**Factsheet 10/09**

**Protected crops**

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**Horticultural Development Company**

Stoneleigh Park
Kenilworth
Warwickshire CV8 2TL
T: 0247 669 2051
E: hdc@hdc.org.uk

# Energy management in protected cropping: Management of $CO_2$ enrichment

Steve Adams and Allen Langton, Warwick HRI, and Chris Plackett, FEC Services Ltd

**This factsheet, part of a series on energy management, outlines why $CO_2$ enrichment is vital to the cost-effective production of many glasshouse crops. However, it can have a high energy cost, and keeping this in check is the focus of this factsheet.**

## Summary points

- For some crops, $CO_2$ enrichment can greatly increase annual energy use. It is important to ensure, therefore, that the benefits outweigh the costs.

- Flue gases from natural gas boilers and CHP units can be used for $CO_2$ enrichment. $CO_2$ from natural gas boilers is essentially a by-product of glasshouse heating, but should be costed at around 13 pence/kg (for a gas price of 2.5 pence/kWh) if the boiler is being used solely for the purposes of $CO_2$ enrichment. CHP units (including microturbines) produce more $CO_2$ per unit of heat output than a boiler, but for reciprocating engines, a catalytic converter is needed to remove harmful pollutants. On economic grounds, the installation of a CHP unit cannot be justified on the basis of $CO_2$ production alone. The flue gases of combusted biomass cannot currently be used as a source of $CO_2$.

- $CO_2$ enrichment using flue gases frequently generates surplus heat and this should be stored as hot water in well insulated storage tanks for later use (Figure 1). A heat storage capacity in the range of 150–200 m³/ha is typically recommended.

- A permanent minimum pipe temperature setting can be used to generate $CO_2$ in the absence of a heat store or if this is full. However, this practice is energy intensive and minimum pipe temperatures greater than 40°C are unlikely to be economic.

- $CO_2$ can also be generated by LPG or kerosene burners within the glasshouse. However, $CO_2$ generated in this way can be expensive, and dealing with the associated products of com-bustion (water vapour, heat and, possibly, aerial pollutants) can be problematic. However, associated heat production in winter will offset glasshouse heating costs.

- Enrichment can also be carried out using pure, liquefied $CO_2$. This is a by-product of industrial processes and its use for enrichment does not increase overall energy use. It has the advantage over flue gases in that it can be used in summer without associated heat production. However, a certified bulk storage

**1 Well insulated heat storage tanks are essential to reduce the energy costs of $CO_2$ enrichment by the burning of fossil fuels**

tank is required. Liquefied $CO_2$ currently costs around 11 pence/kg, but additional surcharges can just about double this.

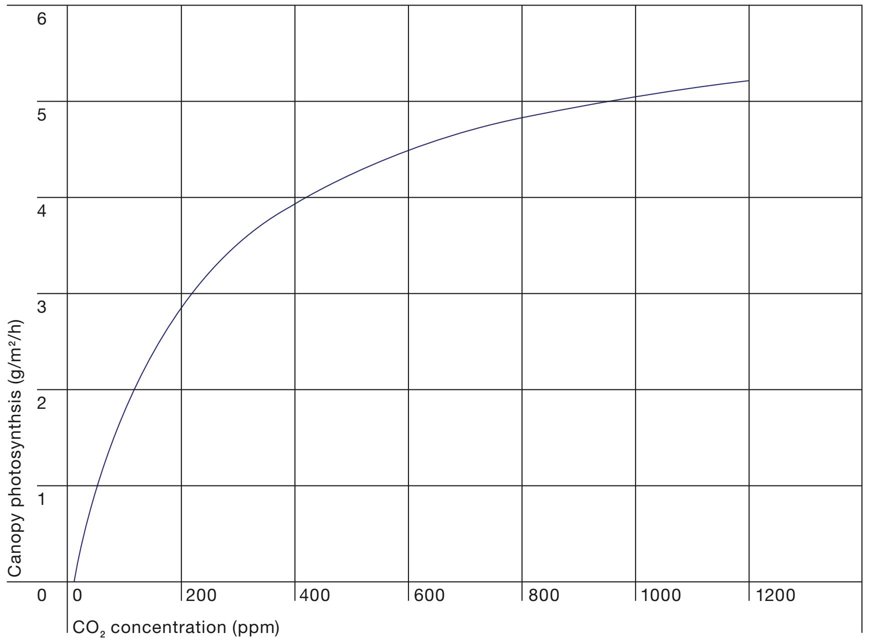
- $CO_2$ needs to be distributed around the glasshouse to achieve uniformity of supply and this is achieved either by integral fans in the case of burners, or by the use of a fan and duct system with perforated supply lines. The supply lines are best sited within the crop canopy or, in the case of benched crops, on or under the benches. Accurate $CO_2$ measurement is important to optimise enrichment practices, and all $CO_2$ sensors should be calibrated regularly.
- Raising the vent temperature for part or all of the day will reduce ventilation losses and increase the potential for $CO_2$ enrichment.
- It is best to spread the use of available $CO_2$ over the whole course of the day to avoid canopy depletion. Ideally, the highest gas burn rates should be around noon in spring and autumn, but in the morning in summer.

