Project title:	The development and commercial demonstration of ducted air systems for glasshouse environmental control
Project number:	PC 278
Project leader:	Tim Pratt, FEC Services Ltd
Report:	Final report, April 2011
Previous report:	Annual report 2008, 09 and 10
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Location of project:	FEC Services Ltd, Warwickshire Mill Nurseries Ltd, East Yorkshire
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Date project commenced:	1st July 2007
Date project completed (or expected completion date):	28th February 2011
Key words:	Energy, heat, air movement, air mixing, air handling unit, fans, ducts, heat exchangers, carbon dioxide

The results and conclusions in this report are based on an investigation conducted over a four-year period. The conditions under which the experiments were carried out, and the results, have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions may produce different results. Therefore, care must be taken with interpretation of the results, especially if used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Tim Pratt
Technical Director
FEC Services Ltd

Signature .... Date ....

Report authorised by:

Andrew Kneeshaw
Managing Director
FEC Services Ltd

Signature .... Date ....

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GROWER SUMMARY

Headline

Water at 50^{o}C or less satisfied 95% of the total greenhouse heat demand, this compares with 60% of heat demand with a conventional heating system.

Background and Expected Deliverables

This report summarises the findings of the second year of commercial trials of a three year project. The purpose of the project was to investigate the performance of a ducted heating and ventilation system installed in a 1Ha tomato greenhouse in E. Yorks.

The project follows on from PC 256 which examined the potential for using closed glasshouse technology in the UK. This concluded that ducted air heating and ventilation systems could offer significant advantages over conventional greenhouse design through:

- Reduced energy consumption.
- Improved crop yield.
- Reduced pest and disease problems.
- Increased opportunities to use alternative heat sources.

Objectives

The aims of the project are to investigate the ability of ducted air delivery systems to:

- Reduce energy use and costs in heated glasshouses.
- Reduce CO_2 emissions associated with glasshouse production.
- Expand the opportunities for glasshouse businesses to use alternative heat sources.
- Improve crop yield and quality.
- Reduce disease incidence and therefore the use of crop protection chemicals.

Summary of the Project and Main Conclusions to Date

Materials and Methods

The project comprised three parts:

- Researching, developing and designing a commercially acceptable ducted air heating and ventilation system for a trial greenhouse at a commercial nursery.

- Installing the selected system at the trial site.
- Carrying out commercial trials to investigate system performance and crop response.

Trial Site and Equipment

Site

The project was carried out in two adjacent 1Ha greenhouse compartments at Mill Nurseries Ltd in East Yorkshire. A fan and duct system installed in one compartment was compared with an adjacent and otherwise identical compartment which has a conventional heating and ventilation system.

Equipment

Figure 1 shows a single air handling unit of the type installed at Mill Nurseries Ltd.

