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This leaflet provides ventilation information applicable to commercial greenhouses in Canada. Much of the information is extracted from the Agriculture Canada contract report Energy Efficient Greenhouse Design and Operation (Towning and Turkewitsch, 1980).

Ventilation of a greenhouse has several functions such as:

1. temperature control (cooling)
2. humidity control
3. CO₂ control

The ventilation system exchanges, circulates and mixes the greenhouse air for more uniformity of the greenhouse climate and also helps the heating system distribute heat. It is important the greenhouse be as airtight as possible so that air circulation and exchange is controlled by the ventilation system, not by uncontrolled air infiltration.

1. TEMPERATURE CONTROL (COOLING)

Greenhouse cooling reduces plant stress caused by high leaf and air temperatures. The root and stem system may not be able to supply adequate water to the leaves, thereby limiting transpiration, the plant cooling mechanism. Also, hot and humid air around the leaves will reduce the effectiveness of transpiration at the leaf surface.

Transpiration makes it possible for photosynthesis to take place on bright days without the plant overheating. Light the leaf absorbs increases its temperature and without transpiration, this temperature could become much higher than the surrounding air. However, by vaporizing water within the leaf and diffusing this vapor through the stomata, about 70% of the energy absorbed by the leaf is released. The amount of water transpired is directly proportional to the temperature difference between the surface of the leaf and the air.

If the plant can supply the necessary water, the leaf surface temperature ranges from 1°C above air temperature on low-light days to almost 10°C on bright days.

As the air temperature rises on a sunny day, more and more demand is placed on the root system to supply water for transpiration. If the demand becomes too high, the plant becomes overheated and the stomata close to prevent further and damaging water loss. This is undesirable because stomatal closure prevents assimilation of CO₂ and consequently, photosynthesis. The efficient operation of a greenhouse requires a controlled environment to induce maximum growth. Optimal conditions for an actively growing plant are an air temperature of 20-25°C, 60-80% relative humidity, 800-1500 ppm CO₂ level, 20-100 W/m² photosynthetically active radiation (PAR), and an adequate supply of water and nutrients for the plant.

Greenhouse temperature control can be accomplished a number of ways:

- 1.1 fan ventilation
- 1.2 natural ventilation
- 1.3 evaporative cooling
- 1.4 shading

1.1. Fan Ventilation

Fan ventilation can provide high rates of air movement in a large greenhouse or one that has inadequate natural ventilation. The advantages include accurate control of airspeed and direction, increased CO₂ uptake and leaf surface humidity control due to the forced air circulation through the leaves. It allows for less complex and more airtight greenhouse construction than ridge vents. The exhaust fans and inlets must be designed to give good uniform airflow through the plants.

Typical ventilation rates for commercial greenhouses are given in the following table:

COMPLETE INSTRUCTIONS

The Canada Plan Service, a Canadian federal/provincial organization, promotes the transfer of technology through factsheets, design aids and construction drawings that show how to plan and build modern farm structures and equipment for Canadian agriculture.

For more information, contact your local provincial agricultural engineer or extension advisor.

RATES

	Ventilation rate* (L/s)/m ²	(m ³ /s•m ²)	(cfm/ft ²)
Winter			
Minimum	2.5	0.0025	0.5
Maximum	10	0.01	2
Summer	40	0.04	8

* Fan selection should be based on a static pressure of 2.5 mm (0.1 in.) of water. With evaporative cooling pads, use a static pressure of 4 mm (0.16 in.) of water.

WINTER MINIMUM VENTILATION when either no ventilation or minimum ventilation is required for humidity control, CO₂ control and heat distribution. During this period, cold ventilation air must be thoroughly mixed with warm inside air to prevent cold drafts on the plants. Maintaining the desired temperature usually requires heating. The ventilation rate should be 2.5 (L/s)/m² (0.5 cfm/ft²), or about four air changes per hour.