## Background

Dry weight increase and yield are functions of crop canopy photosynthesis and this, in turn, is highly dependent on $CO_2$ concentration. As Graph 1 shows, photosynthetic rate increases with rise in $CO_2$ concentration up to at least 1,200 ppm. However, the response is not linear, and photosynthetic rate increases become progressively smaller as $CO_2$ concentration rises. The relationship shown is for tomato, but most other horticultural crops respond similarly. As a consequence, it is now common practice to raise the glasshouse daytime $CO_2$ concentration for many edible crops and some ornamental crops ($CO_2$ enrichment). Sources of $CO_2$ for enrichment include boiler, CHP and burner exhaust gases and liquefied pure gas.

At the very least, enrichment can be used to avoid $CO_2$ depletion which occurs when its utilisation outpaces the rate of natural replacement from outside. Outside levels are commonly around 380 ppm but, without enrichment, levels in the glasshouse can fall in summer to as low as 200 ppm, particularly when crops with a large leaf area are growing in tightly sealed glasshouses. As seen in Graph 1, this degree of depletion will reduce canopy photosynthesis by around 26%. However, depletion is not always as extreme as this, and in commercial tomato production adding only sufficient $CO_2$ to prevent atmospheric depletion typically gives a 5–15% yield increase. It is now rather common, however, to enrich year-round to much higher levels than ambient, and this practice is estimated to increase yields by around 20–30%, depending on the degree of enrichment, species, crop density etc. It needs to be taken into account, however, that in species such as cucumber, very high $CO_2$ concentrations may be damaging. PC 159 showed that cucumber leaves could be bleached under high light levels with $CO_2$ concentrations greater than 1,000 ppm.

**Graph 1 Relationship between tomato canopy photosynthesis and $CO_2$ concentration (simulated from a model developed by Nederhoff and Vegter)**