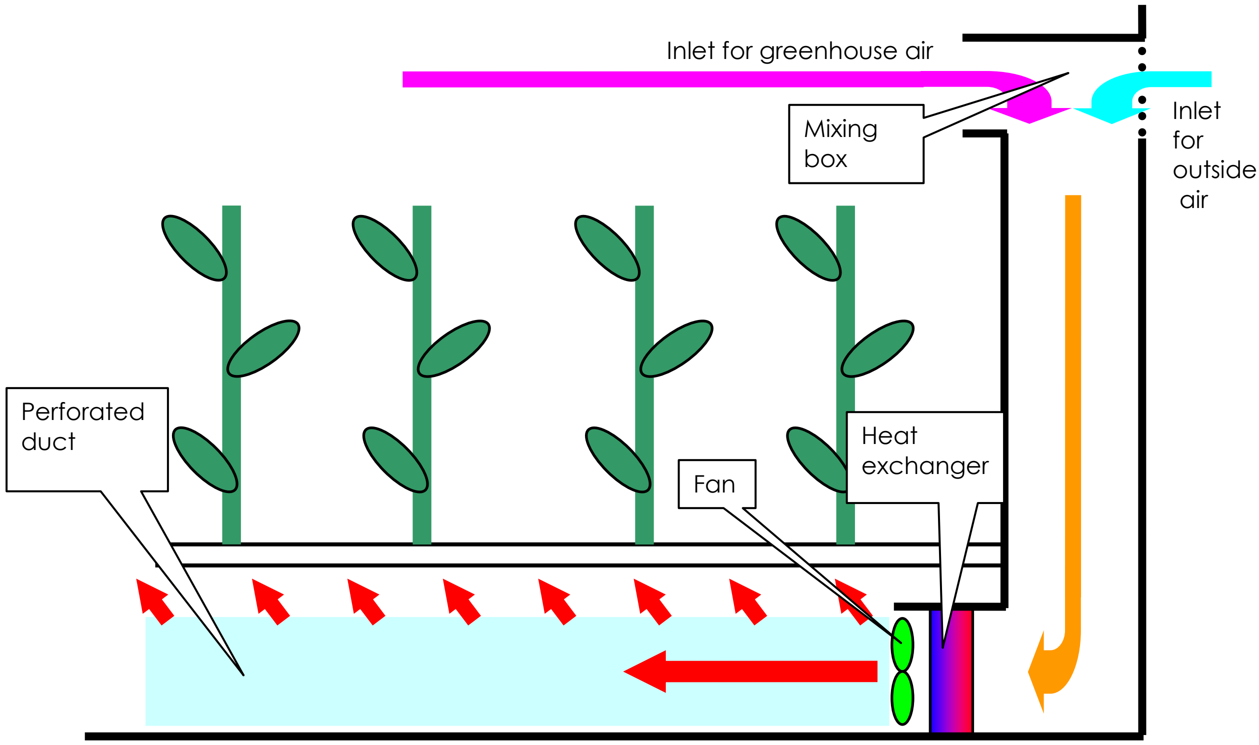

Figure 1. Air handling unit schematic

Collectively the components shown above are referred to as an Air Handling Unit (AHU). Each of the AHUs installed can deliver 6,000m^3/hr and 25kW of heat. The installation uses 18 of these AHUs arranged as shown in Figure 2 (overleaf).

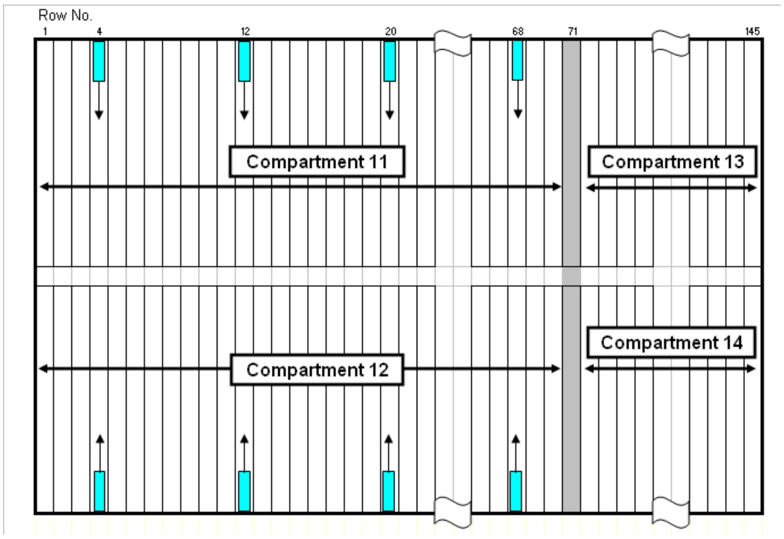

Figure 2: AHU layout

The whole installation has a heating capacity of 450kW/Ha and delivers an airflow of 108,000m^3/hr (2 air changes per hour). The fan and duct installation is not capable of satisfying all the heating and ventilation needs of the greenhouse and the existing pipe rail heating system and roof vents continue to be used.

Results

Temperature uniformity

It was anticipated at the design stage that increased air movement delivered by a fan and duct system would result in improved uniformity of temperature. During the initial operation phase this did not prove to be the case. In fact it made the temperature uniformity worse during the winter when the heat demand was high and there was no venting.

Extensive trials and subsequent modifications were required before a satisfactory solution was proven in January 2010. Figures 3 and 4 below show the temperature uniformity measured between 11th and 26th January 2010.

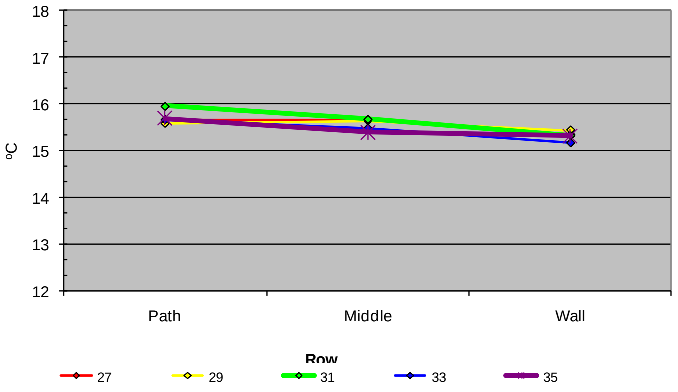

Figure 3. Fan and duct (CMP12)

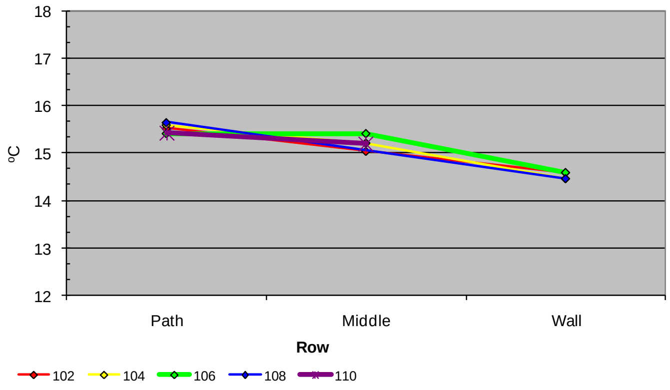

Figure 4. Conventionally heated (CMP14)

This was achieved by:

- Ensuring that the air exited the outlets at 90o to the axis of the duct.
- Blowing a small amount of air back towards the greenhouse wall to solve what were previously dead-spots between adjacent air handling units.