WINTER MAXIMUM VENTILATION when cooling is required but outdoor air is too cool to directly contact the crop. This typically applies during daylight with temperatures from -15 to +15°C (+5 to +60°F). Supplemental heating usually will not operate during this period but cold ventilation air must still be mixed with the warm inside air to prevent cold drafts on the plants. The ventilation rate should be 10 (L/s)/m² (2 cfm/ft²), or about 15 air changes per hour.

SUMMER VENTILATION for temperature control when outside air is warm enough (usually 15°C (60°F) or higher) to permit ventilation air to be drawn directly into one side or end of the greenhouse and exhausted out the other. The ventilation rate should be 40 (L/s)/m² (8 cfm/ft²), or about 60 air changes per hour.

1.1.1. Winter Ventilation

During winter, ventilation is required for reasons other than cooling. With the trend to tighter greenhouses, natural infiltration may no longer be adequate to control humidity and CO₂ levels. This is particularly true for polyethylene greenhouses. Although it is possible to simply open the roof vents slightly in glass greenhouses, it is desirable to have controlled air movement through the crop. Usually, a ventilation system that provides positive air movement through the crop is installed.

Figure 1 shows a ventilation system consisting of a recirculating fan with an attached perforated polyethylene tube, a motorized air inlet louvre and, for fan ventilation only (not for natural ventilation), an exhaust fan. The capacity of the recirculating fan should be at least 10% greater than the

winter maximum rate of 10 (L/s)/m² (2 cfm/ft²) of greenhouse floor area. This will ensure that the cool air brought in by the exhaust fan adequately mixes with the warm inside air.

The exhaust fan should be 2-speed with capacities of 2.5 and 10 (L/s)/m² (0.5 and 2 cfm/ft²) of greenhouse floor area, permitting about 15 air changes per hour at the higher speed. If shade and/or thermal curtains are installed, the polyethylene-tube ventilation system should be located under the curtains.

If CO₂ addition is not used, ventilation is important to maintain near-ambient levels of CO₂ in the greenhouse. A vigorously growing crop will rapidly deplete the CO₂ supply within the greenhouse, and ventilation may be necessary even before it is required to cool the greenhouse.

During the day, the CO₂ levels immediately surrounding the leaves can become depleted. Positive air movement minimizes this condition.

On clear nights, the leaf surface is cooler than the surrounding air because of radiant-heat loss to the cold sky, especially in polyethylene greenhouses without a curtain. Only by positive air movement through the plants can condensation on the plants be minimized.

