesis of a crop in an environment with regions of high and low CO_2 concentrations is lower than if the concentration was uniform at the same average value.

2.2.2 Vertical uniformity

2.2.2.1 Air speed

Figures 3(a) and 3(b) show the air speeds measured around and within the canopy, at distances of 6 and 15 m from fan number 5. At 6 m from the fan, large differences in air flow rates were measured between paths with and without fans. The average air speed measured at the centre of the canopy with the fans running was 0.20 m s^{-1}, compared with 0.06 m s^{-1} in still air.

2.2.2.2 Temperature

Figure 4 shows the maximum differences in temperature measured between the sampling points in experiments carried out on sunny days (average values: temperature = 34 °C; water vapour pressure = 4.77 kPa; external radiation = 515 W m^{-2}). Measurements in still air (Fig. 4(a)) showed how the temperature increased with height, with a maximum difference of 4.7 ° between top and bottom of the canopy. The air flow produced by the fans reduced these differences, but still variations of more than 2 ° were recorded in the vertical profiles. Changes in the vertical temperature distribution caused by air movement have been mentioned in the literature[6], but no detailed data given.

2.2.2.3 Humidity

No clear influence of the fans on water vapour pressure distribution was found (Fig. 5), because a reasonably uniform vertical profile occurred in still air. The measurements were carried out under the same conditions as those for temperature which are given in the preceding section.

2.2.2.4 Carbon dioxide

Figure 6 shows the averages of the differences in CO_2 concentration observed in vertical profiles measured at the centre of the glasshouse, at a position 3 m in front of fan 4. The experiments were made on sunny days, with some CO_2 depletion (average concentration 256 ml m^{-3}, measured at the centre of the glasshouse). In still air (Fig. 6), the higher concentrations of CO_2 were found in the lower parts of the canopy, where a certain amount of the gas is produced by the respiration of the crop. A similar tendency was observed in the open field by Desjardins et al (1987) in a maize crop and by Francis and Parks (1988) in soyabean. With the fans running (Fig. 6), the vertical differences were significantly reduced, giving a quite homogeneous profile over nearly the whole height of the plants.

2.3 The air flow pattern produced by a single fan

The pattern of air flow produced by a fan is the region within which the air speed exceeds some minimum residual value. In this study 0.15 m s^{-1} was used as this was higher than the average speed of 0.12 m s^{-1} measured in 'still' air conditions, i.e. when no attempt was made to promote air movement. The air flow pattern was determined using a single fan, mounted 1.8 m above the floor, and positioned centrally at one end of the uncropped 4 span SRI Venlo glasshouse. The air speed at different distances from the fan was measured both parallel and perpendicular to the fan axis. The shape and dimensions of the air jet were also determined by observing the motion of pieces of paper suspended from strings installed across the house. The strings, placed in a horizontal plane which contained the axis of the fan, were spaced at 1.5 m intervals over the whole glasshouse area and the pieces of light paper were attached to the strings at 0.5 m intervals.

The shape of the air jet produced when the fan was running at its normal speed is shown in Fig. 7. The cone of air leaving the fan expanded with an angle of 25 degrees. This, and other characteristics were found to be similar to those observed in studies of air jets from different outlets (Farquharson, 1952; Tuve and Priester, 1944; Koestel et al. 1950). Figure 8 shows the air speeds measured along the fan axis. Though the data show a rapid decrease in air speed as the distance from the fan increases, the air jet travelled a considerable distance from the fan. The speed measured 24 m from the fan was 0.19 m s^{-1}, which was still greater than the values measured in still air conditions. The maximum speed of 4.1 m s^{-1} was measured 1.5 m from the fan.

Farquharson (1952), Tuve and Priester (1944), and Koestel et al. (1950) all used similar equations to predict the distance the jets travelled before the air speeds had decayed to the background value, which gave reasonably accurate descriptions for jets produced from almost any type of opening. These equations are difficult to use in the case of the air jet produced by a fan, since the air turbulence in front of the fan makes of some of the required parameters difficult to measure. However, a similar equation was derived in which some of the parameters had been replaced by others easier to measure when a fan is used:

$$V_x = K_c V_{1.5} \frac{\sqrt{A_f}}{X} \qquad 1$$

where the axial speed in the air stream V_x (m s^{-1}), is a function of the axial air speed measured 1.5 m from the fan $V_{1.5}$ (m s^{-1}), the area of the fan aperture A_f (m^2), the distance from the fan x (m), and a constant of proportionality K_c. The value of K_c was calculated by comparing the measured values of V_x with those calculated from the equation of Farquharson (1952); this resulted in the theoretical value of K (7.9 for a jet which expands with an angle of 24 deg.) being multiplied by 0.61. Koestel et al. (1950) also observed lower values of K when turbulence was imparted to the air stream, as occurs with a fan. Figure 9 shows that the air speed falls off rather more slowly than this equation predicts. This may also be due to the turbulence produced by the fan in the zone of the air stream close to it, which was not present in the case of ventilating air jets from the outlets studied by Farquharson (1952), Tuve and Priester (1944), and Koestel et al. (1950).

Equation 1 can be used to determine the distance over which a fan will provide effective air movement, i.e. the throw of the fan.

2.4 Effect of the number and position of fans on air movement

Experimental investigations of the spatial distribution of air speed in large greenhouses is limited by the low speeds, which entails the use of very sensitive and therefore expensive instrumentation, and the time required to carry out a systematically survey through the large volume. In this project limited experimental measurements were combined with theoretical studies using computational fluid dynamics (CFD). CFD is a computer-based technique for simulating fluid flow. The region of interest is divided into a grid of small cells and the equations that govern fluid flow within each cell are solved. This enables the speed of the fluid and the flow pattern in a space to be predicted given its dimensions and details of the flow is created. Thus, given the greenhouse dimensions, the fan positions and the fan discharge air speed, the air speeds and flow pattern throughout the greenhouse can be calculated. Potentially, the advantages of CFD over the experimental method are greater speed and lower cost. However, it is standard practice to measure air speed using anemometry at selected points to confirm the predicted values.

The work was divided into three sections; firstly, the calculated air speeds in a small (12.8 m x 33.3 m) Venlo glasshouse at SRI were compared with experimentally measured values to establish the accuracy of the CFD predictions; secondly, the effect on the air distribution of moving the position of a single fan in the same Venlo glasshouse was studied; and thirdly, the effect on the air distribution of using two fans in different positions in a larger glasshouse (56.7 m x 47.5 m) on a commercial nursery was investigated.

2.4.1 Validation of CFD predictions

The first stage of the investigation compared measured and predicted air speeds at a number of positions in the Venlo glasshouse at SRI. The glasshouse was fitted with eight fans for experimental purposes but was otherwise configured as a commercial unit for tomato production. Fig. 10 shows the fan locations and their discharge directions, and also the positions where air speeds were measured. The fans were 0.355 m diameter, flange mounted, giving an air flow rate of 0.75 m^3 s^{-1} (2700 m^3 h^{-1}), and were fixed at a centre height of 2.5 m from the floor, well below gutter level (3.3 m). Mean air speed was monitored at three positions along the length of the house, 12 m, 21 m and 24 m from the west gable end, each measurement was made 1.8 m from the side-wall. At each position five anemometers were fixed in a vertical line, 0.6 m, 1.2 m, 1.8 m, 2.4 m, and 3.0 m above the floor.

Air speeds were measured under a variety of fan configurations without a crop present and also at three stages of growth of a tomato crop, 1.4 m, 2.5 m before layering, and 2.5 m after layering. All measurements were made with roof ventilators closed, and under isothermal conditions, i.e without internal heating and in dull overcast weather conditions to minimise solar heating.

The CFD grid used for calculating the air flow is shown in Fig. 11. The overall internal geometry was reproduced in the grid, including valley gutters and the nft staging. Small section obstructions such as roof trusses, stanchions, glazing bars, etc. were not included. As the fan driven air flow within the glasshouse is turbulent the k - ϵ turbulence model was used in the CFD simulation to account for the momentum losses due to turbulence; k is the turbulence kinetic energy and ϵ is the dissipation rate. The simulation assumed isothermal conditions. Fig. 12 compares measured and predicted air speeds in the glasshouse, when empty and with the 2.5 m unlayered crop present. The effect of the crop in reducing air speed was simulated in the CFD calculations by a simple crop model (Walklate, personal communication) representing a momentum sink due to leaf frictional and form drag.

Figure 13 compares the measured and predicted air speeds with various combinations of fans operating. Figures 13 and 14 show that the measured and predicted air speed profiles have similar shapes in most cases, and also that the predicted profiles in Fig. 13 are ranked in the same order as the measured profiles. However, two features of the results in Fig. 14 should be noted, firstly, the predicted air speeds are generally lower than the measured values near the floor, and secondly, the inclusion of the crop model in the CFD calculations has not produced the changes in shape of the predicted air speed profiles, particularly near the floor, that are evident in the measured profiles. More work is clearly required to identify a suitable crop model. For this reason the effect of a crop has not been considered in the rest of the investigation.

2.4.2 Effect of fan position - Venlo glasshouse

The second stage of the investigation studied the effect of the placement of a single fan on the total volume of air moved within the SRI Venlo glasshouse (12.8 m x 33.3 m) with total volume 1600 m^3. This was carried out using CFD alone, without experimental measurements. Twelve positions in one quarter of the glasshouse were simulated and the percentage of the building volume with air speed below 0.2 m s^{-1} calculated. The minimum acceptable air speed was taken as 0.2 m s^{-1}. The results of this calculations are shown in Fig. 14, and presented as the percentage volume below heights of 2.5 m and 1.0 m, which correspond to tall and short crops, with low air speed. These limits were selected because it was assumed that low air speeds are unimportant if they are in zones of the building which are unused. The trends in both cases are the same with values ranging from 34% to over 60%. However, these values are likely to be overestimates because the CFD simulation tends to underestimate air speeds near the floor, as discussed earlier with reference to Fig. 12. Despite this, there is no reason to believe that the relative values are not correct. It is important to note that the low air speed volume from a single fan can double if the fan is not in the best position. Both sets of data show an optimum position for the fan at x/w=0.26 and z/l=0.27. With the fan in the optimum position Fig. 15 shows the spaces within the greenhouse where the air speeds are above 0.5 m s^{-1}, which includes the jet from the fan. The spaces where air speeds are below 0.2 m s^{-1} are shown in Fig. 16, and it is clear that the largest volume with low air speeds is on the inlet side of the fan. Moving the fan upstream, such that z/l becomes less than 0.27, increases the volume of low speed air downstream because the downstream distance is greater than the throw of the fan. Air circulation patterns for the four fan positions across the greenhouse at z/l=0.27 are shown in Fig. 17. This shows that air circulation patterns are complex, even from a single fan. The vector plots which relate to a horizontal plane 0.5 m above the floor, well below the height of the fan at 2.5 m, show several zones of recirculation, which change as the fan position changes. In addition, there are zones of recirculation in vertical planes.

The effect of additional fans is shown in Table 3. As expected, eight fans produce the greatest air movement, but the low air speed volume is still 11% compared with a value of 34% from a single fan in the optimum position. Surprisingly, the effect of two fans in the positions shown is to increase the low speed air volume to 48% rather than to reduce it. To find the optimum positions for two fans is a major task, considering the large number of possible combinations, and could not be attempted in this investigation.

2.4.3 Effect of fan position - Commercial glasshouse

The third stage of the investigation studied the effect of the placement of two fans on the volume of air moved within a commercial glasshouse block (56.7 m x 47.5 m), with a total volume of 8000 m^3. This was achieved using CFD alone, without experimental measurements. The fans were 0.55 m diameter, each producing an air flow rate of 1.53 m^3 s^{-1} (5500 m^3 h^{-1}), and the fan axes were aligned with the ridges. They were placed within the roof space because practical considerations dictated that the fans should be above gutter height (2.4 m). Two horizontal positions 10 m and 20 m from the upstream wall were simulated, and the percentage of the building volume with air speed below 0.2 m s^{-1} calculated. The fan positions and the predicted air circulation patterns 1.0 m from the floor are shown in Fig. 18. Table 2 gives the percentage volume with air speed below 0.2 m s^{-1} for volumes below 2.5 m and 1.0 m. The circulation patterns are very similar and this is also reflected in almost identical percentage volumes with low air speed (Table 4). Figure 19 shows the zones below 1.0 m in which the air speed is below 0.2 m s^{-1}. These zones cover almost 60% of the floor and have implications for growers using the floor area for small plants. Two fans fixed as shown in Fig. 18 are relatively poor in circulating the air and their behaviour may be similar to that highlighted for two fans in Table 3, see previous section. The air circulation may well be better from a single fan mounted in the optimum position described in the preceding section.