Greenhouse environment

The climates in the trial and control compartments were managed according to the needs of the individual crops. This meant there were times when the greenhouse temperatures in particular, were different between the compartments. In general, a lower humidity deficit (HD) was targeted in CMP 12 (fan and duct) than in CMP 14.

Temperature

Temperature control was the most important environmental 'tool' for manipulation of plant growth and condition. The greatest differences in temperature control strategies between compartments occurred between weeks 4 and 12. The same 'rules' of growing (warm day, cold night for a generative effect etc.) were applied in both compartments.

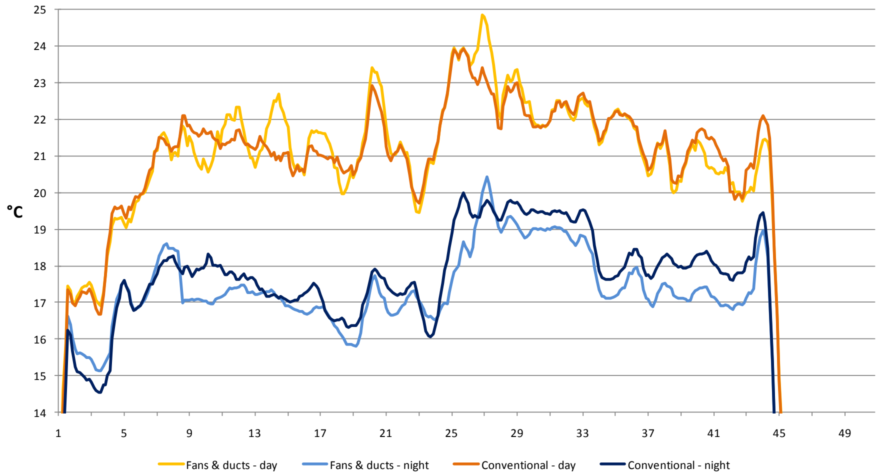

Figure 5. Weekly average temperature at the top of the crop

The greatest difference between temperature treatments in the compartments occurred during the night time. Between weeks 9-12 this was a result of different heating temperature set points. During the summer months it was largely due to lower energy inputs for humidity control.

Humidity

At low humidity deficits (HDs), the grower felt that the environment in the fan and duct compartment was better than in the conventional compartment even when the measured HD was almost the same. This provided the confidence to experiment with lower HDs in the fan and duct compartment. As a result the target HD in the fan and duct compartment was typically 0.3-0.5g/m^3 lower than in the conventional compartment. Figure 6 shows the average HD measured at the top of the crop.

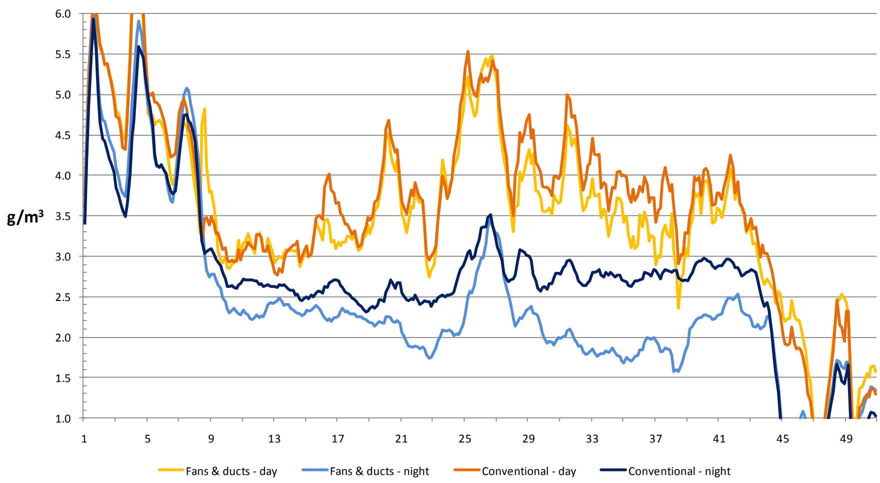

Figure 6. Average humidity deficit measured at the top of the crop

The difference between treatments during the night time is most obvious between weeks 30-40. The difference in daytime HD is most notable between weeks 35-39 when the weather was poor. In addition to energy saving, accepting lower HD's during the daytime meant there was less venting and consequently higher CO_2 levels in the fan and duct compartment.

CO_2

Both compartments are served by a single CO_2 enrichment system controlled according to the higher of the two measurements taken in either of the compartments.