1.1.2. Summer Ventilation

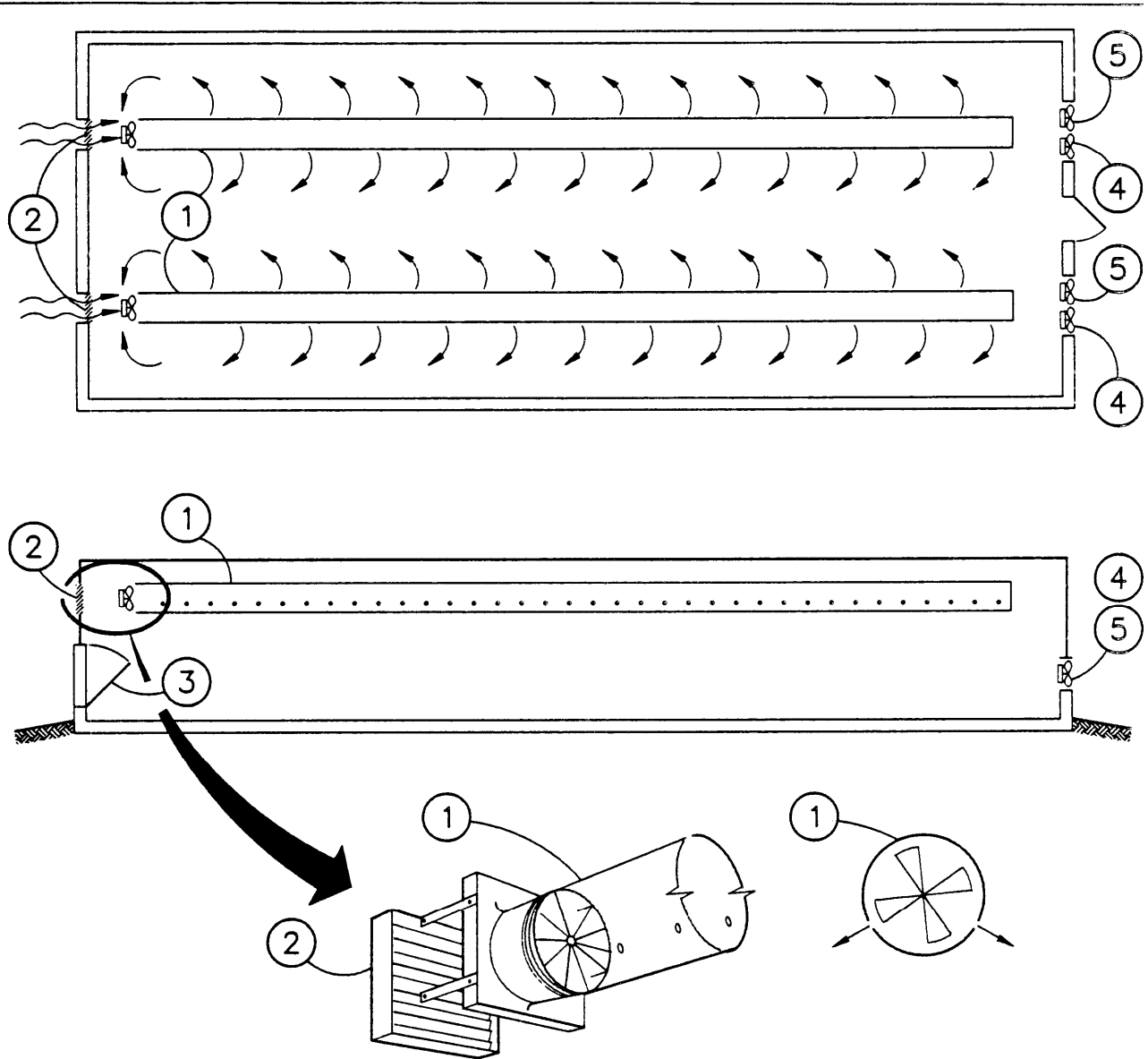
Forced ventilation can be costly, both initially and in operation. The electrical consumption can reach 30 000 kWh per season for a 4100 m² (1 ac) range. Design of fan spacing and inlet location depends on the type of greenhouse and crop, and the direction of airflow in relation to the greenhouse ridge and the growing beds.

The Glasshouse Department of the National Institute of Agricultural Engineering at Silsoe, England has done considerable research in fan ventilation and much of the following information is extracted from their work.

Large inlets like those used with evaporative cooler pads give uniform distribution of airflow through the crop, and a uniform temperature gradient along the airflow path. The maximum recommended temperature rise along the airflow path is 4°C (7.2°F).

Fans should be spaced at a maximum distance of 7.6-9.0 m (25-30 ft). If the fans are operated in banks, such as alternate fans or one in every group of three or four, these spacings would be too large. For summer ventilation, for example, fans should be spaced at 3 m (10 ft) for uniform airflow through the crop. The fan capacity can then be calculated as:

FIGURE 1 TYPICAL GREENHOUSE FAN VENTILATION SYSTEM



1. Fan with attached perforated polyethylene tube recirculation and distribution duct
2. Winter air inlet with motorized louvre
3. Summer air inlet, full width with insect screen and optional evaporation pad for cooling
4. Large summer exhaust fans)
5. Winter exhaust fans)

Fan capacity in m³/s (cfm) = $V_s \times L \times S$

where

- V_s = summer ventilation rate in (m³/s)/m² (cfm/ft²) of greenhouse floor area
- L = distance between fan and inlet in m (ft)
- S = fan spacing in m (ft)