2.4.4 Use of a water table

The flow of a fluid in a two dimensional space can be studied using a shallow tank, having the same profile as the space, which contains water. The flow can be generated using water supplied from a pump through small horizontal tubes. These can be placed to simulate the position of fans. Water is removed from the tank to supply the pump so the total quantity of water in the system is constant. The flow can be visualised by sprinkling pepper onto the surface of the water. This technique was used to investigate the air flows created using perforated air ducts resting on the greenhouse floor and discharging air vertically upwards. When these ducts were placed under alternate greenhouse gutters it was expected that the jets would entrain surrounding air and create vertical air circulations in the spans on either side of the duct. Using a water table with the cross sectional shape of the greenhouse enabled the flow patterns shown in Fig. 19 to be obtained. This confirmed the feasibility of using ground level ducts to generate air circulation, and also showed that a water could be used to simulate the movement of air in a greenhouse.

The water table technique could be used to determine the influence of the number and positions of fans on the general air movement in a greenhouse, but it would not be easy to make detailed studies on the influence of the crop. The method will give a qualitative representation of the flow but will not permit quantification of the speeds.

2.4.5 Conclusions

Predictions of air speed using CFD agree sufficiently well with measured values to allow optimum fan positions to be found.

The effect of a crop on air circulation has not been included because a suitable method of representing the flow resistance of the crop is not available.

A single fan, sited in the correct position, can be extremely effective in terms of the volume with air speed below 0.2 m s^{-1}. In a 12.8 m x 33.3 m glasshouse the position for a 0.35 m diameter fan (2700 m^3 h^{-1}) is approximately at a quarter of the width and a quarter of the length.

A second fan can make the air circulation worse rather than better if incorrectly positioned. The optimum positions for multiple fans is beyond the scope of this investigation.

The effectiveness of two 0.55 m dia. fans (5500 m^3 h^{-1}) in a large commercial glasshouse 56.7 m x 47.5 m, mounted at the half-length position is relatively poor, measured in terms of the volume with air speed below 0.2 m s^{-1}. A single fan mounted in the optimum position may well be more effective.

The influence of fan position and number on the general air flows created in a greenhouse can be determined using a water table.

2.5 Effect of air movement on greenhouse heat loss

The resistance to the flow of heat through a greenhouse cover is the sum of the resistances at the inner and outer surfaces of the cover and of the covering material itself. The resistance at the inner surface is the combination of the individual resistances associated with the transfer of heat by condensation, convection and thermal radiation. The resistance of the cover is proportional to the thickness and inversely proportional to the thermal conductivity of the material. The external resistance is the sum of resistances to heat transfer by thermal radiation and convection, the latter being influenced by wind speed. In practice the internal resistance forms approximately two thirds of the total resistance of the cover and the external resistance one third, the resistance of single layer covers contributes less than 5% to the overall thermal resistance of the cover. At the inner surface the air speed is generally low and increasing it will reduce the net resistance of the inner surface thus reducing the overall thermal resistance and increasing the heat loss through the cover.

Measurements of the air speed near the roof of the 4 span Venlo glasshouse at SRI were made using hot sphere anemometers, in still air conditions i.e. when no attempt was made to create air movement, and when air movement was created using one fan and conditions the air speed is in the region of 0.1 m s^{-1}, but that it is increased to 0.3 m s^{-1} by the ducts and to 0.4-0.5 m s^{-1} by the fan.

A heat transfer model, which included the forms of heat transfer described above, was used to investigate the effect of air speed at the inner surface of the cover on the rate of heat loss from a greenhouse covered with a single layer of glass. The results are shown in Fig. 21. It is evident that unless the air speed close to the greenhouse roof exceeds 0.5 m s^{-1} the effect on heat loss is less than 2%. At higher air speeds the heat loss increases in proportion to the air speed.

2.5.1 Conclusions

The conclusion therefore is that provided the air speed close to the inner surface of the greenhouse cover is less than 0.5 m s^{-1} that the increase in heat loss will be less than 2%. However, an air speed of 1 m s^{-1} near the glass, which was measured in some regions of the greenhouse, will increase heat loss by 7%, compared to 'still' air conditions.

2.6 Influence of air movement on transpiration

To determine the air speed effect on transpiration, young tomato plants were placed within a transparent wind tunnel (width 0.6 m, length 4.0 m, height 1.0 m) in which air movement was created by an extractor fan. The wind tunnel was inside a double acrylic greenhouse compartment where temperature and vapour pressure deficit were controlled by a climate computer, through heating, ventilation and fogging. Light was provided by natural solar radiation only. To avoid cross-related influences of climate variables, set points were chosen according to a factorial experimental plan in the range defined in Table 5.

Solar radiation was measured outside the greenhouse and within the wind tunnel. Air temperature (aspirated Platinum Resistance Thermometer 100 Ω), leaf temperature PRT 100; according to Bourgeois *et al*; 1986), humidity (dew point), air speed and CO_2 concentration in the middle of the crop were recorded every 5 min. Transpiration was measured by placing one tomato plant on a balance and by recording the minimum, average (10 s interval) and maximum weight every 5 min. Measurements were then averaged over periods between 0.5 and 2 h, to eliminate the noise due to the fan effect on the balance and to ensure a 5% precision. Pots were covered with a sheet of plastic to avoid soil evaporation. The leaf area of every leaf of the plant on the balance was assessed by non-destructive measurements of length and width during the experiment, and by planimeter measurements at the end of the experiment.

The cultivar used was Moneymaker, sown on 1 December and grown in pots. The experiment was carried out between 31 January and 6 February. The measured plant was surrounded by guard plants, reaching a density of 2 plants m^{-2}.

The influence of the various climatic factors on transpiration was assessed by a multiple linear regression analysis. The following factors were found to have a significant influence:

(1) incoming global solar radiation on a horizontal surface inside the greenhouse, I (W m^{-2});

(2) air vapour pressure deficit, vpd (kPa);

(3) air speed inside the wind tunnel, u (m s^{-1})

Transpiration is given by the following regressions, the number in parentheses representing the 95% confidence interval for each coefficient:

$$E_{at} = \underset{(\pm 6\%)}{0.089 \cdot I} + \underset{(\pm 23\%)}{1.54 \cdot vpd} + \underset{(\pm 36)}{1.46 \cdot u} \qquad (mg\ m^{-1}\ s^{-1}) \qquad 2$$

(February, 103 hourly measurements, $R^2 = 0.90$; S.E. = 1.1 mg m^{-1} s^{-1})

The wind tunnel experiment showed that air speed can have an important influence on tomato transpiration: in February, an air speed of 1 m s^{-1} increased the transpiration by 0.13 mm day^{-1} (+ 50%) and was equivalent to an additional inside solar radiation of 1.44 MJ m^{-2} day^{-1} (compared with an average inside solar radiation of 2.7 MJ m^{-2} day^{-1} in February at Silsoe). A sensitivity study was performed using Stanghellini's model on the June-July data. It showed that an air speed of 1 m s^{-1} resulted in an increase in transpiration of 2.2 mm day^{-1}. Therefore the influence of air speed can also be important for a mature crop (air speed of 1 m s^{-1} equivalent to 7.5 MJ m^{-2}), if good air circulation can be provided throughout the greenhouse.

The effect of air movement is related to the increase in the aerodynamic conductance at the surface of the leaf, as it is the only parameter which depends on air speed in the Stanghellini (1987, p.32) model. In the regression analysis of the wind tunnel data, the relationship between transpiration and air speed was assumed to be linear. To test this hypothesis, Fig. 22 presents the calculated transpiration as a function of the air speed; the increase in transpiration is nearly linear between 0.05 and 0.5 m s^{-1}, but the dependence is reduced above 0.5 m s^{-1}.

Finally, the air speed influence given in Fig. 22 assumes that the air vapour pressure deficit remained constant. In practice, however, an increase in transpiration leads to an increase in humidity within the greenhouse. Therefore a reduction in the influence of air movement can be expected, of about 5-20% for a young crop and of 25-45% for a mature crop; this estimate was obtained by using the conservation equation for heat and water vapour in the greenhouse.

2.6.1 Conclusions

Air flowing at a speed of 1 m s^{-1} near the leaves of young tomato plants increases the transpiration by 40-50%. The effect diminishes as the season progresses because transpiration is increased by the higher levels of solar radiation. In mid summer, an air speed of 1 m s^{-1}, if created over all leaves, is estimated to increase transpiration by 20%.

2.7 Ways of creating air movement

The conventional way of creating air movement is to use fans suspended in the space between the top of the crop and the greenhouse roof, to create a horizontal flow of air.

An alternative is to use horizontal film plastic air ducts having a row of holes along the top of each so the jets of air which emerge are directed upwards. When the ducts are on the floor the jets will entrain air and create an upward motion of air above each duct. By placing the ducts under alternate gutters in a Venlo greenhouse the roof will help to produce the re-circulation of the air, as illustrated in Fig. 19.

Another mechanism which produces air movement is the natural convection created by heating pipes. The air heated by the pipes rises because it is has a lower density than the surrounding cooler air which descends to replace the rising air. This mechanism has been utilised in single span houses when extra pipes can be placed on the side walls to create upward air movement, the air rises up the side walls and roof slopes gradually cooling and eventually descends half way across the house before moving back to the sidewalls. This circulation gave very uniform temperatures across the greenhouse. In greenhouses with heating pipes spaced over the floor it is not so easy to create strong air circulation, but it should be possible when heating pipes are banked on the stanchions, as occurs for example with lettuce production.

Determinations of the air speeds produced by these three methods were made using five heated sphere anemometers. The measurements were made at heights of 1, 2 and 3 m above the floor with the sensors spaced across the southern span of the glasshouse half way along the length, as shown in Fig. 23(a), when the tomato plants were approximately 1.5 m high.

The results obtained with the air ducts showed clear evidence of the upward flow of air above the duct along the south wall where air speeds of 0.2-0.3 m s^{-1} were found, Fig. 24 and 25. The average speed over the three heights and the five measuring positions was 0.16 m s^{-1} with a maximum speed of 0.35 m s^{-1}. Flow visualisation studies, using soap bubbles, revealed the existence of an air flow pattern similar to that shown in Fig. 19. Air ducts could serve the dual functions of distributing CO_2 obtained from the flue gasses of natural gas fired boilers and creating air movement within the crop canopy.

Measurements were made using two configurations of fans. The first used a single fan in position 1 (see Fig. 7) and the second used two fans in positions 1 and 2. The average air speeds obtained using one and two fans were 0.27 and 0.45 m s^{-1} respectively. The single fan gave similar air speeds within the crop canopy as obtained using the ducts, but higher speeds were found with the second fan was used, Fig. 24 and 25. In interpreting these results it should be realised that because of their relative positions, the air had to travel almost 3/4 the distance around the house from the single fan before reaching the measurement position. The high speed air from the fan had been dissipated and so the measurements reflected the general air movement. Whereas when two fans were used, the air from the second fan had only to travel 1/2 way along one wall before reaching the measuring position.

When the heating pipes were used to promote air movement, the average pipe temperature was 69 °, and the maximum air speed was 0.19 m s^{-1}. This is consistent with the value of 0.25 m s^{-1} measured by Aubinet and Deltour (1994) above a pipe dissipating 400 W m^{-1}, which corresponds to a pipe temperature of approximately 120 °. The average air speed over the three heights and the five measuring positions, was 0.1 m s^{-1} which is very similar to that found in still air conditions. However, flow visualisation using small soap bubbles showed the air was moving up the side wall above the double heating pipe, but it was not possible to identify a distinct circulation pattern.

2.7.1 Conclusions

Fans create horizontal air movement through the greenhouse, but ducts can produce more effective movement of the air through the crop. Ducts could be used to distribute CO_2 obtained from flue gases as well as promote air movement within the crop. Heating pipes create air circulation but the air speeds are low and the effect is limited to periods when heat inputs are high.

2.8 Overall Conclusions

The main conclusions from this research were:

1. The optimum greenhouse air speed is in the range 0.2 to 0.4 m s^{-1}.

2. Persistence of air movement, rather than high air speed, is required to improve uniformity of the environment.

3. A single fan correctly positioned in a 426 m^2 glasshouse can provide the required air speed in 65% of the space below gutter height; this was only increased to 90% by using eight fans.

4. Fans should be positioned to create circulatory air movement, so they should reinforce the motion each creates. The fans should not all be directing air in the same direction.

5. A floor level ducted air system can create more uniform air flow through a tomato crop than overhead fans.

6. Air speeds below 0.4 m s^{-1} increase heat loss by less than 1%; higher speeds increase heat loss proportionally more.

7. Air movement can increase the transpiration of young tomato plants by up to 50%, and by up to 20% for mature plants if air movement can be created over all leaves.

8. The potential of computational fluid dynamics to analyse the influence of fan location on air circulation, and enable practical recommendations on fan installations to be made, was identified. However, shortcomings were identified in the specific CFD program used, which limited its practical application.

9. The CFD studies indicate that a single fan should be capable of creating effective air movement in an area of 1000-1500 m^2.

10. The water table provides a simple and easy to use tool to determine the positions and numbers of fans required to create effective air movement in greenhouses having different dimensions.