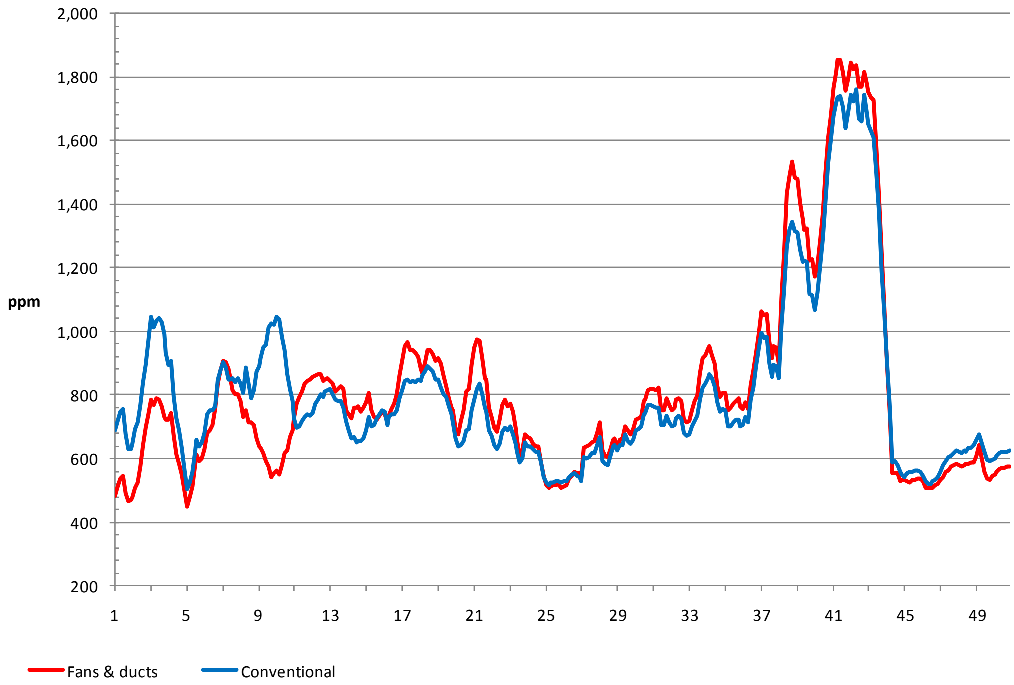

Figure 7. Daytime CO_2 concentration

Data up to week 10 are erroneous due to a fault with the Priva climate control computer. However, as there was no venting at all during this period so it is reasonable to assume that the CO_2 concentrations were broadly the same in both compartments.

With lower humidity in the fan and duct compartment, less venting and therefore higher CO_2 levels were achieved. In 2009, CO_2 concentration was limited to 450ppm because of delivery constraints. In 2010, 800ppm was nearer the norm. The high levels shown around week 42 are correct and were due to problems with the CO_2 enrichment system.

Crop data

Growing strategy / crop management

The grower and crop consultant felt that the increased air movement from the fan and duct system resulted in better transpiration at lower HDs, compared with that which would be achieved in a conventional growing environment at similar HD levels. Normally, increased transpiration is only achieved by increasing HD through greater (and more expensive) use of heat and ventilation. During the early part of the cropping year when the HD was equally good in both treatments more generative growth took place in the fans and ducts compartment. Generally, this can be regarded as beneficial or undesirable depending on the particular stage of development of the crop. If it is felt to be undesirable, some modification of the environmental control parameters is required to "overcome" this generative effect. These modifications are no different to those used for a crop grown with a conventional heating system. They might include:

- Increasing irrigation to produce a more vegetative growth and use night watering to prevent the slab moisture content dropping too low - this should only be carried out where accurate moisture content readings are available as increased irrigation can reduce slab electro-conductivity (EC) etc.
- Reducing the day night heating temperature differential.

Yield

Figure shows the total yield.

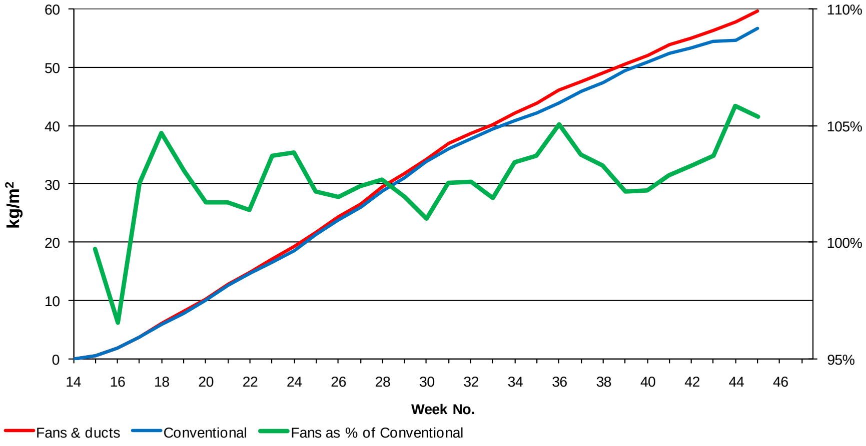

Figure 8. Total yield

Picking of the first fruit in the fan and duct compartment started 2-3 days later than in the conventional compartment. Prior to the installation of fans and ducts this picking delay was sometimes up to 7 days, so this delay was felt to be intrinsic to the performance of compartment rather than to the fans and duct system. Total yield was not affected by this issue.

Higher yields were evident in the fans and duct compartment from week 30 onwards. This was also seen in the 2009 season. This coincided with higher CO_2 levels in the fan and duct block. Table 1 compares the final yield in 2009 and 2010.