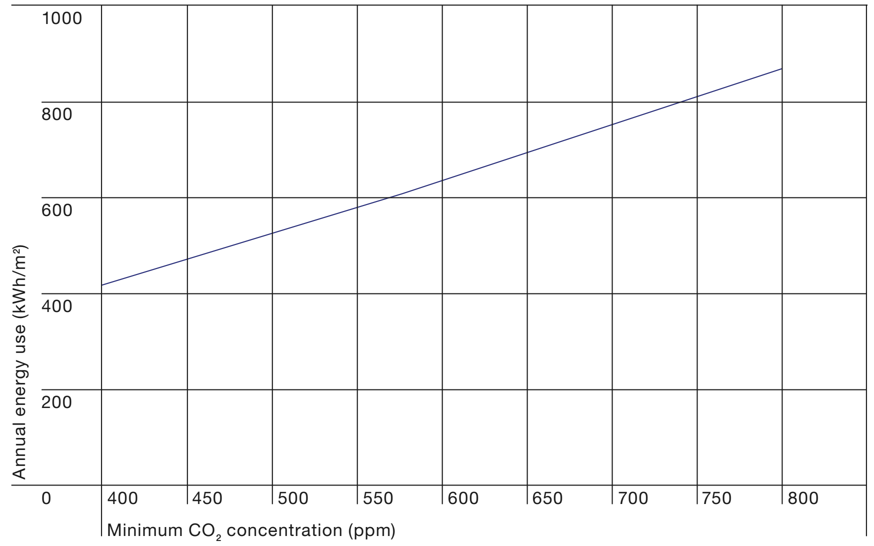



## Energy cost of $CO_2$ enrichment

$CO_2$ enrichment increases crop yield and quality but it also has an associated energy cost, depending on how it is accomplished and the extent to which it is practiced. It is usual in tomato production, for example, to employ $CO_2$ enrichment using flue gas from natural gas boilers (see below) and, because this is essentially a 'by-product', it is widely considered to be 'free'. However, there would be little enrichment in the summer months if reliance were placed solely on greenhouse heating to supply the $CO_2$ and, in practice, the boiler is frequently run with the sole aim of generating $CO_2$. This clearly has a major impact on energy consumption, and simulations have shown, for example, that maintaining a minimum daytime $CO_2$ concentration of 600 ppm could increase the energy use from 387 kWh/m² (without $CO_2$ enrichment or humidity control) to 645 kWh/m² (Graph 2).

In commercial practice, a boiler would not be operated as in the simulation to maintain a fixed $CO_2$ concentration, regardless of the burn rate and cost. Instead, the burn rate will be determined by the minimum pipe and heat store strategies, and the achieved concentration will vary depending on the ventilation. Furthermore, pipe temperature may also serve to control humidity (Factsheet 07/09) and some of the heating cost should be attributed to this. Nevertheless, energy will still be expended to produce $CO_2$ and, in a recent trial of advanced climate control in sweet pepper production, the additional energy expenditure was equivalent to 52 kWh/m² of gas (PC 227a) - probably a quite conservative figure had the study been on tomato. The $CO_2$ from natural gas boilers can only be considered to be free when there is a heat demand in the greenhouse, or the heat can, in some way, be stored for use at a later time (see below). Otherwise, the surplus heat has to be dissipated to the external environment ('destroyed').

**Graph 2 Annual energy use expended in maintaining the minimum $CO_2$ concentration in tomato production at levels between 400 and 800 ppm using flue gases from a natural gas boiler. The simulation assumes heating set-points of 18°C (day) and 17°C (night) with venting at 19°C, a heat store of 175 m³/ha and no thermal screens (simulated using a model developed in HH1333SPC)**




## Sources of $CO_2$

### Exhaust gases

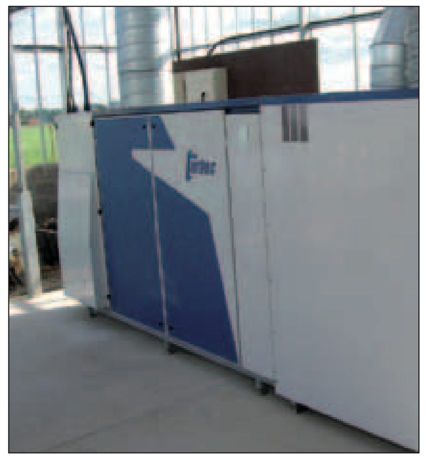
**Natural gas boilers**

Flue gases from natural gas boilers are widely used in UK horticulture as a source of $CO_2$ for enrichment. They are initially very hot, and have to be cooled before being introduced into the glasshouse. This is done by mixing the exhaust with fresh air or by passing it through a flue gas condenser. This latter method has the advantage of taking out most of the water vapour which would otherwise tend to increase glasshouse humidity. This operation can also save energy by 'capturing' the remaining heat in the flue gases. This source of $CO_2$ is generally thought to be sufficiently 'clean' to require no further treat-ment, but this is being re-examined in PC 287. As shown in Table 1 overleaf, the production of 1 kg of $CO_2$ requires the burning of 5.26 kWh of natural gas and, assuming a cost of 2.5 pence/kWh for natural gas, each kg of $CO_2$ that is generated purely to enable enrichment will cost around 13 pence.

**CHP installations**

The exhaust gases from CHP units can also be used to supply $CO_2$ for enrichment, together with heat and electricity. They are highly efficient, typically converting over 90% of the input fuel into heat and electricity, and produce more $CO_2$ per unit of heat output than a glasshouse boiler. However, most of the units installed on UK nurseries use natural gas-fuelled reciprocating engine generators with outputs in the range of 1–3 MW (electrical output), and it is necessary to incorporate catalytic converters to "clean up" the exhaust gases before these can be used in the glasshouse. This inevitably adds to the cost of the installation. Those located on glasshouse sites were originally installed with the primary aim of generating income from electricity export sales. However, the market price for exported electricity is currently insufficient to justify the maintenance and capital repayment costs, and this is currently limiting the installation of new units. For a grower with access to a CHP (with catalytic converter), therefore, this is a good source of $CO_2$. The installation of a CHP unit cannot currently be justified on the basis of $CO_2$ production alone, but investment prospects in CHP may become more attractive in the future and growers should maintain a watching brief.