For example, if the summer ventilation rate V_s (Table 1) is 0.04 (m³/s)/m² (8 cfm/ft²) of floor area, the distance L between the fan and inlet is 60 m (200 ft), and the fan

spacing S is 3 m (10 ft), then the fan capacity for each fan would be:

$$0.04 \text{ ac } 60 \times 3 = 7.2 \text{ m}^3/\text{s}$$

$$(8 \times 200 \times 10 = 16\,000 \text{ cfm})$$

The air inlet for summer ventilation should be continuous along a side or end wall of the greenhouse and located on the prevailing-wind side, if possible. It should be sized and automatically adjusted to provide a low air velocity of 0.75-2.5 m/s (150-500 ft/min) at the inlet. This will minimize turbulence and mixing of the incoming air with the hot air in the upper

1.3. Evaporative Cooling

Evaporative cooling is most effective in climates where outdoor relative humidity (RH) is less than 60%. The amount of cooling that can be achieved by evaporative cooling depends on the dryness of the air and the effectiveness of the water evaporation system. The most effective systems reduce air temperature by 80% of the difference between the air temperature and the wet-bulb temperature.

The wet-bulb temperature is the temperature at which air is fully saturated (100% RH). Table 2 shows the potential reduction in air temperature with evaporative cooling.

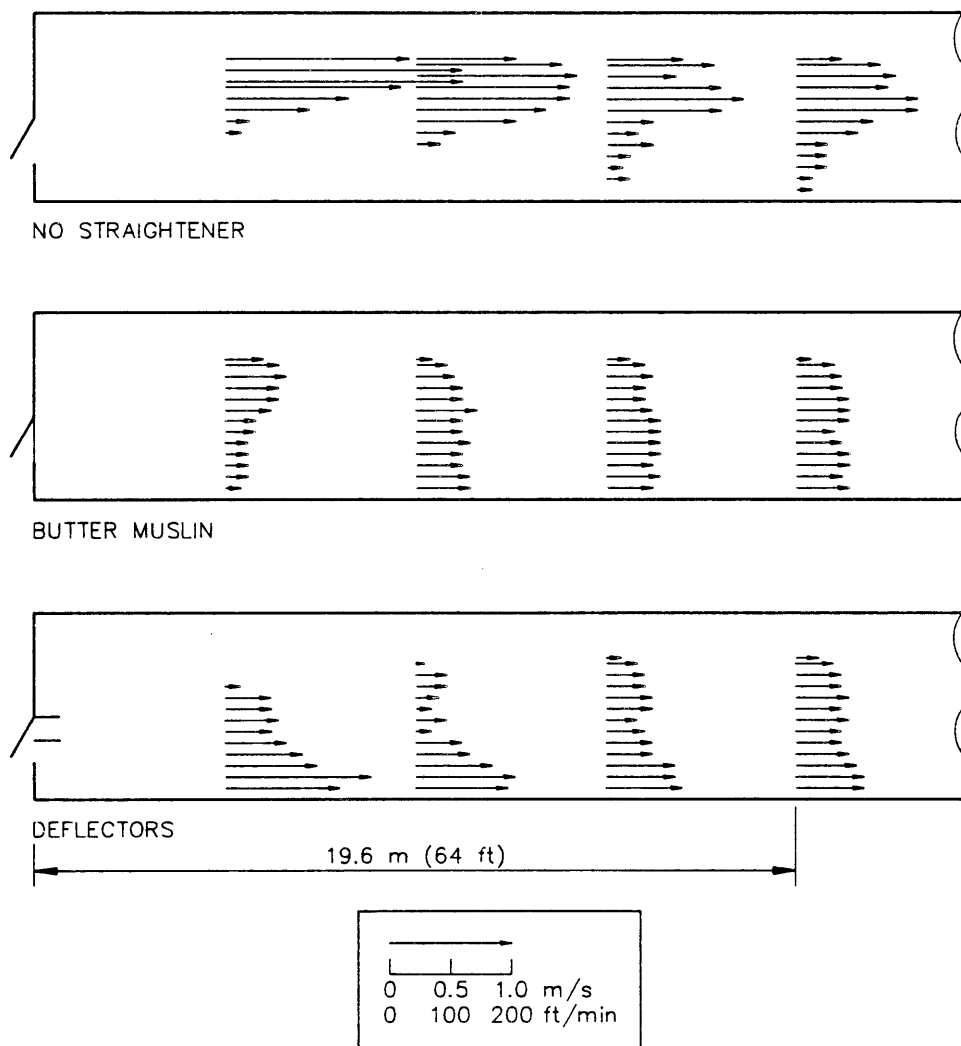
Evaporative cooling pads and misting systems are two evaporative cooling techniques used in greenhouses.