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Table 1. Air speeds (m s^{-1}) at two heights for four states of the tomato crop

Height of crop	Height of measurement					
	1 m			1.8 m		
	mean	min.	max.	mean	min.	max.
No crop				0.64	0.48	0.82
0.6 m	0.33	0.24	0.48			
1.8 m	0.24	0.17	0.33			
2.6 m	0.29	0.11	0.79			

Table 2. Influence of fans on uniformity of greenhouse climate

	Height of measurement, m	Absolute value	Standard deviation	
			Fans off	Fans on
Height of crop	2.6			
Temperature	3.1	36 °C	5.6 °C	0.8 °C
	8	36 °C	1.5 °C	0.7 °C
Vapour pressure	3.1	5.19 kPa	0.43 kPa	0.23 kPa
	0.8	5.19 kPa	0.81 kPa	0.17 kPa
CO_2	3.1	630 ml m^{-3}	100 ml m^{-3}	10 ml m^{-3}

Table 3. Effect of fan configuration on the percentage volume with predicted air speed below 0.2 m s^{-1} in the SRI Venlo glasshouse (12.8 m x 33.3 m)

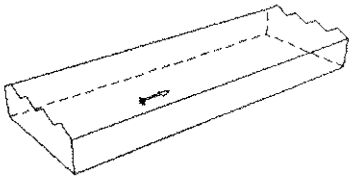
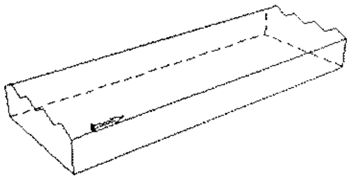
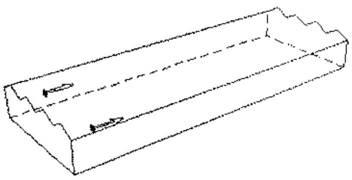
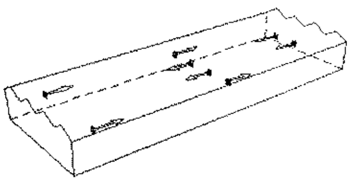
Fan configuration	Volume below 2.5 m	Volume below 1.0 m
	34%	38%
	35%	46%
	48%	53%
	11%	17%

Table 4. Effect of fan positions on the percentage volume with predicted air speed below 0.2 m s^{-1} in a commercial glasshouse (56.7 m x 47.5 m)

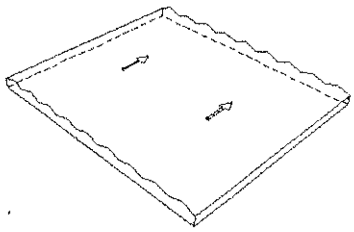
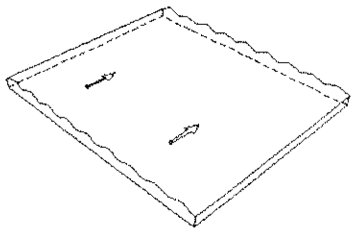
Fan configuration	Volume below 2.5 m	Volume below 1.0 m
	54%	57%
	52%	56%

Table 5. Experimental conditions, plant characteristics and average transpiration

	Wind tunnel (31 January - 6 February) daylength - 9.5h
Plant density (plants m^{-2})	2.0
Leaf Area index	0.56
Plant height (m)	1.0
Control type	Factorial

	Range		
	Minimum	Average	Maximum
Inside solar radiation (W m^{-2})	0	17	135
Daily total (MJ m^{-2})	-	1.5	-
Air vpd middle (kPa)	0	0.78	2.0
Air speed (m s^{-1})	0	0.20	1.2
CO_2 concentration (ppm)	260	306	530
	No enrichment		
Air temperature middle (°C)	10.6	17.9	29.9
Air temperature top (°C)	-	-	-

	Averages		
	24h	Day	Night
T_{leaf}-T_{air} middle (°C)	-0.1	0.4	-0.3
T_{leaf}-T_{air} top (°C)	-	-	-
Transpiration rate (mg m^{-2} s^{-1})	3.1	6.3	1.1
		203%	35%
Total daily transpiration (mm day^{-1})	0.27	0.21	0.06
	100%	78%	22%

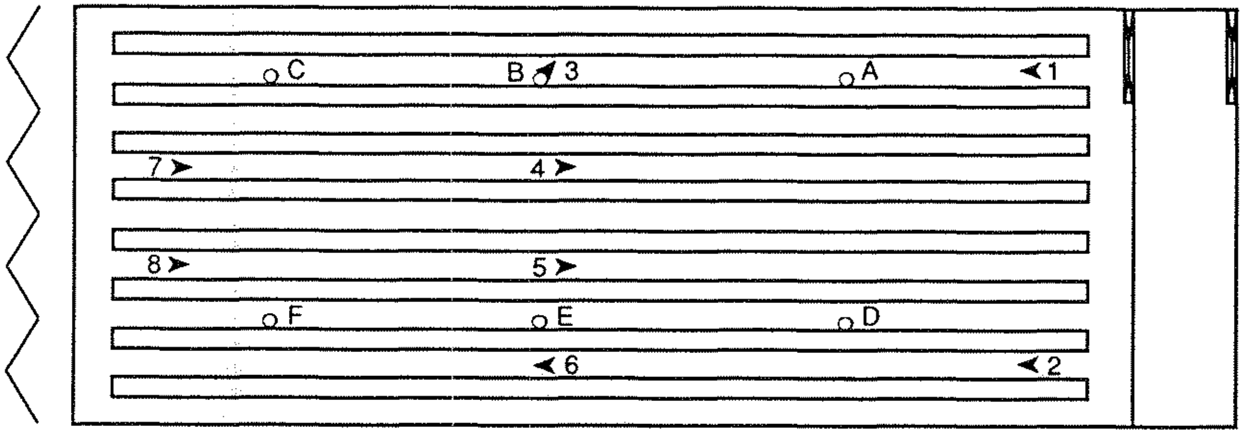


Fig. 1. Plan of experimental glasshouse
Position of fan and direction of air flow (1-8)
○ *Measurement position (A-F)*

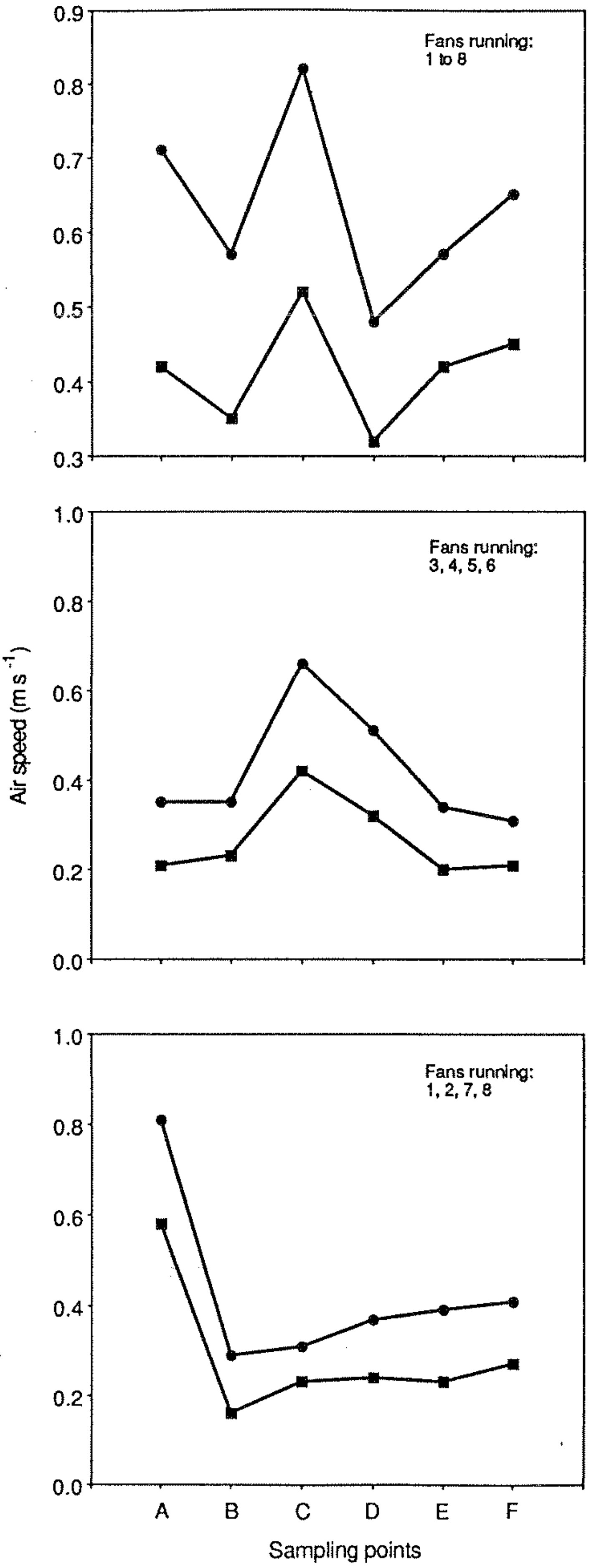


Fig. 2 Horizontal distribution of air speed in empty greenhouse

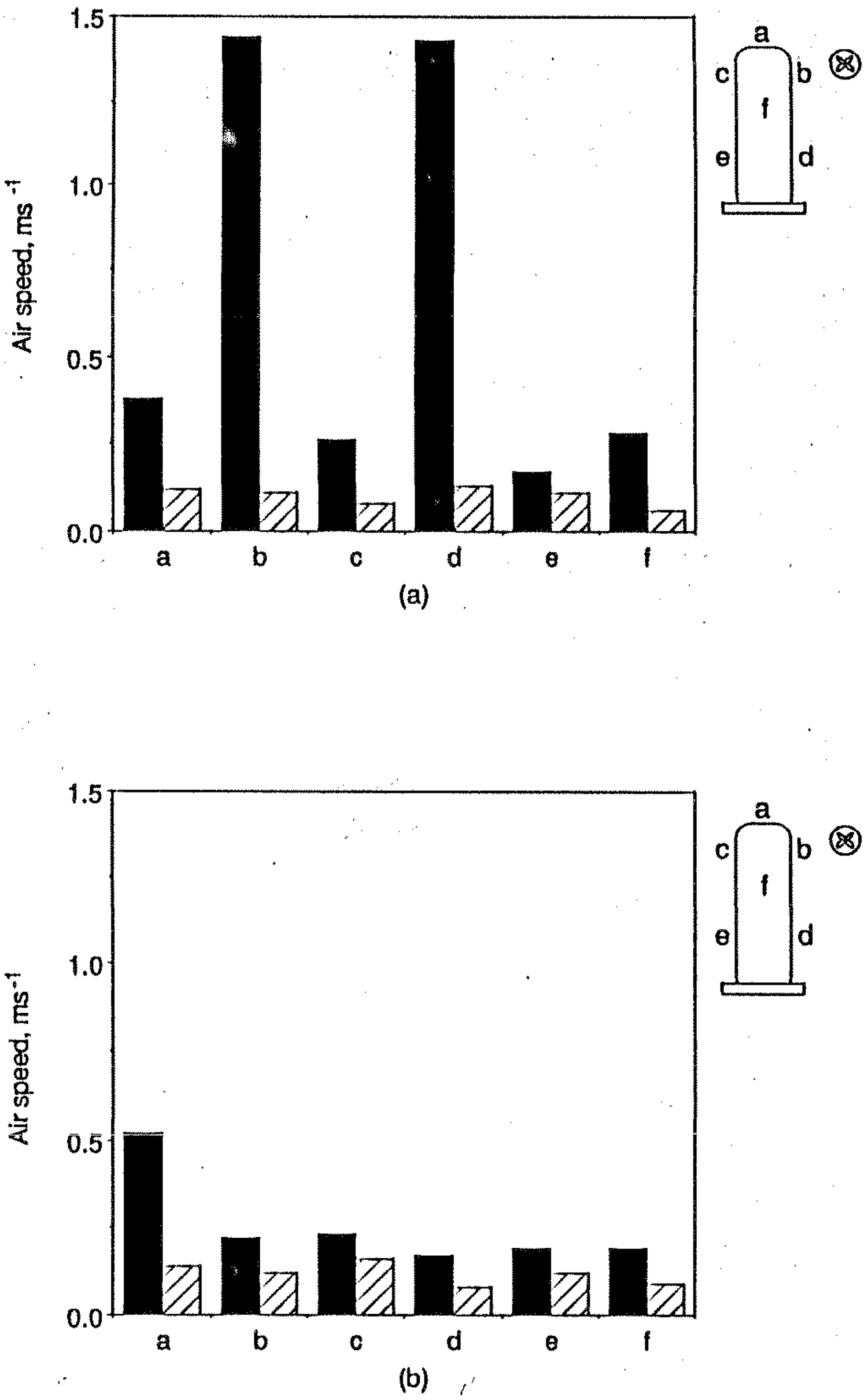


Fig. 3 Vertical distribution of air speed;
(a) 6m, and (b) 15m, from fan number 5.
■ *fans on* ▨ *fans off*