Table 1. Yield 2009 and 2010

	2009 Total yield kg/m^2	2010 Total yield kg/m^2
Conventional compartment	48.73	56.61
Fan and duct compartment	52.41	59.63
Difference	3.68kg/m^2 (+7.6%)	3.02kg/m^2 (+5.3%)

2010 yield was higher for both treatments than those recorded in 2009. This was due to higher availability of CO_2 from the nursery's CHP installation in 2010. The smaller difference in yields between the two treatments in 2010 is probably linked to the wholesale increase in CO_2 levels from 2009 to 2010. As overall CO_2 levels rise, the extra yield for each additional 100ppm reduces. Therefore, in 2010 the 'head room' for yield improvements between the two treatments was less than in 2009.

Disease

Disease assessments carried out by Dr Tim O'Neil (ADAS UK Ltd) showed that there was no difference in disease levels in 2010. This compares to a slight reduction in disease in 2009.

It is reasonable to conclude that the reduced energy use and lower HD's, which occurred with the fan and duct installation, did not result in higher disease levels.

Energy

Heat

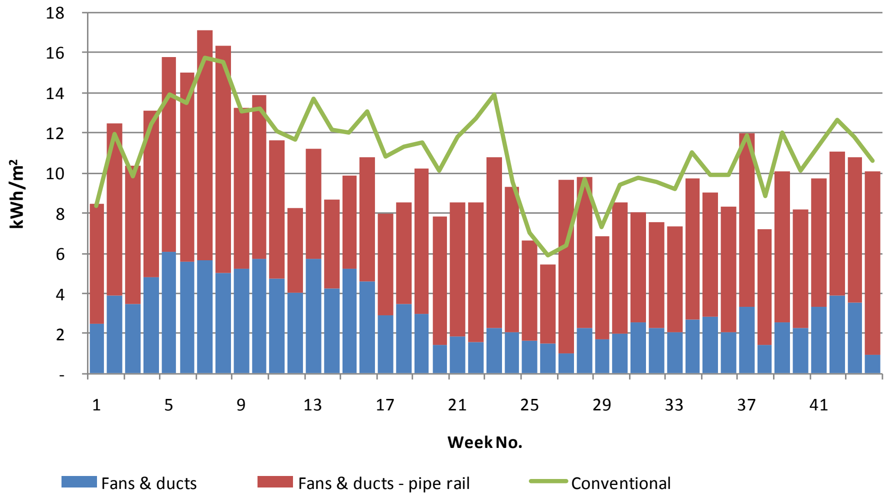

Figure 9. Weekly heat use (as boiler gas)

Up to week 10 (2010), the fan and duct compartment tended to use more heat than the conventional compartment. During this period no venting was required for humidity control, the thermal screen set points were the same and similar greenhouse temperatures were achieved. It could be argued that increased air movement due to the fans increases heat loss. However, the airflow delivered is relatively low and in 2009 energy use during this period was almost identical. One possible explanation could be a change in the prevailing wind direction. Although it was not possible to validate this theory, we are confident that the difference was not caused by the fan and duct installation.

As the difference up to week 10 is not expected to be due to the fan and duct installation the figures in the table below exclude it.

Table 2. Heat usage in 2009 and 2010

	2009 Total kWh/m^2	2010 Total kWh/m^2
Conventional	458	488
Fan & duct	399	436
Saving kWh/m^2	59 (12.8%)	52 (10.7%)

The slightly lower saving in 2010 is due largely to the period between weeks 27-28 when an alternative (but unsuccessful) control strategy was used.

Further analysis of the data showed that 95% of the heat used in the fan and duct compartment was from water of 50^{o}C or less. In the conventional compartment this proportion was only 60%. Furthermore, 40^{o}C water satisfied 60% of the heat required in the fan and duct compartment compared to only 13% in the conventional compartment. This is of particular interest when considering the use of low temperature heating systems such as heat pumps or waste heat sources.

Electricity

In 2010 a simple control regime was employed to reduce fan running hours and therefore electricity consumption when the greenhouse conditions were favourable. The regime was as follows:

Turn the fans off during daylight hours when:

The HD was >4.5g/m^3

AND

The lee side vents were >15% open

Although the fans were turned off for significant periods, especially during the day in summer, only a slight reduction in electricity was recorded over the whole year – 10.7kWh/m^2 compared to 11.0kWh/m^2 in 2009.

One major issue which resulted in the relatively small difference in running costs between the years was associated with a change of filter type in the air handling units. The newer filters allowed a higher airflow delivery and this increased the energy requirement of the fans. Had the airflow remained the same, electricity consumption is estimated to have been 8.1kWh/m^2.

Electricity use remains a major factor affecting the cost effectiveness of the fans and ducts systems.

Financial

Energy

Heat

The amount of heat energy saved through the use of the fans and ducts system compared to the conventional system in 2010 was 44.2kWh/m^2.

The value of this saving depends on the fuel and system used for heating. At Mill Nurseries Ltd heating water comes from a CHP system. However, the majority of growers still rely on mains gas fuelled boilers. Assuming the latter, and allowing for boiler and system losses, 44.2kWh/m^2 of heat would be associated with the use of 52kWh/m^2 of gas. The value of this depends on the cost of gas. Based on a gas price of 2.4p/kWh (typical projected price for 2012) this would be worth £1.25/m^2.

Electricity

The recorded electricity use of the fans was 10.7kWh/m^2 but a fairer future projection allowing for efficiencies realised by the filter system might be nearer 8.1kWh/m^2. At current mains electricity prices this would cost about £0.69m^2.