1.3.1. Evaporative cooling pads

Evaporative cooling pads are used in conjunction with fan ventilation to reduce the temperature of the outside air brought into the greenhouse. The air is drawn through pads that are continually wetted. Pad systems perform best in tightly-built greenhouses because they rely on the ventilation fans to pull outdoor air through the wetted pads.

By installing wetted pads of cedar shavings or synthetic matting in the wall inlets, the incoming air stream can be cooled. Thicker pads and finer matting increases the effectiveness of the system, but also increase the resistance

FIGURE 2 DISTRIBUTION OF THE HORIZONTAL COMPONENT OF AIR VELOCITY ALONG THE AIR PATH IN A GREENHOUSE WITH AND WITHOUT AIR STRAIGHTENERS AT THE INLET



to airflow. With cooling pads, fan selection should be based on a static pressure of 4 mm (0.16 in.) of water because of the increased resistance to airflow through the pads. The inlet area for fan and pad cooling is therefore usually much larger than that of regular vents. Evaporative pads often cover entire walls. Follow manufacturers' recommendations when installing evaporative pad systems.

In most Canadian locations, fan and pad cooling is not likely to be necessary if alternate methods of cooling such as misting and shade cloth are used in conjunction with natural or fan ventilation.

1.3.2 Misting

Both high and low-pressure misting are used in greenhouses to maintain high humidities, prevent excessive water loss from leaf surfaces and cool the greenhouse air by evaporation.

Applying a fine spray or mist to the plant canopy on a bright day reduces the leaf surface temperature which in turn reduces the rate of transpiration from the leaves. Since the transpiration rate from the leaf surface is not as great, water stress on the plant is reduced and the root system is more likely to be able to cope with sudden water demands brought on by sudden bursts of sunlight. The stomata remain open and CO₂ assimilation can continue under brighter conditions than when ventilation without misting is used. In fact, it is preferable to reduce the incident radiation using shade cloth if it will prevent stomatal closure.

Although mist cooling increases the humidity, it is used only on bright, sunny days when drying conditions are good and the warm air can hold considerably more moisture.

Since the leaves are warmer than the surrounding air, they will dry well if the spray is fine and of short duration so that droplets do not form.

It is important to properly control misting. Too much water increases the humidity unduly, may cause spotting and leeching of nutrients from the leaves and exposes the lower shaded leaves to disease problems. Also, misting should be stopped if the greenhouse temperature is less than optimal for the current light level. That is, before mist is applied, the leaf surface temperature should be allowed to rise until maximum photosynthesis takes place.

By using mist cooling, ventilation can be delayed for temperatures up to 30 °C (86 °F) because the leaf surface is cooled directly. This delay prolongs CO₂ enrichment and results in better growth rates.

1.3.2.1. High-pressure misting

High-pressure misting systems force water through very small nozzles at very high pressure, dispersing microscopic-sized water droplets (fog) into the greenhouse air or the ventilation air stream. These very fine droplets evaporate quickly, resulting in effective evaporative cooling.