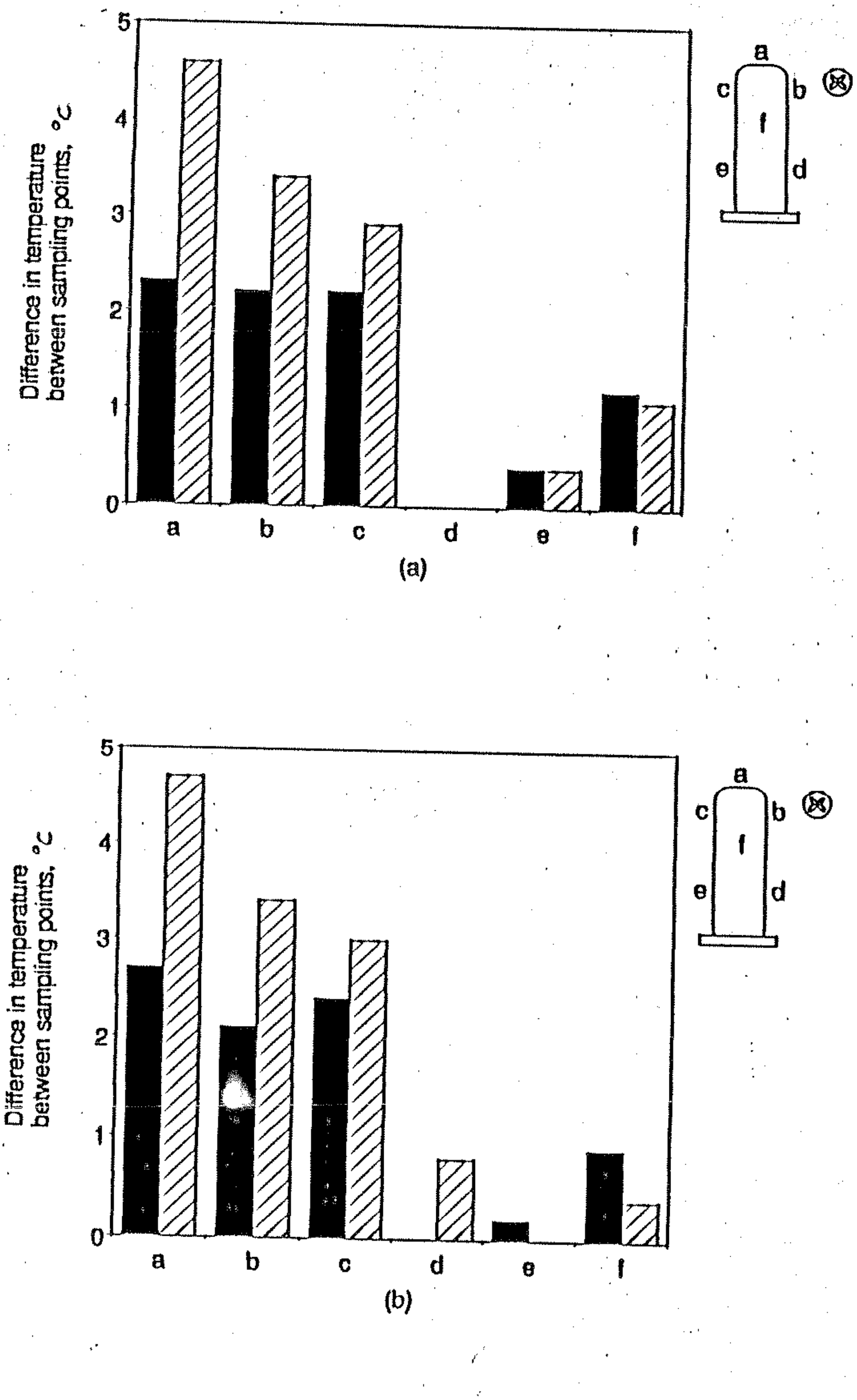


Fig. 4 Vertical distribution of air temperature (a) 6m and (b) 15m from fan number 5.
fans on *fans off*

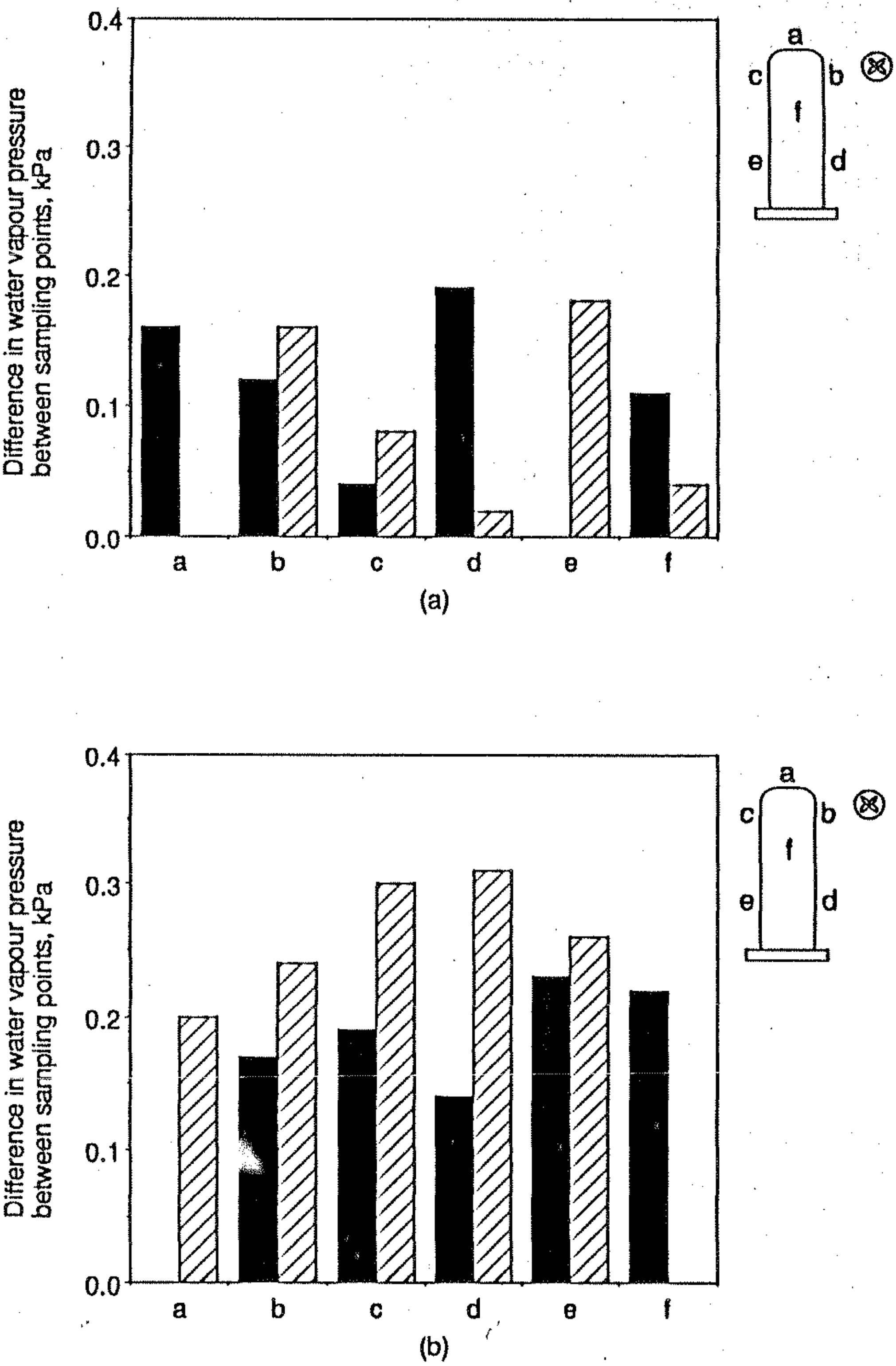


Fig. 5 Vertical distribution of water vapour pressure
(a) 6m and (b) 15m from fan number 5.
■ fans on ▨ fans off

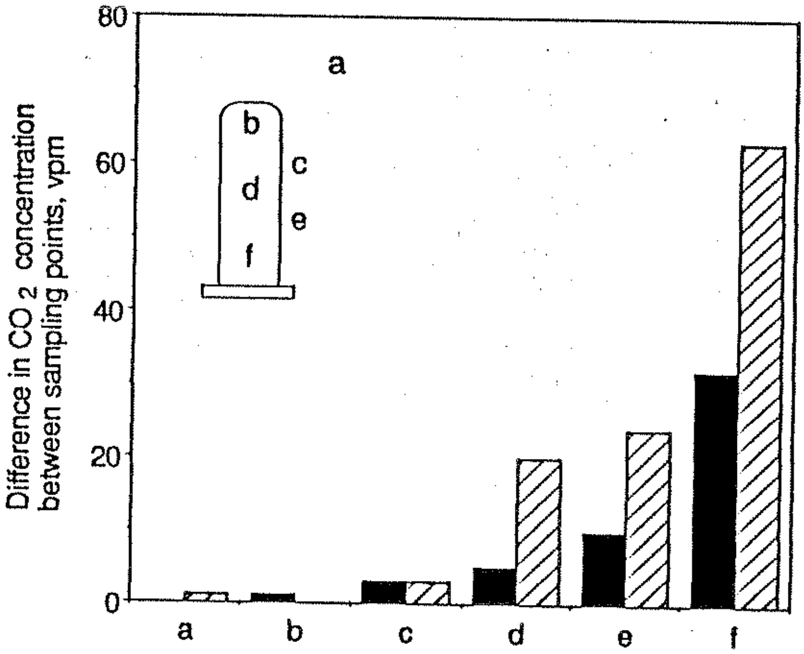


Fig. 6 Vertical distribution of CO_2 3m from fan number 4
■ fans on ▨ fans off

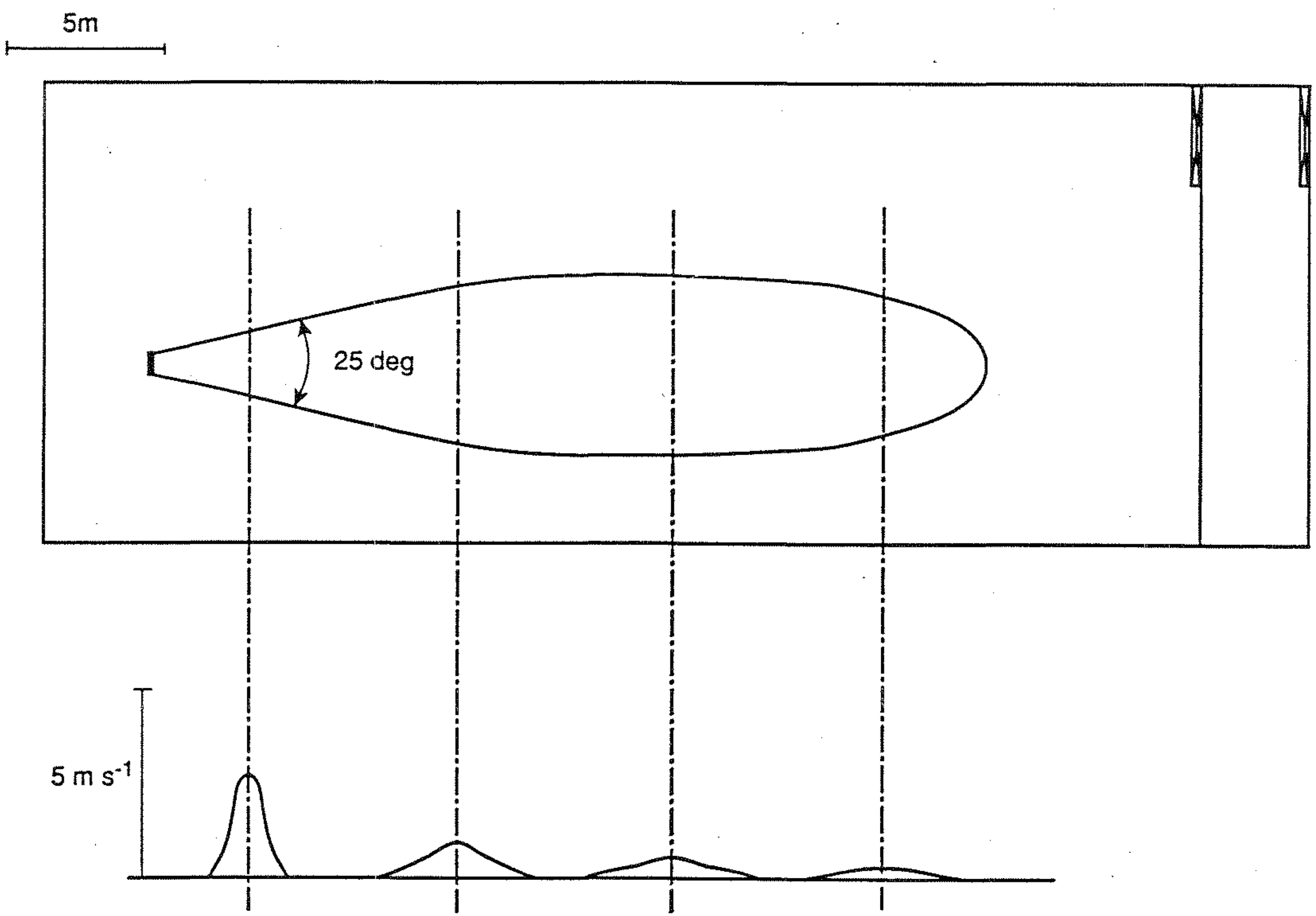


Fig. 7 Shape of air jet produced by single fan with air speed profiles for different distances from fan