This leaves a net energy cost saving of £0.56/m^2 (£0.50/m^2 in 2009).

Maintenance

Since initial teething problems were resolved in 2008, the fan and duct installation has been reliable. To date, maintenance costs have been almost exclusively associated with the fans. Three required replacement bearings which, due to their construction, were relatively easy to fit and cost around £50/fan. Two fan motors burnt out and required re-winding, costing £350 each.

The only ongoing maintenance items to date have been the replacement of air filters in the air handling units. Alternative filter media has been identified which cost £1/fan unit (18 in total). Filters are replaced every six months.

Crop

A yield increase of 3.0kg/m^2 was achieved. This occurred from week 27 onwards and as such coincides with typically lower prices for the fruit. As the crop was of the loose round variety, Encore, additional yield in terms of kilos will deliver additional income. The same may not be the case with tomatoes on the vine. However, if consistently overweight vines are produced, this would provide the opportunity to produce more vines by increasing the crop density or to reduce levels of CO_2 enrichment and associated energy use.

Assuming a value of £0.50/kg, the extra yield would be worth £1.50/m^2.

Capital cost

The capital cost of the installation was £15.90/m^2. It should be remembered that this technology is very much in its early adoption stage and costs are expected to come down. There have been several similar products brought to the market since the installation of the system in March 2008. As a result, growers who are interested in this technology are advised to obtain quotes for a fan and duct installation specific to their own circumstances, as significant variance is expected.

Taking the specific example discussed above, the total financial benefit (net energy saving plus yield increase) has been worth £2.06/m^2. This gives a simple payback on investment of 7.7 years.

Conclusions

- Yield - the average increase achieved over 2-years attributable to the use of a fan and duct system was 3.4kg/m^2 (6.5%). This was largely as a result of the achievement of higher CO^2 levels from reduced venting for humidity control.
- Disease – reducing energy use and accepting a lower humidity deficit with fans and ducts did not result in higher incidence of disease levels.
- The average heat energy (from gas) saving over the 2-year project was 56kWh/m^2 (11.8%).
- The lowest electricity consumption to date was 10.7kWh/m^2. However, lower airflows which are expected to be possible could reduce energy use by 50% without reducing the heat energy saving.
- Low temperature / waste heat sources – the existing installation satisfied 95% of the total greenhouse heat demand with water that was 50ºC or less compared to only 60% with a conventional heating system.
- Reliability – since early teething problems were resolved the installation has been very reliable. Total repair costs after 3-years of operation have been £900.

- The interaction between fan-based air movement systems and natural air movement patterns in large scale commercial greenhouses is complex. Simply 'adding a few fans' can just as easily make temperature uniformity worse as make it better.
- Further investigation to reduce capital/operational costs and of lower airflow systems is required.

Action points for growers

The fans and ducts technique has greatest immediate potential where it can enable lower grade heat sources to be utilised.

Growers with a potential source of low grade heat should:

- Determine the amount of heat that is available and the synergy between production and greenhouse heat demands.
- Explore the feasibility and cost of accessing the heat. This could be significant. For example, in the case of CHP this may require additional heat exchangers, pumps and control systems.
- Identify potential suppliers of fan and duct systems. There were at least six exhibiting at the Hortifair 2010.
- Continue to track progress of this project in 2011 for further results.
- Growers who do not have access to lower cost heat sources should continue to track progress of this project through 2011 as the simpler (lower cost) installation being trialled may have benefits for them.

SCIENCE SECTION

Introduction

High energy costs and greater awareness of climate change issues continue to affect the viability of glasshouse horticultural production in the UK. PC 256 (2007) investigated the potential for using closed glasshouse technology in the UK and concluded that ducted air heating and ventilation systems that are widely used in closed glasshouses may offer considerable benefits if applied to conventional glasshouses.

When this project started in August 2008 there were no commercially available 'off the shelf' systems on offer by horticultural suppliers. At Hortifair 2010 at least six such systems were on show. The presence of these systems is stimulating interest and demand for unbiased and commercially proven information on viability, performance, benefits and disadvantages which this project continues to deliver.

Objectives

The aim of the project is to investigate the ability of ducted air delivery systems to:

- Reduce energy use and costs in heated glasshouses.
- Reduce CO_2 emissions associated with glasshouse production.
- Expand the opportunities for glasshouse businesses to use alternative heat sources.
- Improve yield and quality.
- Reduce disease incidence and therefore the use of crop protection chemicals.

Materials and methods

The project comprises three parts:

- Researching, developing and designing a commercially acceptable ducted air heating and ventilation system for the trial greenhouse at a commercial nursery.
- Installing the selected system at a trial site.
- Carrying out commercial trials to investigate system performance and crop response.

The project is being carried out at tomato growers Mill Nurseries Ltd in East Yorkshire. Previous reports (PC 278 Interim report, 2008; PC 278 Annual Report 2008, 2009, 2010) cover items 1, 2 and commercial trials in 2008 and 2009. This report details the commercial trials in 2010.

Trial site and equipment

The trial site, equipment and data collection procedures remain the same as in previous years. For ease of reference they are repeated below.