High-pressure mist systems have very fine nozzles rated at 7-10 L/h (2.0-2.7 US gal/h) and a high pressure pump rated at 3500-7000 kPa (500-5 000 psi). High-pressure mist systems require a good quality water supply and an ultra-fine filtering system to minimize nozzle plugging.

1.3.2.2. Low-pressure misting

Low-pressure misting systems force water through small nozzles at home water pressures of 170700 kPa (25 to 100 psi). The droplets dispersed into the air are larger than with high-pressure systems and do not evaporate as quickly.

TABLE 2 POTENTIAL GREENHOUSE TEMPERATURE REDUCTION* WITH EVAPORATIVE COOLING

Outdoor conditions					Greenhouse with evap. cooling		
Temperature							
RH %	Air		Wet bulb		RH %	Air Temp.	
	°C	(°F)	°C	(°F)		°C	(°F)
20	30	(86)	16	(61)	75	18	(65)
35	30	(86)	19	(66)	82	21	(70)
50	30	(86)	22	(72)	87	24	(74)
65	30	(86)	25	(77)	92	26	(78)
80	30	(86)	27	(81)	93	28	(83)
20	35	(95)	19	(66)	75	22	(72)
35	35	(95)	23	(73)	82	25	(77)
50	35	(95)	26	(78)	87	28	(82)
65	35	(95)	29	(84)	92	30	(87)
80	35	(95)	32	(90)	93	32	(90)

*Assumed evaporative efficiency 80%

The size of the larger droplets gradually reduces until it is in the fog range and droplets eventually evaporate.

1.4. Shading

Shading does not actually cool but rather reduces the amount of solar radiation reaching the plant. It reflects or absorbs incoming solar radiation before it reaches the crop. Several shading methods exist.

Many growers still shade in the summer by applying whitewash. The whitewash is quite inexpensive but some labor is required to apply it, and even more to wash it off before the low-light fall months. The disadvantages of whitewashing are that it remains in place even when not required and usually does not wear off in time and must be washed off. It is therefore considered to be the least desirable method of shading, although it is usually the least costly.

Exterior shading is sometimes used on smaller glass greenhouses. This consists of slats that are connected with links. The amount of shading can be varied by changing the length of the links during manufacturing. The exterior shading is adjustable by rolling the slats up toward the ridge of the greenhouse. Even when rolled up, they block about 5% of the light. Some advantages are that it provides light where and when required and protects the glass from storms. Exterior shading is quite costly and is usually controlled manually, and so it is not likely to be used on larger scales.

Shade cloth is being installed in more and more greenhouses because it gives the most accurate control and can be controlled automatically. The use of shade cloth at night can also significantly reduce the heat loss through the roof. A distinct disadvantage, especially for existing greenhouses, is that it requires clear spans. This means that obstructions such as posts, heating pipes, crop supports and lights make installing shade cloth difficult. Despite this, many growers have found it advantageous to move obstructions and install shade cloth. The cloth itself may consist of coarse weave cotton or non-woven synthetics. Shading values of 35-80% are readily available. A porous material is usually chosen to allow humid air to escape from the immediate vicinity of the crop. If an impermeable sheet is used for shading, controlling the humidity below and above the sheet becomes very important.

Deployment mechanisms for shade cloth are usually more costly than the cloth itself, especially when automatic control is desired. The deployment mechanisms are similar or identical to those used for thermal and blackout curtains.

Shade cloth can be used to great advantage with a cooling strategy involving misting, shading and ventilation. The gains

in productivity usually more than cover the expenses involved.

Shade cloth deployment is typically controlled by light or temperature sensors, or a combination of both. Shade cloth would be closed under high light intensity in conjunction with high greenhouse temperature for light-loving crops or under high light intensity alone for shade-loving crops. It should also be deployed automatically on cold nights and retracted at dawn. If photoperiod or supplemental lighting is being used, the shade cloth should be deployed after sunset so that it will reflect back light that would normally be lost through the roof. Shade cloth does not provide photoperiod control; only blackout cloth (100 shading) can do this. Sometimes both shade and blackout cloth systems are installed.