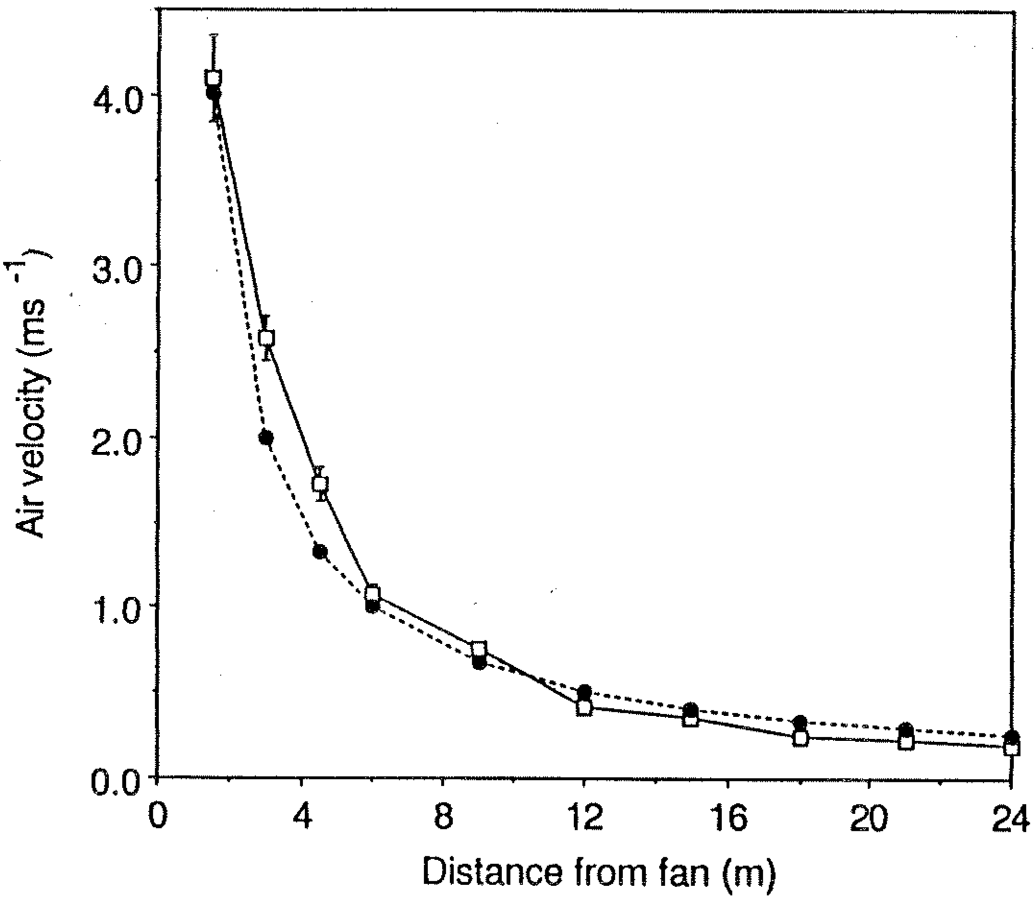


Fig. 8 Air speeds along fan axis
□ *measured*
● *predicted by equation 3.1*

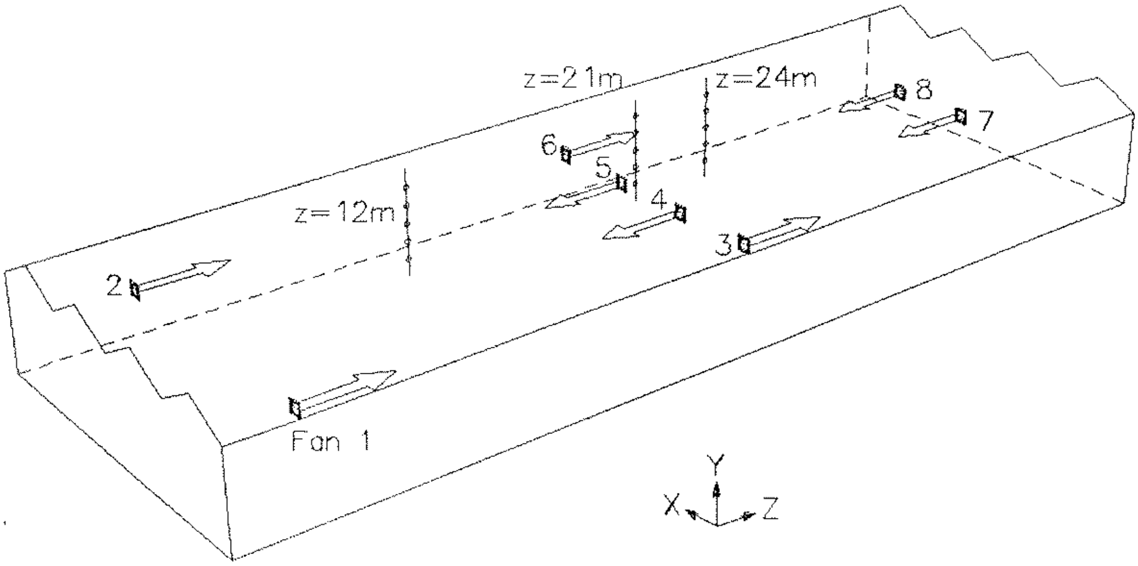


Fig. 9 Fan positions, ◘ *; air speed measurement positions,* •

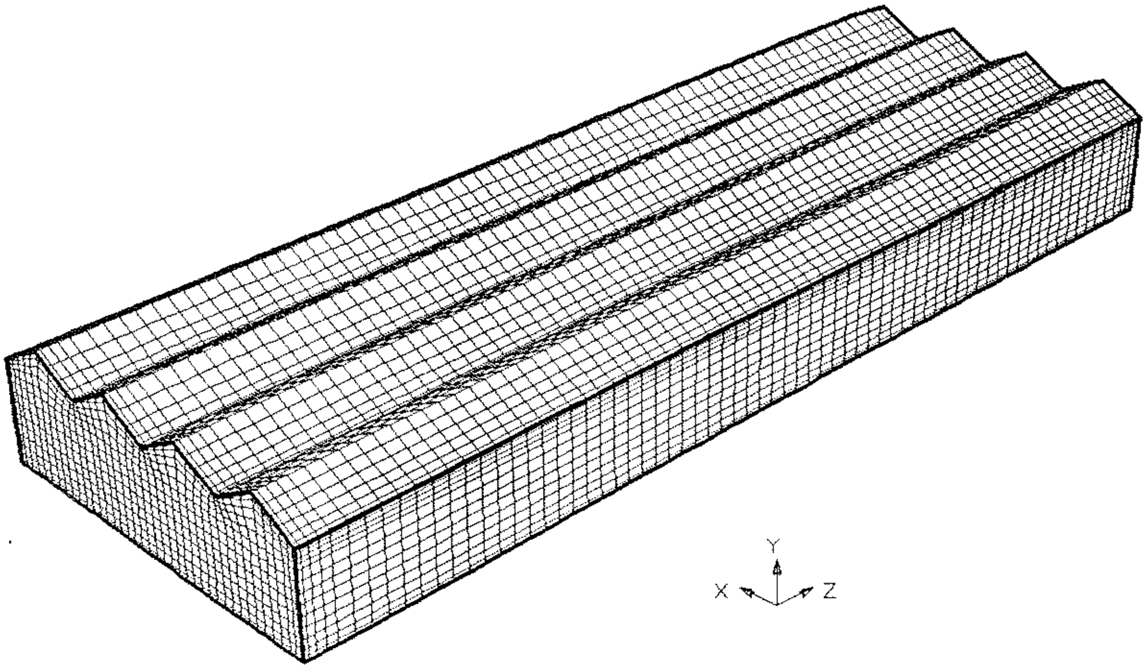


Fig. 10 Venlo glasshouse with CFD grid superimposed

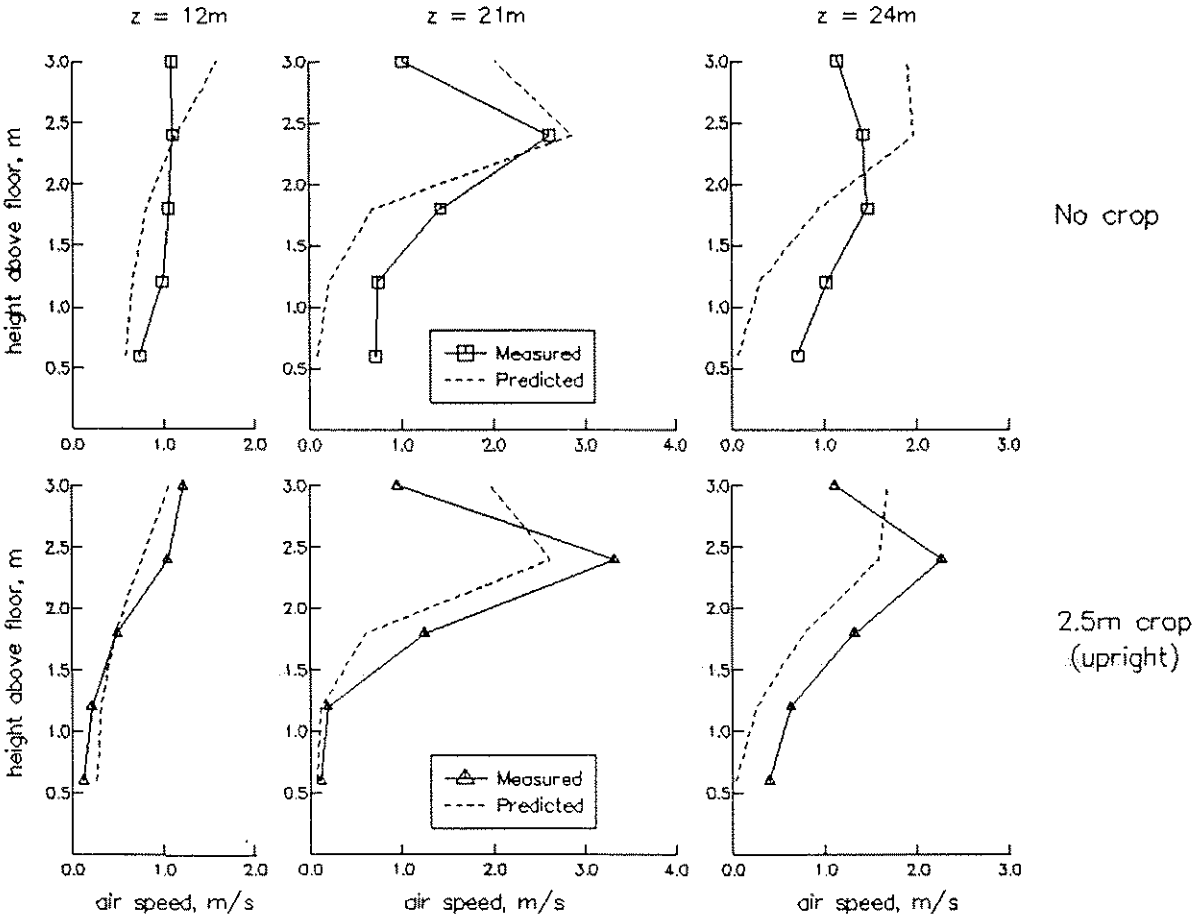


Fig. 11 Measured and predicted air speeds at three stations, 8 fans operating

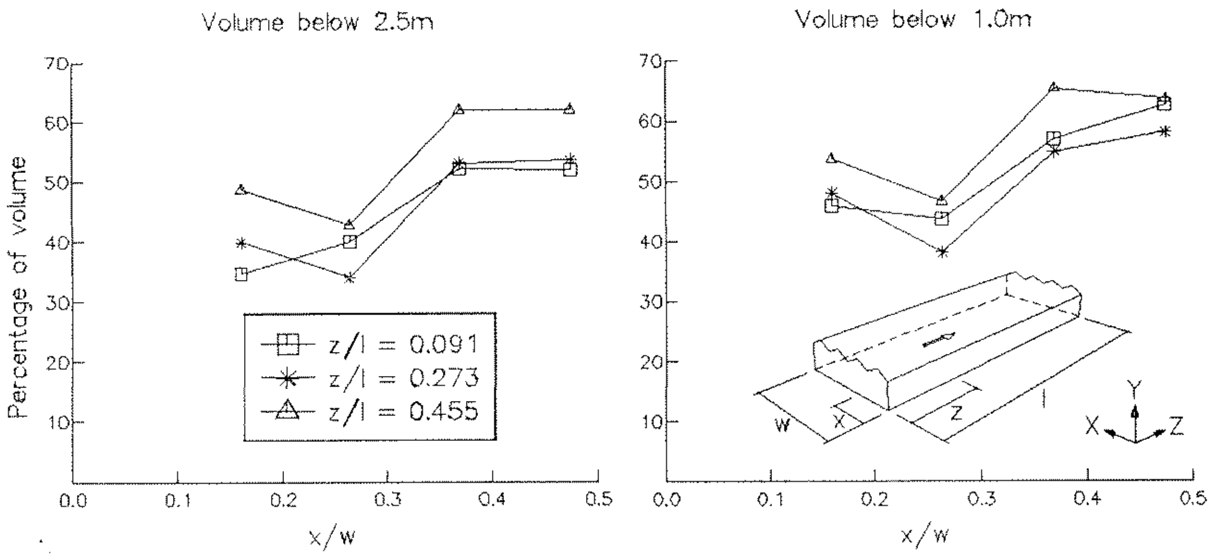


Fig. 12 Effect of the position of a single fan on the volume with air speed below 0.2 m s in a Venlo glasshouse