Micro-turbine CHP units (Figure 2) are also commercially available and suitable for nursery installation.



**2 Micro-turbine CHP units can provide $CO_2$ for glasshouse enrichment without the need for a catalytic converter to remove harmful pollutants**

These typically have an electrical generation capacity of 100 kW or less, and use a small gas turbine to drive the electricity generator. They can be used in a modular fashion to provide installations with higher generation outputs and have the advantage over reciprocating systems in that their exhaust gases are relatively free of harmful pollutants. There is therefore, no need to install expensive exhaust gas cleaning equipment. However, uptake of micro-turbine CHP units has also been low, largely due to unfavourable energy market economics. As with large CHPs, the purchase of micro-turbine CHP units cannot currently be justified on the basis of $CO_2$ production alone and growers should continue to watch developments. Detailed information on micro-turbine CHP is available in the HDC Grower Guide – Micro Turbine CHP Units.

**Biomass boilers**

Although it is theoretically feasible to recover $CO_2$ from the flue gases of combusted biomass fuels (eg woodchip, straw etc), the technology to do this is not yet proven. This means that, currently, if biomass fuels are being considered, alternative sources of $CO_2$ will need to be sought. A feasible option could be to use two boilers and a combination of fuels, such as wood alongside natural gas. The low carbon (and, hopefully, lower cost) biomass fuel would deliver the base load heating at times when $CO_2$ demands were low, but the grower would switch to (or use as a top-up) the cleaner burning natural gas (and flue gases) at times of high $CO_2$ demand (see PC 265). An alternative would be to use pure $CO_2$ alongside a renewable fuel fired boiler, but this may be cost prohibitive.

**$CO_2$ burners**

$CO_2$ burners (air heaters) differ from heating boilers in that they are suspended within the glasshouse above growing crops (Figure 3). They typically burn LPG (propane) or kerosene, but can be operated on natural gas. As well as generating $CO_2$, burners produce water vapour and this can raise glasshouse humidity. They also produce heat and this will offset glasshouse heating costs in winter. Regular maintenance is essential to prevent incomplete combustion and incorrect flame temperature since these result in the production of aerial pollutants (see later). It may be necessary in well-sealed houses to provide the burners with their own outside air supply. A particular problem with $CO_2$ burners is that it is frequently difficult to adjust the $CO_2$ output, making control very difficult and leading to $CO_2$ gradients within the house. The cost of the $CO_2$ from burners has traditionally been far more expensive than that from natural gas boilers, but the volatility in the fuel supply market has recently changed that (see Table 1).

3 $CO_2$ burner (air heater) within a pot chrysanthemum house

**Table 1 The cost of $CO_2$ derived from the combustion of fossil fuels**

| Fuel | Fuel required to produce 1 kg $CO_2$ | Fuel cost* | $CO_2$ cost |
|---|---|---|---|
| **Natural gas** | 5.26 kWh | 2.5 pence/kWh | 13 pence/kg |
| **Kerosene** | 0.4 litres | 35 pence/litre | 14 pence/kg |
| **LPG (propane)** | 0.66 litres | 35 pence/litre | 23 pence/kg |

* typical costs at the time of writing

## Pure $CO_2$

Pure $CO_2$ can be obtained in liquefied form as a by-product of industrial processes and its use for $CO_2$ enrichment does not increase overall energy use. This source of $CO_2$ has the advantage of being free of injurious pollutants. It can also be used independently of the need for glasshouse heating, and is easily piped into the glasshouse. However, a certified bulk storage tank is required (Figure 4). Liquid $CO_2$ currently costs around 11 pence/kg (£110/tonne) which is similar to the cost of $CO_2$ from the burning of natural gas (Table 1). However, some suppliers may introduce surcharges at times when energy costs are high or when manufactured supplies do not meet market demand. At these times, costs may increase to around 20 pence/kg (£200/tonne).