2. HUMIDITY CONTROL

Relative humidity (RH) is important to plant growth. It affects size and thickness of leaves, stems and fruits. It controls fungus growth and affects plant transpiration and cooling. Optimal values of RH are 60-80% for most plants.

Raising or lowering greenhouse air temperature without exchanging greenhouse air with outside air affects greenhouse RH. For each degree Celsius temperature change, the RH will change about 4% (about 2% RH change for each degree Fahrenheit); raising temperature reduces RH while lowering temperature increases RH. This raising and lowering of greenhouse air temperature occurs when changing from day to night temperature settings and vice versa.

2.1 High RH

High RH is a problem at the end of the day when lowering greenhouse temperature to the night setting. In cold weather, high RH caused by plant transpiration is also a problem. The amount of water vapor a full crop of cucumbers, tomatoes, chrysanthemums, and roses generates under optimal conditions is estimated to be up to 5 litres of water per square metre (0.1 gallons per square foot) of greenhouse floor area per 24 hours. Evaporation from soil and the use of burners for CO₂ addition also increase greenhouse RH.

Condensation on interior greenhouse surfaces and air leakage reduce high RH. These mechanisms are more effective in leaky single-skin greenhouses than in well-sealed double-skinned greenhouses. Ventilation may also be necessary to reduce high RH, but this can result in significant loss of heat or any CO₂ added. Ventilation and air leakage reduce high RH by replacing moist greenhouse air with dry outside air. Ventilation controlled by both temperature and humidity sensors will reduce high RH but may require heating to maintain temperature.

2.2 Low R H

Low RH can be a problem on bright sunny winter days when the ventilation system brings in large amounts of dry outside air to control temperature. Misting systems controlled by a humidity sensor prevent low RH.

3. CO₂ CONTROL

Outside air contains about 350 ppm (0.035%), by volume, of CO₂. On a bright day, ventilation required to replace CO₂ used by the plants can reach 0.01 m³ of outside air per m² (2 cfm/ft²) of floor area, per second. This means that most greenhouses require 15 air changes per hour. The crop demand for CO₂ does not necessarily coincide with ventilation requirements for cooling. In particular, airtight plastic greenhouses require some ventilation to maintain CO₂ levels even under low-light conditions. Under bright sunshine, the crop demands CO₂ almost immediately, while the greenhouse air takes some time to warm up. Ideally, light intensity on the crop should control the CO₂ enrichment in the greenhouse. Many greenhouses use a polyethylenetube overhead ventilation system for continuous low volume ventilation during the day. This system improves general air circulation, maintains CO₂ levels and controls humidity during cloudy weather.

Ventilation must be suppressed during CO₂ addition, so methods of cooling other than ventilation are required to make maximum use of CO₂ enrichment. Irrigation and nutrient requirements must also be met for effective CO₂ addition.

CO₂ levels in the greenhouse should be controlled by CO₂ sensors in combination with temperature, humidity and light sensors.

3.1. Plant CO₂ requirements

During photosynthesis, plants absorb CO₂ from the air to produce carbohydrates necessary for plant growth. This process takes place only when the plant receives sufficient visible solar radiation. As a result of the plant using CO₂, the levels in the greenhouse could drop below the outside air ambient level of 350 ppm and negatively affect plant growth.

Research shows that increasing CO₂ levels to between 800 and 1500 ppm, depending on the crop, can significantly improve growth.

3.2. CO₂ addition

When calculating injection rates of CO₂, it is necessary to consider the number of air changes per hour likely to occur within the structure. Most modern glass structures in good repair will have 0.75 to 1.5 air changes per hour. Plastic structures are generally more airtight than glass structures

and have 0.5 to 1.0 air changes per hour. For structures in locations exposed to prolonged periods of wind, the higher air-change value should be used.