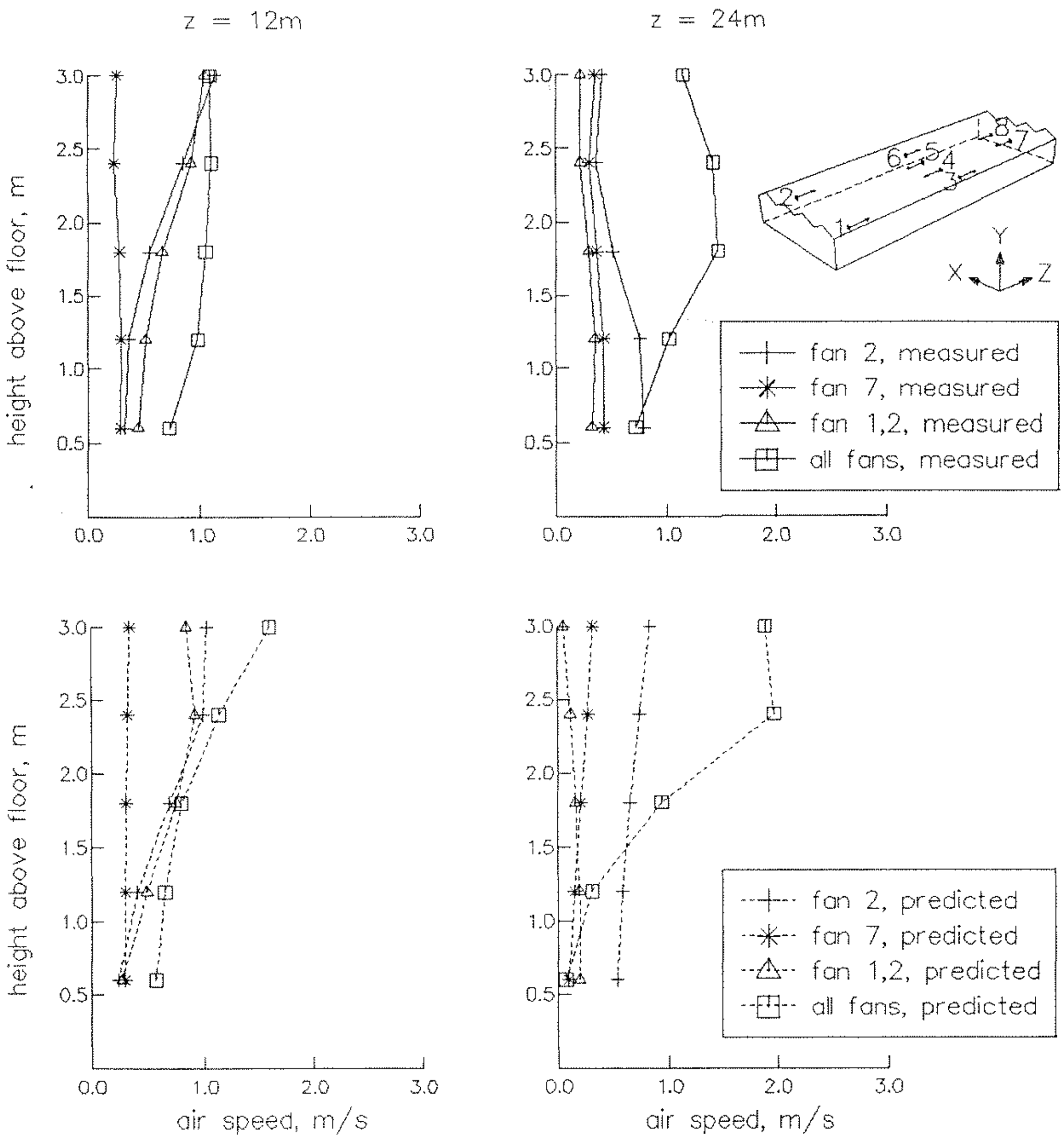


Fig. 13 Measured and predicted air speeds in Venlo glasshouse with various fan combinations and no crop

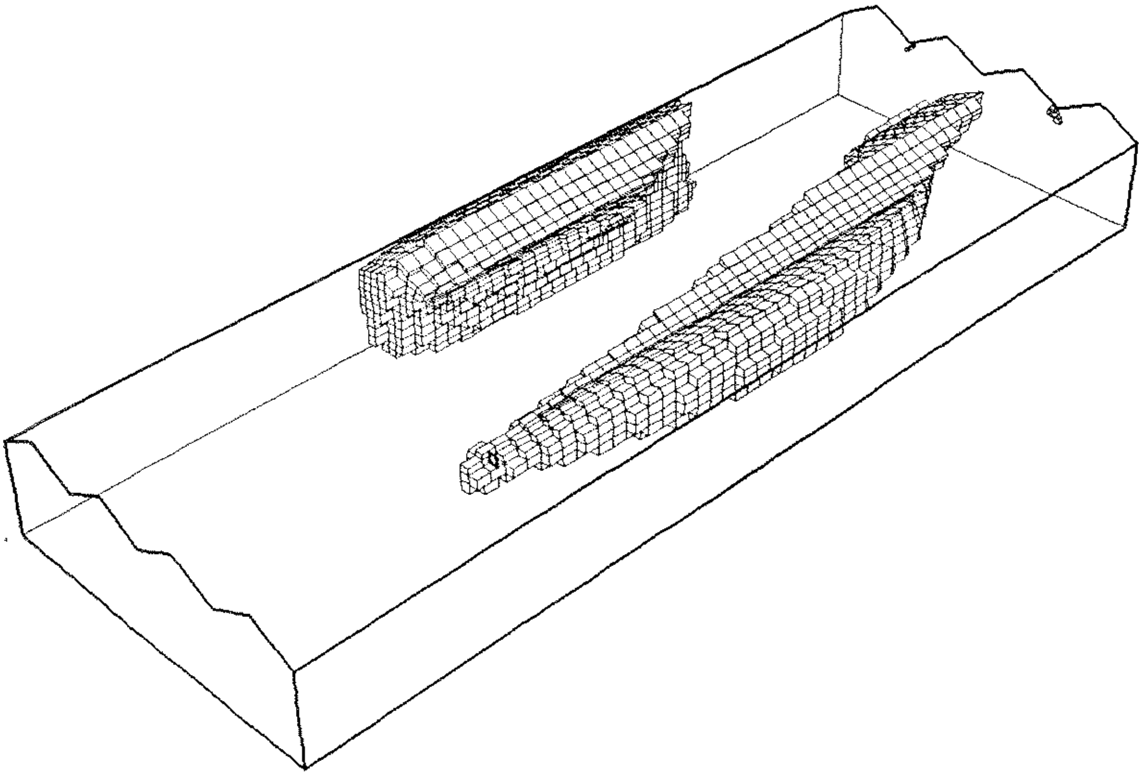


Fig. 14 Zones in Venlo where predicted air speeds are above 0.5 m/s; fan ■ in optimum position

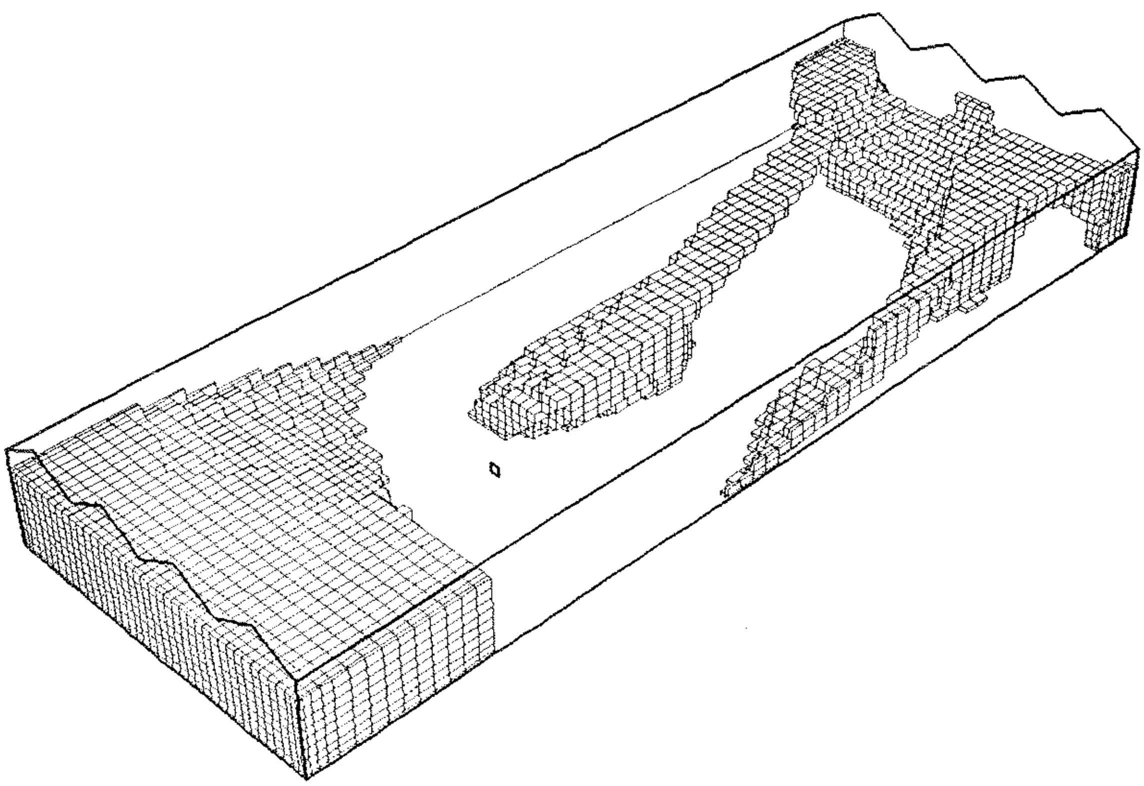


Fig. 15 Zones in Venlo where predicted air speeds are below 0.2 m/s; fan ■ in optimum position

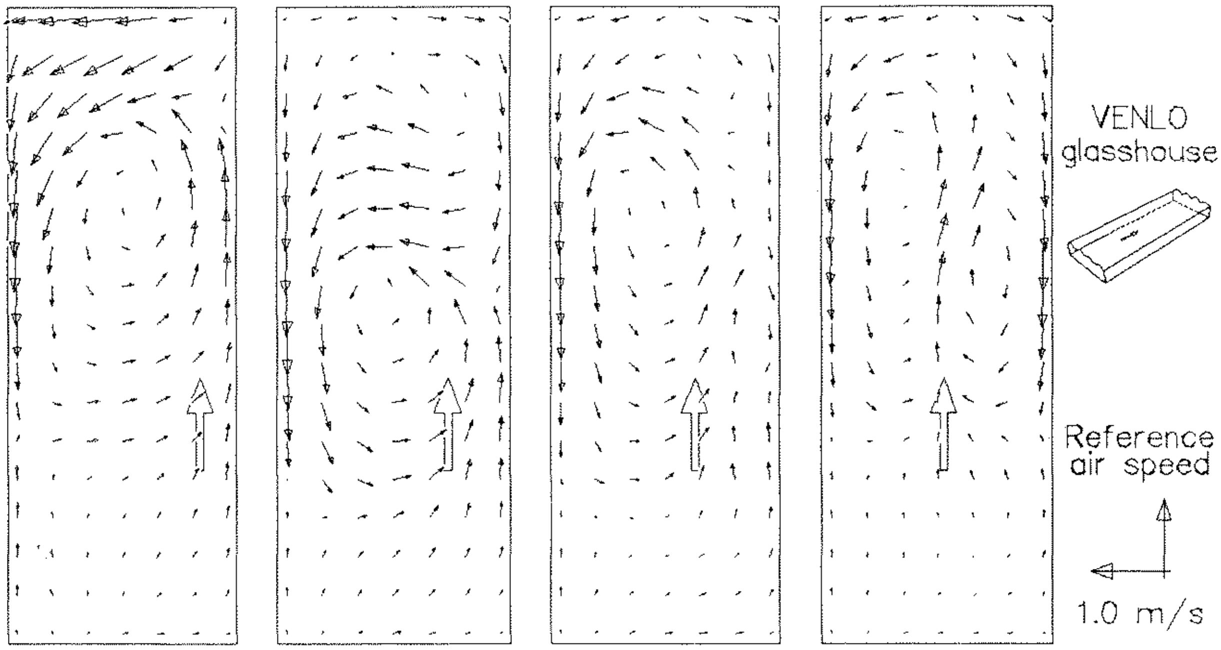


Fig.16 Predicted air circulation patterns 0.5 m above the floor produced by four fan (symbol) positions in a Venlo glasshouse (12.8 m x 33.3 m)