4 Bulk $CO_2$ storage tank

# Distribution systems and $CO_2$ measurement

## Distribution

It is necessary to distribute $CO_2$ around the glasshouse to achieve uniformity of supply. In the case of $CO_2$ burners, distribution is achieved by means of integral fans which blow the products of combustion around the glasshouse. However, as noted above, this inevitably results in the creation of both vertical and horizontal $CO_2$ gradients within the glasshouse. In the case of pure $CO_2$ and flue gases from natural gas boilers and CHP units, a distribution system has to be installed. Usually, this comprises a central header, from which run small bore, perforated tubes, taking $CO_2$ to all areas of the glasshouse. $CO_2$ supply lines are best sited directly in the crop canopy where active photosynthesis takes place or, in the case of benched crops, on or under the benches.

## Measurement

It is important to measure $CO_2$ levels accurately in order to avoid wasteful generation and, possibly, adverse plant reactions, and to optimise crop production. Concentrations have traditionally been measured using infra-red gas analysers (IRGAs). These can be very accurate and reliable, but regular calibration is important. This can be done using calibration gases of known concentration. The zero value can also be tested by removing the $CO_2$ from the air with an appropriate absorbent such as soda lime.

To reduce capital costs, a single analyser is often used to measure several glasshouse areas. Consequently, sample pipes may be of considerable length. Air is often drawn continuously from all of the pipes via a multiplexer, although only one will be measured at any given time. Even so, sufficient time needs to be allowed for the system to purge and start accurately recording new $CO_2$ levels when switching between areas. If measurements are taken too soon, air from the first block may still be present, and the readings will be for a mixture of the two blocks. It is good practice to sample at a height that will reflect the $CO_2$ concentration in the upper crop canopy, since this is where most photosynthesis takes place.

More recently, electronic $CO_2$ sensors (Figure 5) have become more widely available. There is still a need to calibrate these regularly, but because each growing area can have its own sensor, they overcome some of the problems associated with a centralised IRGA and long runs of pipe work. Recent commercial experience suggests that these are reliable and give accurate readings.

5 Electronic $CO_2$ sensor

# Optimising $CO_2$ availability

## Storing surplus heat

As noted above (Energy cost of $CO_2$ enrichment), surplus heating energy is frequently generated in summer by the use of natural gas boilers to provide $CO_2$. In this case, the surplus heat should be stored for later use as hot water in heat storage tanks (Figure 1). Modern nursery installations can burn gas at rates in the region of 200 m³/hr/ha, and a heat storage capacity of around 150–200 m³/ha is typically recommended. The heat store should be suitably insulated to ensure that heat is not wasted.

## Minimum pipe temperature

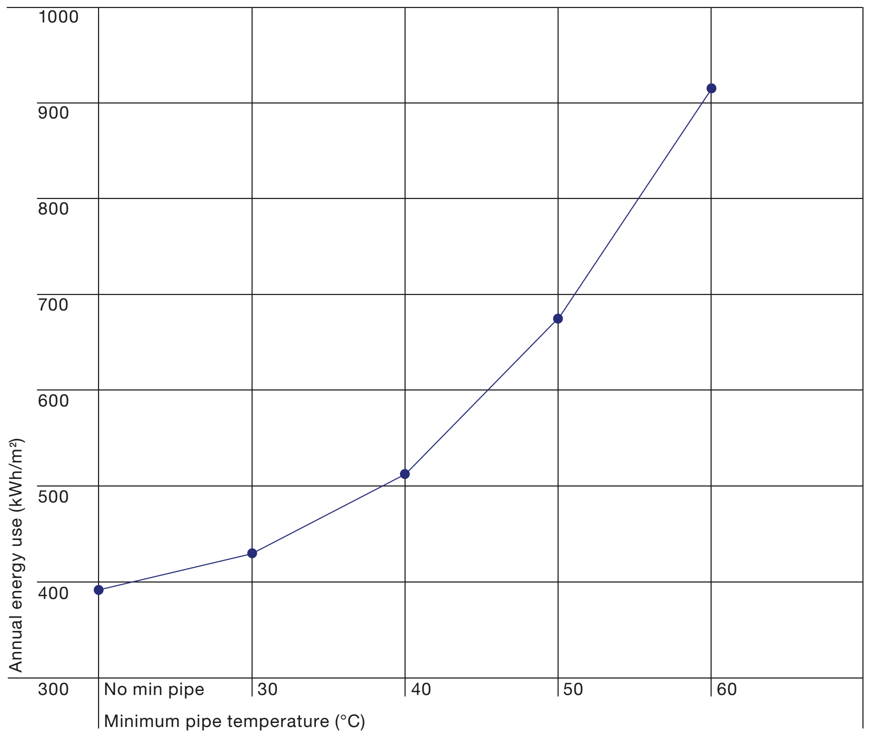
A permanent minimum pipe temperature setting can be used to dissipate surplus heat if there is no heat store, or the heat store is full. However, this practice is energy intensive (Graph 3) and the cost of generating the $CO_2$ has to be balanced against the likely increase in crop yield. Increasing the minimum pipe temperature increases the supply of $CO_2$. However, it also increases the amount of heat dissipated into the glasshouse, and this will increase ventilation and $CO_2$ losses. The optimal strategy will clearly be dependent on gas and tomato prices, but simulations carried out for classic tomatoes (PC 110a) indicated that minimum pipe temperatures greater than 40–45°C were unlikely to be economic. However, these simulations were carried out for gas prices ranging from 0.5 to 1.5 p/kWh, and given that gas prices have tended to increase more than fruit prices, the maximum economic pipe temperature is now likely to be somewhat lower.