Carbon dioxide injection rates are normally expressed in kg (lb) of CO₂ per hour. Due to the various anomalies between structures, locations, crops and type of injection equipment used, etc., it would be almost impossible, in practice, to calculate precise values. However, initial requirements may be calculated from the following formula and final adjustments made once the system is operable:

$$\begin{aligned} \text{kg CO}_2 \text{ required} &= V \times E \times A \times 1.89/1000000 \\ (\text{lb CO}_2 \text{ required}) &= V \times E \times A \times 0.12/100000G \end{aligned}$$

where

$$\begin{aligned} V &= \text{volume of greenhouse in m}^3 \text{ (ft}^3\text{)} \\ E &= \text{desired concentration of CO}_2 \text{ in ppm} \\ A &= \text{number of air changes per hour} \end{aligned}$$

Natural gas burners that are used for CO₂ enrichment produce about 2 kg of CO₂ per m³ of natural gas (131b of CO₂ per 100 ft³ of natural gas). Propane gas burners produce about 3 kg of CO₂ per kg of propane (3 lb of CO₂ per lb of propane). Flue gas extracted from the stack of natural gas boilers with modulating burners can also be used for CO₂ enrichment. Mixing the hot flue gas with ambient air before it is distributed in the greenhouse will cool it. Boiler experts should be consulted before using boiler flue gas for CO₂ enrichment. Also, make certain that flue gas use in the greenhouse is permitted in your area. In some locations, it may be illegal.

The CO₂ produced from burning natural gas and propane is usually adequately pure, but if combustion is faulty or sulphur is present in the gas, toxic by-products may be produced and damage plants. The maximum safe concentration is 0.05 ppm for ethylene, 0.1 to 0.4 ppm for sulphur and 50 ppm for carbon monoxide.

Liquid or pure CO₂ is without doubt the safest method of enriching greenhouse atmospheres, although the cost may be somewhat higher than natural gas. The pure CO₂ is best distributed from the storage tanks by 12 or 25 mm (1/2 or 1 in.) lay flat polyethylene tubing laid on the ground between the rows of plants. For some crops, placing the tubing within the plant canopy instead of on the ground may be a better alternative. The tubing is connected to a manifold at the ends of the greenhouse which in turn is connected through a flow meter to the storage tanks. The number of distribution tubes will vary with the type of crop, but at least one tube every 2.5-3 m (8-10 ft) should be supplied. The spacing of the perforations will depend on the level of enrichment required, the length of the beds and the diameter of the perforations.

CO₂ addition should be stopped at night. It should be initiated immediately at dawn to raise CO₂ levels to the desired values before significant consumption occurs.

An early start would also make use of the heat that propane or natural gas burners generate to raise the greenhouse temperature from the night setback setting. In cases where movable curtains are deployed during the night, CO₂ addition should take place below the curtain.

4. INTEGRATED CONTROL

The various types of ventilation and cooling discussed in this leaflet all use the same control sensors which often depend on each other as well as other systems in the greenhouse. This points to the need for integrated control of the greenhouse. Integrated computer-based control systems for greenhouses are now available and should be considered for all commercial greenhouses.

5. ALARM SYSTEMS

An alarm system should be installed in a greenhouse to monitor critical conditions such as:

- low temperature
- high temperature
- loss of power to the greenhouse

Some growers may also wish to monitor other critical conditions such as CO₂ and humidity levels as well as heavy snowfalls. The alarm should also monitor critical equipment such as the heating system, ventilating fans and nutrient solution pumps.

The alarm system should be tested on a regular basis. It should be set up so that the contacts open to sound the alarm. This protects against a broken alarm wire by sounding

the alarm if the circuit is interrupted.

ACKNOWLEDGEMENTS

The comments and suggestions from T. Blom, R. Stone, J. Butt, M. Mohyuddin, the Canada Plan Service Fruit, Vegetable and Greenhouse committee members D. Small, D. Allen, W. Allison, G. Belzile, H. Fraser, G. Linkletter, K. van Daltsen and the artwork by R. Pella are appreciated.

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