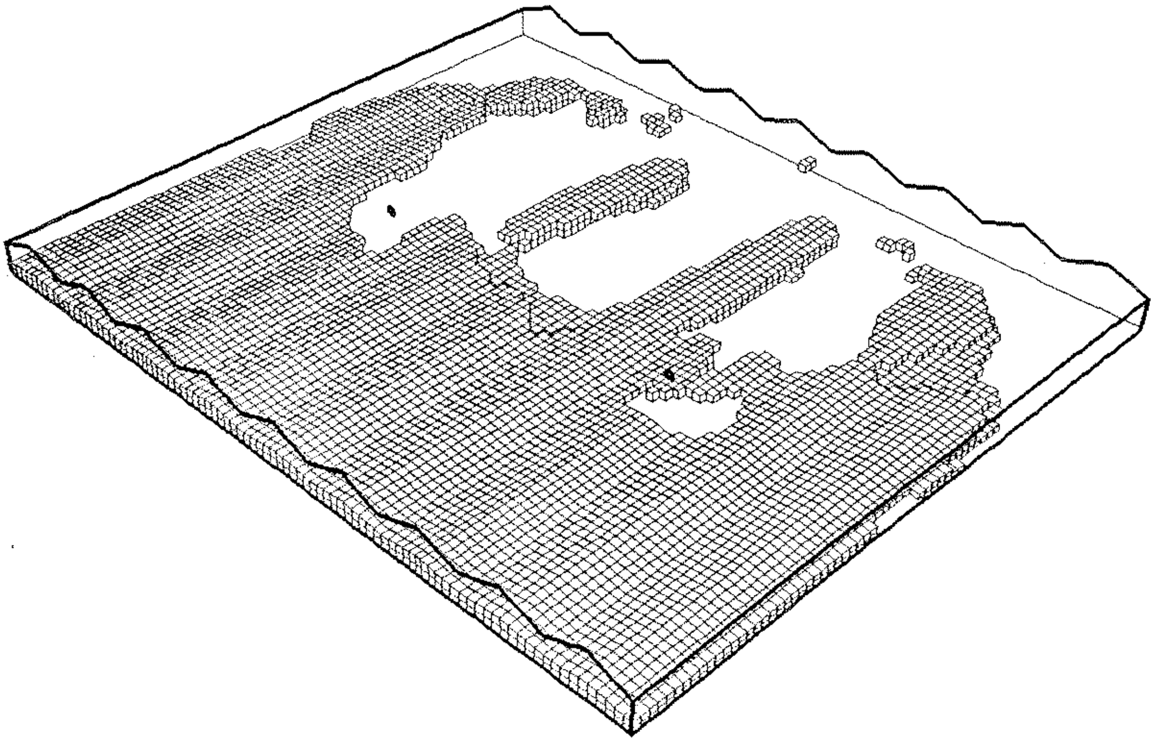


***Fig.18** Zones within 1.0 m of the floor in a commercial glasshouse (56.7 m x 47.5 m) where predicted air speeds are below 0.2 m/s; 2 x 0.55 m dia. fans ◘ 20 m from upstream wall*

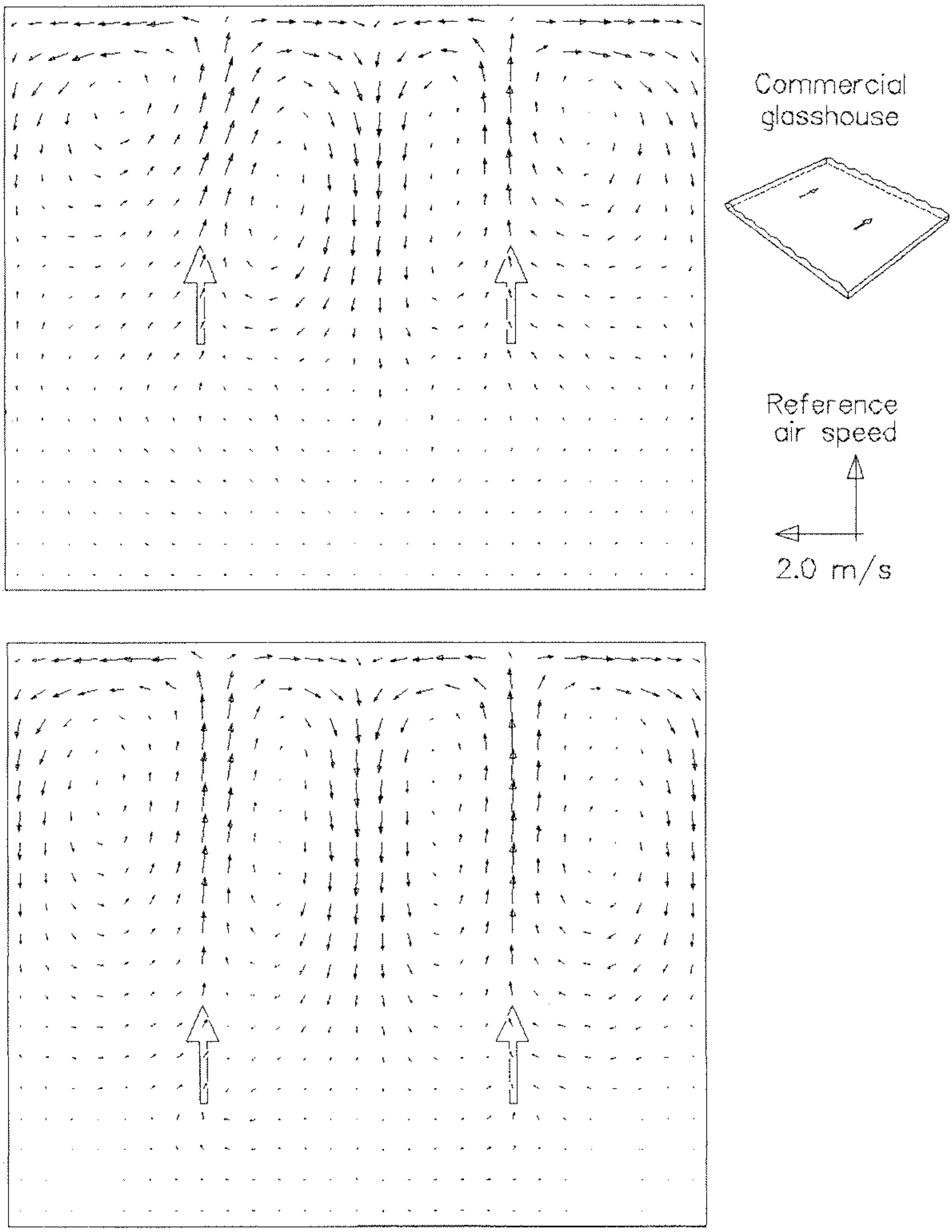


Fig.17 Predicted air circulation patterns 1.0 m above the floor produced by two fans in a commercial glasshouse (56.7 m x 47.5 m); Top, fans 20 m from upstream wall; Bottom, 10 m from upstream wall

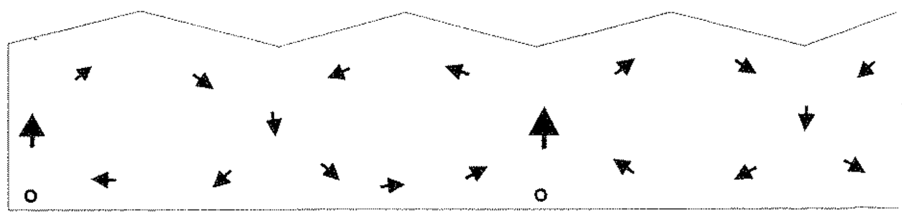


Fig. 19 *Vertical air circulation using perforated air ducts with air discharged upwards, simulated using a water table.*

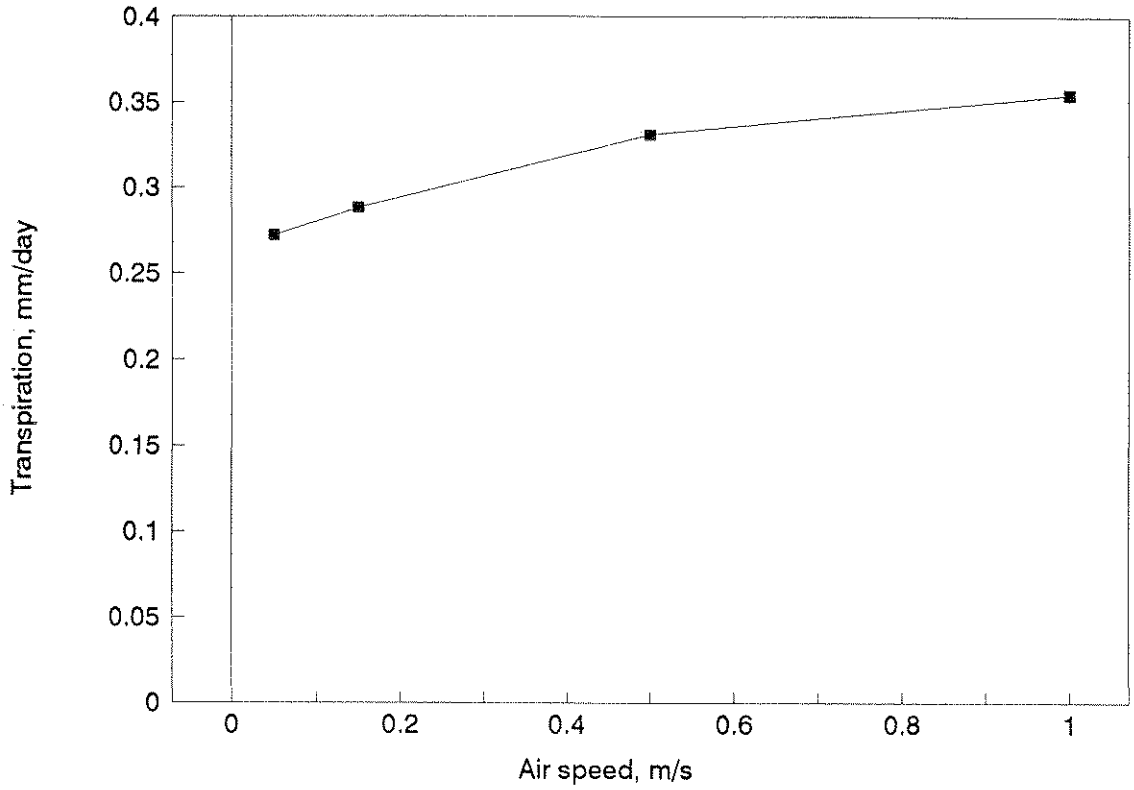


Fig. 22 *Transpiration calculated by Stanghellini model as a function of air speed. Average values between 21 January and 6 February 1991.*