## Vent management

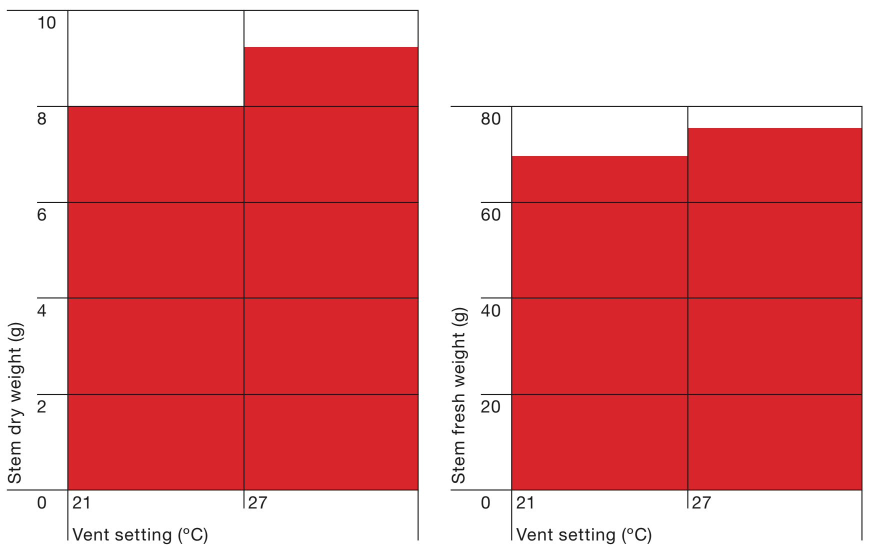
Although $CO_2$ is heavier than air, it is still rapidly lost from the glasshouse through the vents! For this reason $CO_2$ enrichment protocols (whatever the source) need to take account of vent operation. One strategy is to optimise $CO_2$ dosing according to ventilation rate (see 'When to add $CO_2$' below), while a second is to manipulate ventilation set-points.

In 2000, Dr Debbie Fuller trialled protocols with spray chrysanthemums where $CO_2$ was enriched to 1,000 ppm whenever vents were less than 10% open (HH1318SPC). Raising the vent temperature setting from 21°C (control) to 27°C for the first four hours of each day had little effect on average 24 h temperature, but markedly increased the average daily duration of enrichment. The result was a 15.7% increase in dry weight (averaged over cultivars) and an 8.8% increase in fresh weight (Graph 4). There was, however, an associated increase in plant height and pedicel length necessitating additional PGR treatment. Raising the vent temperature for the whole of the day will increase further the potential for enrichment, and this is a feature of the energy-saving procedure, temperature integration (TI) (see Factsheet 06/09). It was shown for tomato in PC 188a, for example, that TI gave better $CO_2$ utilisation and increased the yield by 4.3%.