Site/greenhouse

The project is being carried out in a 2.1Ha greenhouse at Mill Nurseries Ltd in East Yorkshire. A fan and duct system was installed in one half of the greenhouse in March 2008 and is being compared with the other half of the greenhouse which has a conventional heating and ventilation system. A temporary partition was installed to create two separate airspaces as shown in Figure 10.

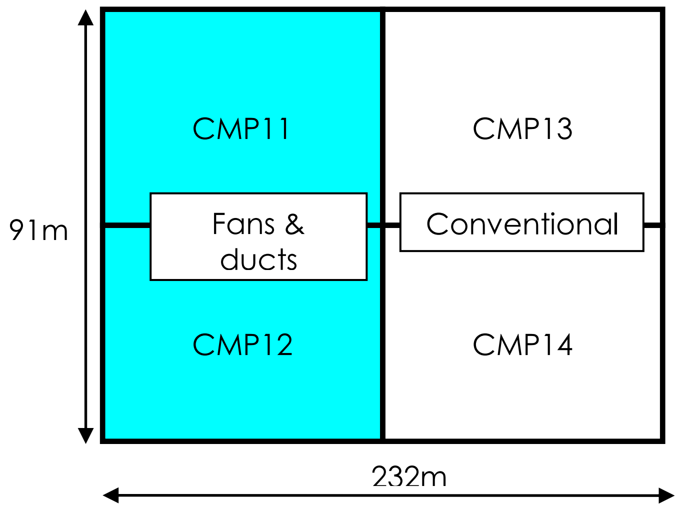

Figure 10. Layout and dimensions of the trial greenhouse

Equipment

The installation comprises 18 air handling units (AHU). Figure 11 shows a single air handling unit of the type installed.

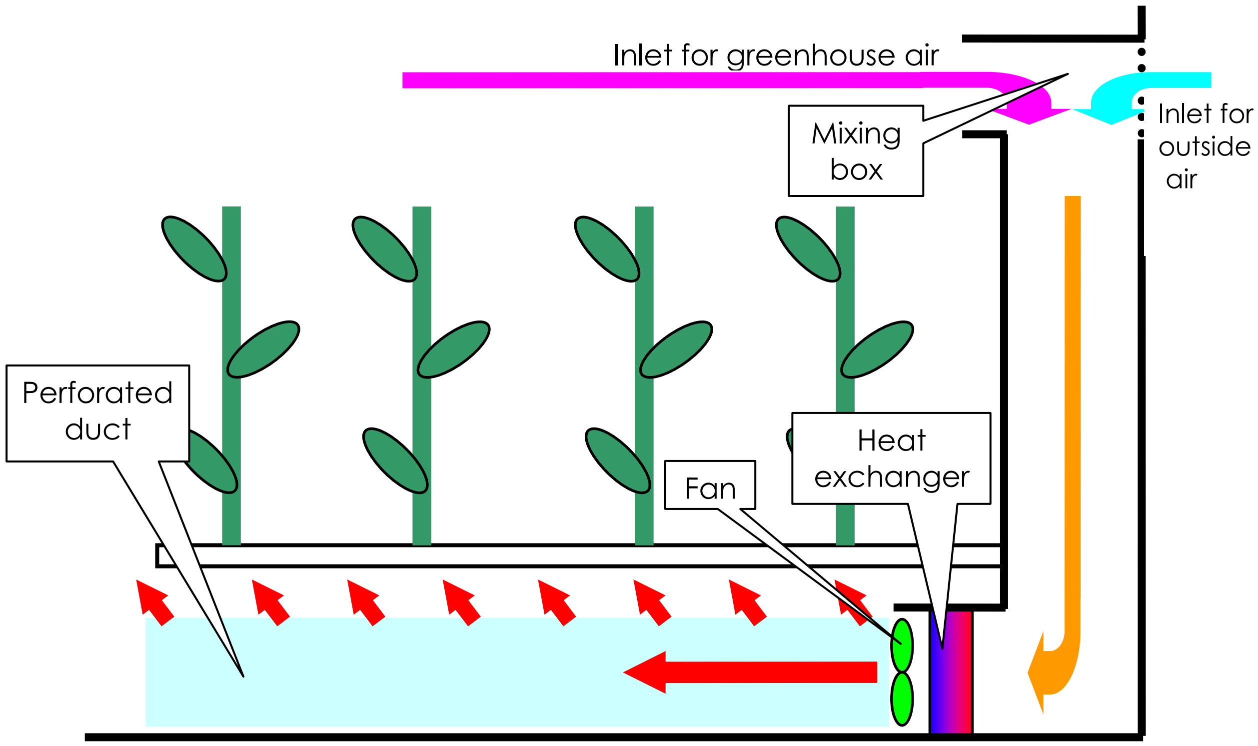

Figure 11. Air handling unit schematic

The fan and duct installation has a heating capacity of 450kW/Ha and delivers an airflow of 108,000m^3/hr (2 air changes per hour). It should be noted that it is not capable of satisfying all the heating and ventilation needs of the greenhouse and the existing pipe rail heating system and roof vents continue to be used.