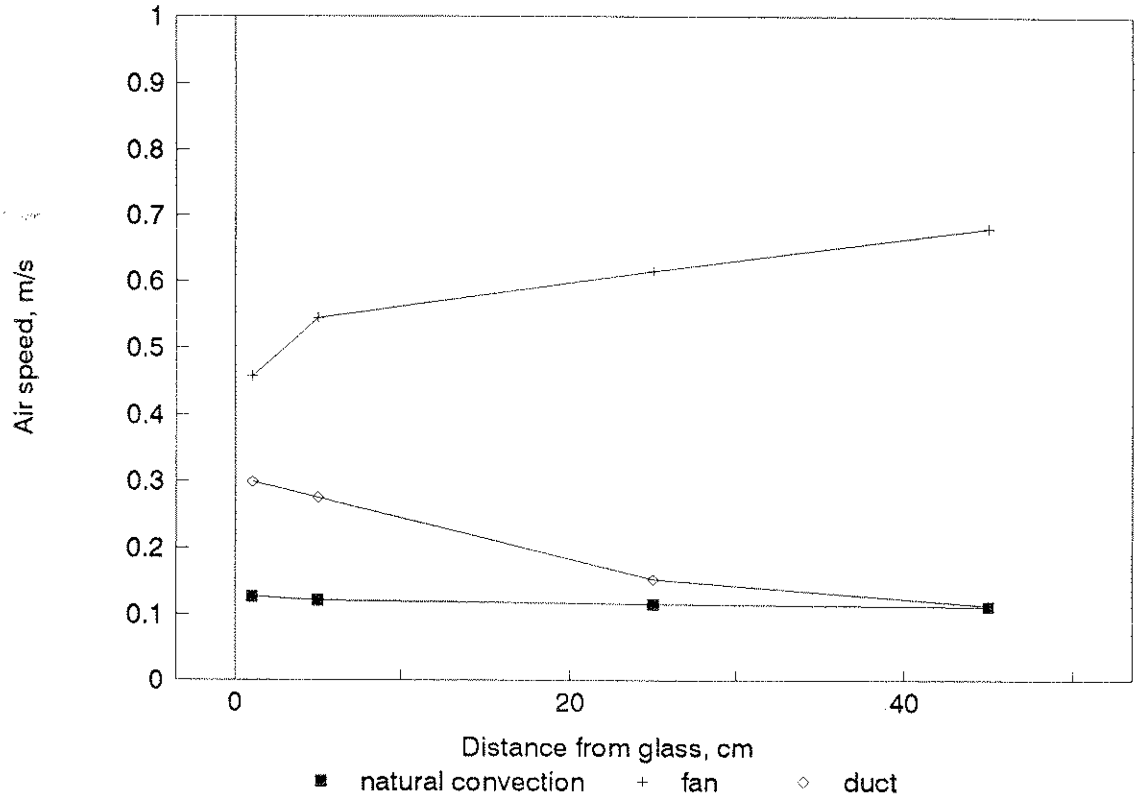


Fig. 20 Air speed measured near glasshouse roof

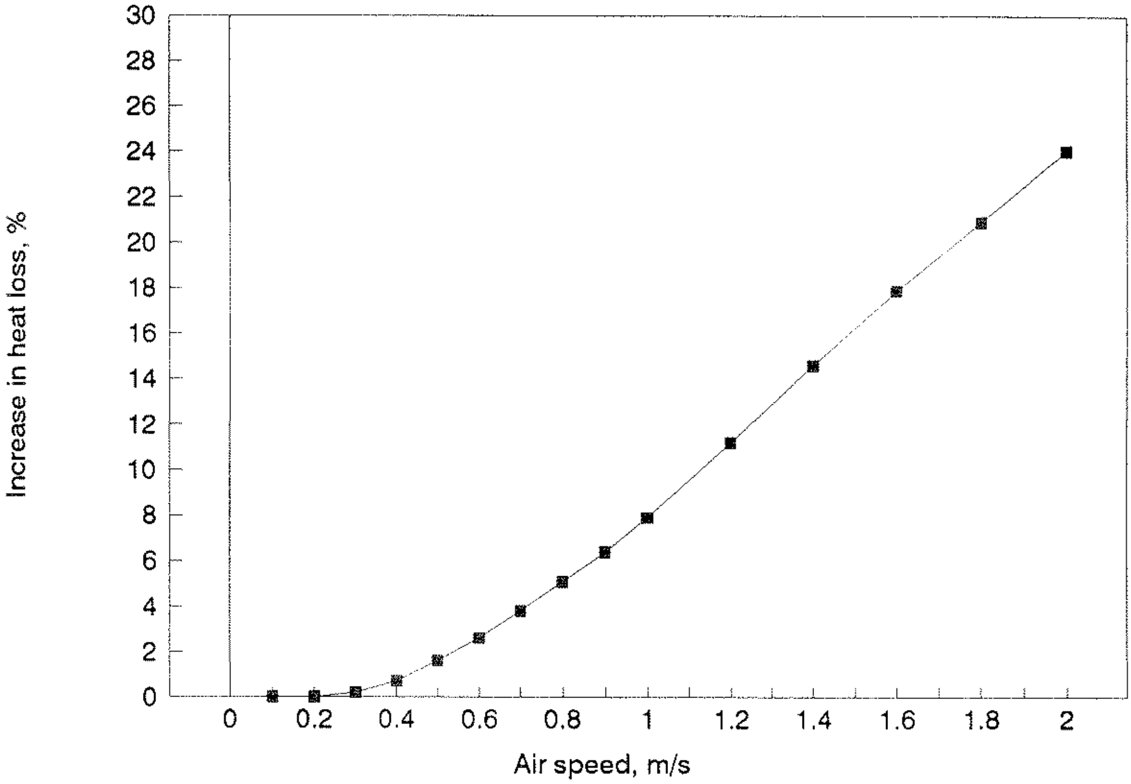
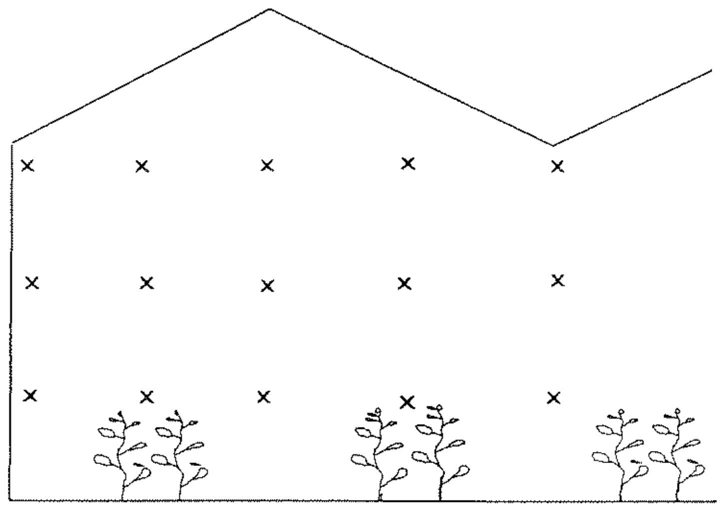
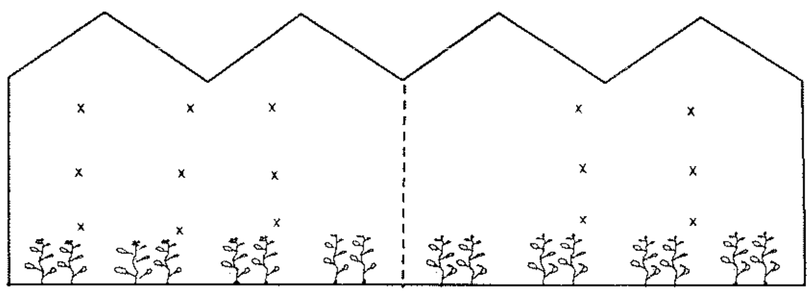


Fig. 21 Influence of air speed near glass on predicted heat loss



(a) In southern span



(b) Across whole house

Fig. 23 Sites of air speed movement

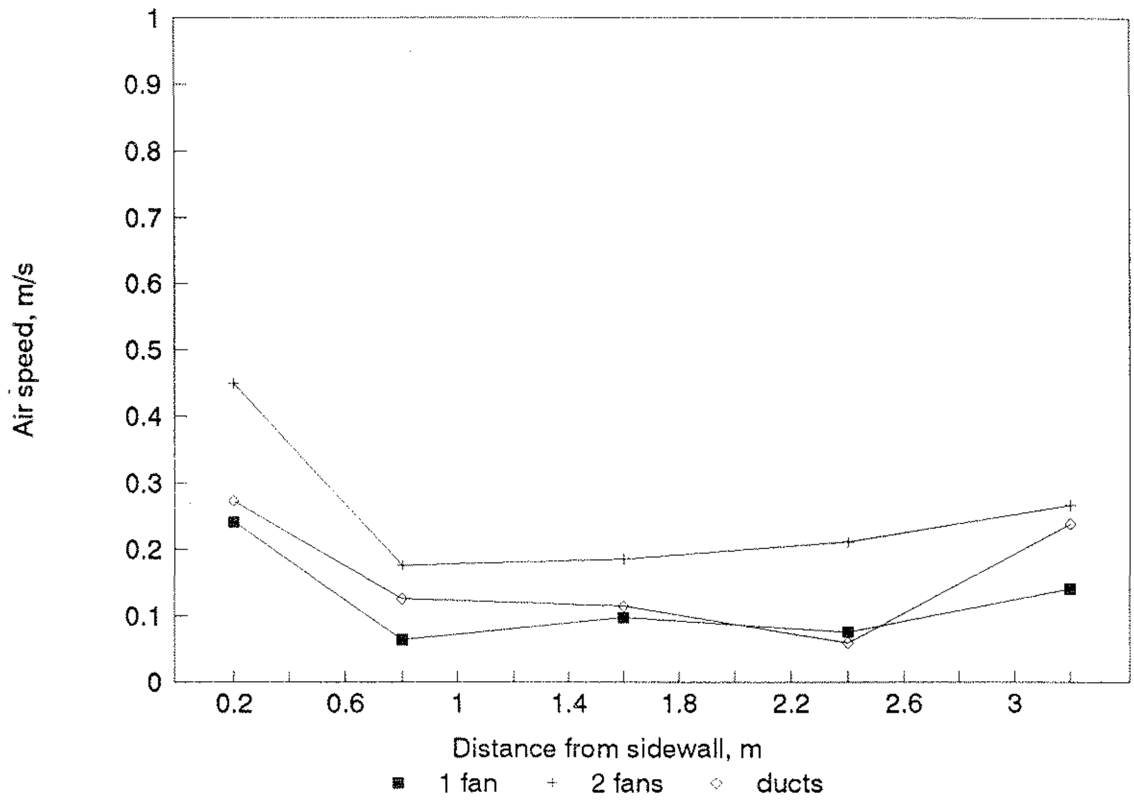


Fig. 24 Air speeds measured at 1m, crop 1.5m high

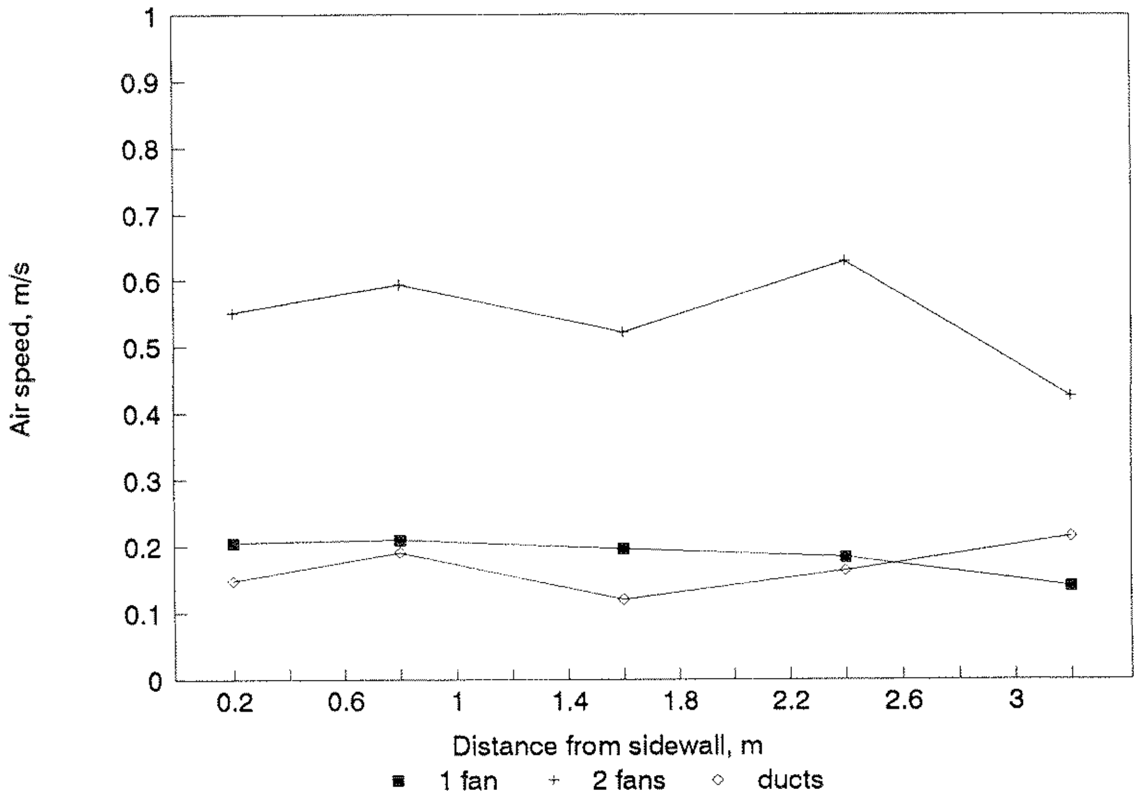


Fig. 25 Air speeds measured at 3m, crop 1.5m high