**Graph 3 The influence of a permanent, minimum pipe temperature on energy use in tomato production with a screen, and with humidity controlled at 90% RH (simulated using a model developed in HH3611SPC)**




**Graph 4 Effects of vent opening temperature during the first four hours of each day on average stem dry weight (left pair) and fresh weight (right pair) for spray chrysanthemums given $CO_2$ enrichment to 1,000 ppm whenever vents were less than 10% open (HH1318SPC)**




## When to add $CO_2$

Experiments with tomato have shown that morning and afternoon $CO_2$ enrichment give similar yield benefits. Consequently, it is best to spread the use of the available $CO_2$ over the whole course of the day, and so avoid canopy depletion. However, the optimal $CO_2$ concentration will change over the course of the day. The benefits of $CO_2$ enrichment increase at higher light levels, but the efficiency of enrichment decreases with higher ventilation rates. Simulations carried out as part of PC 110a suggest that $CO_2$ levels should ideally be highest around noon in spring and autumn, but that in the summer they should be highest in the morning when ventilation rates tend to be lower.

## $CO_2$ Optimiser ™

Two Excel based programmes are available from the HDC to provide guidance on the optimisation of $CO_2$ enrichment for tomatoes where a boiler or CHP is used. Unfortunately these programmes do not interact with climate control computers to provide real time outputs and guidance.

# Pollutants

As already noted, one of the disadvantages of burning a hydrocarbon fuel to produce $CO_2$ is that the combustion products can contain pollutants which are potentially harmful to plants and/or humans. It is possible to monitor the concentration of pollutants at the back of the boiler or, for a reciprocating CHP, after treatment. However, it is their concentration in the glasshouse that is more critical in determining effects on plants or workers, and this requires very sensitive equipment able to detect concentrations as low as parts per billion (ppb). Such work is currently being carried out as part of PC 287.

## Oxides of Nitrogen ($NO_x$)

$NO_x$ is a generic term for mono-nitrogen oxides (NO and $NO_2$) which can be produced to harmful levels. Plants are damaged by $NO_x$ at levels below those judged to be harmful to human health, so it is plant response that determines what are acceptable levels in the glasshouse.

Tomato leaves exposed to high $NO_x$ concentrations (2,000 ppb or more) for one or two hours can show water-soaked areas or 'windows' that later turn white or brown. Leaves may also develop damaged margins. Longer-term exposure to lower concentrations (500 ppb) can result in a temporary increase in leaf greenness, which is followed by chlorosis and premature leaf fall. The effects of lower concentrations can be more insidious; a concentration of 250 ppb can reduce tomato plant growth but without any visible leaf damage. Lettuce is also sensitive to $NO_x$ and a concentration of 500 ppb can inhibit growth. Overall, it is difficult to be precise as to 'safe' levels of $NO_x$ given wide variation in response between species and cultivars. Furthermore, plant sensitivity is affected by stage of development and other environmental conditions, including $CO_2$ levels and the presence of other pollutants.

## Ethylene ($C_2H_4$)

Ethylene is a naturally occurring plant hormone, but is also released into the glasshouse aerial environment as a result of incomplete combustion. Symptoms of ethylene injury include reduced growth, reduced apical dominance and shorter internodes, epinasty of leaves, premature senescence of leaves and flowers, delayed and malformed flowers, and abscission of flower buds. Epinasty may be induced in tomato at 100 ppb, and 500 ppb for four days is sufficient to cause flowers to either abort or drop off (see Figure 6). Propylene pollution, which can be associated,

**6 Flower bud abscission in tomato after exposure to 500 ppb ethylene for four days**

for example, with leaky propane lines, causes symptoms similar to those of ethylene.

## Carbon monoxide (CO)

Plants are more tolerant to CO than are humans, so it is the permissible levels for humans that need to take priority. The Health and Safety Executive (HSE) set the occupational health limits in the UK. However, the presence of CO at levels above 50 ppm in flue gases is an indication of the likely presence of injurious levels of other pollutants.

## Sulphur dioxide ($SO_2$)

The risk of damage from $SO_2$ has become greatly reduced. This is because kerosene is only used to a minor extent for $CO_2$ generation, and is now 'low sulphur'.

# Further information

Factsheets in this series

- HDC Factsheet 05/09 – Energy management in protected cropping: Good housekeeping
- HDC Factsheet 06/09 – Energy management in protected cropping: Manipulation of glasshouse temperature
- HDC Factsheet 07/09 – Energy management in protected cropping: Humidity control
- HDC Factsheet 08/09 – Energy management in protected cropping: The use of screens
- HDC Factsheet 09/09 – Energy management in protected cropping: Horticultural lighting

## Other useful publications

HDC Grower Guides: 'Micro-turbine CHP units', 'Tomatoes: Guidelines for $CO_2$ enrichment'

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