The design of the installation is provided in more detail in report PC 278 Interim report, September 2008.

Regular data collection

Greenhouse environment

The aerial environment within CMP12 (fans & ducts) and CMP14 (conventional) was recorded using the site climate control computer. Data was downloaded every week via broadband connection by FEC consultants. Table 3 below lists the measurements taken in each compartment.

Table 3. Greenhouse aerial environment measurements

Location	Temperature °C	Humidity deficit g/m^3	Relative humidity %	Dew-point temperature °C	CO_2 concentration ppm
30-50 cm above the growing media	✓	✓	✓	✓	
30-50 cm below the growing point of the crop	✓	✓	✓	✓	✓

The following equipment status was recorded:

- Set points – heating and ventilation temperatures, minimum heating pipe temperature.
- Heating system – calculated and measured heating pipe temperature.
- Ventilation system – calculated and measured vent position.
- Thermal screen position.

Energy use

Heat use was measured using non invasive ultrasonic flow meters connected to a heat meter integrator.

The electricity used by the fans was measured by a meter built into the variable speed drive used to control them.

Yield

This was recorded as total kilos of fruit harvested each week in each area.

Disease

Disease levels, principally botrytis, were assessed in defined areas in two ways:

- Plants removed - recorded by nursery staff.
- Detailed assessment at key stages of the season

Temperature uniformity

This was assessed by placing compact data loggers on a grid pattern within each greenhouse compartment. The data loggers were mounted approximately 30 cm above the growing media to be at a similar height to the plants.

Results

Temperature uniformity within the greenhouse

Increasing air movement within a greenhouse is generally considered to be a reliable and universal method by which the uniformity of the growing environment can be improved. This project has shown that this assumption is a vast oversimplification and that achieving a uniform climate within the fan and duct greenhouse is, in fact, a big technical challenge.

Figures 12 and 13 show the average temperature recorded by each data logger between 07/01/2009 and 13/01/2009. Both compartments were colder at the wall of the greenhouse than at the central path. However, the temperature differential in the case of the fan and duct compartment was 2.3^{o}C compared to 1.5^{o}C in the conventionally heated greenhouse. Continued monitoring showed that this trend was maintained whenever the greenhouse vents were closed.

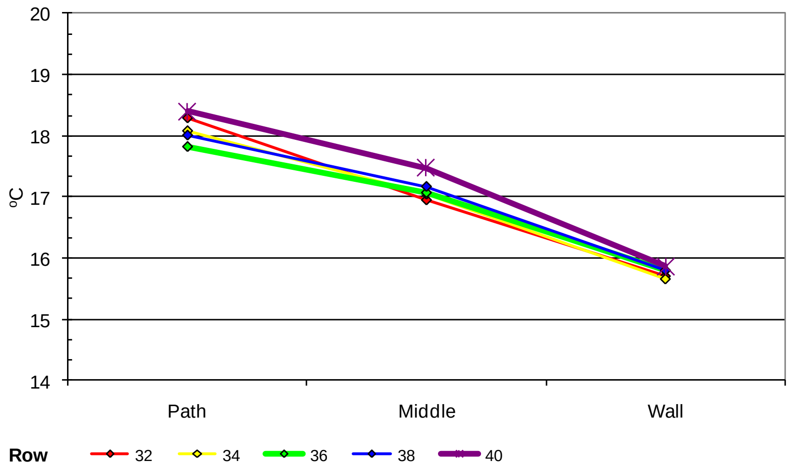

Figure 12. Fan and duct compartment (CMP12)

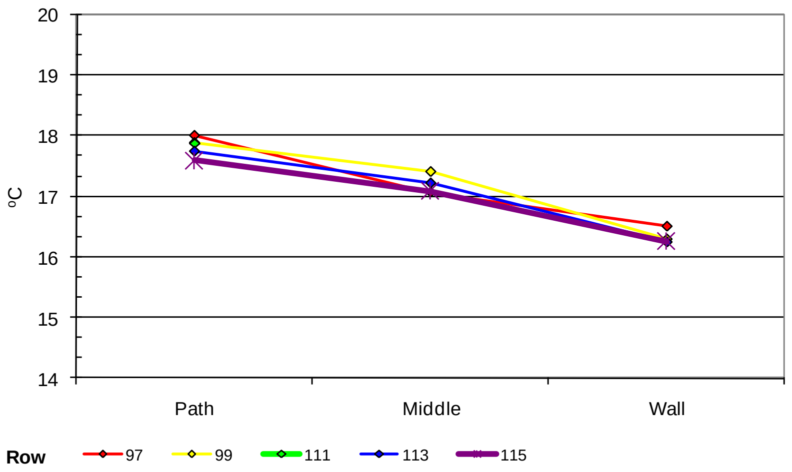

Figure 13. Conventionally heated compartment (CMP14)

Various modifications to the air distribution system were carried out and tested during 2009 (for more detail see the annual report published in April 2010). A concluding solution was finally adopted at the end of the 2009 season. However, it was only in early 2010, on the return of cold weather, that it was possible to prove that this final solution was effective.

Underlying cause of poor uniformity

Smoke tests confirmed that there were two primary air circulation patterns in the greenhouse (Figure 14).

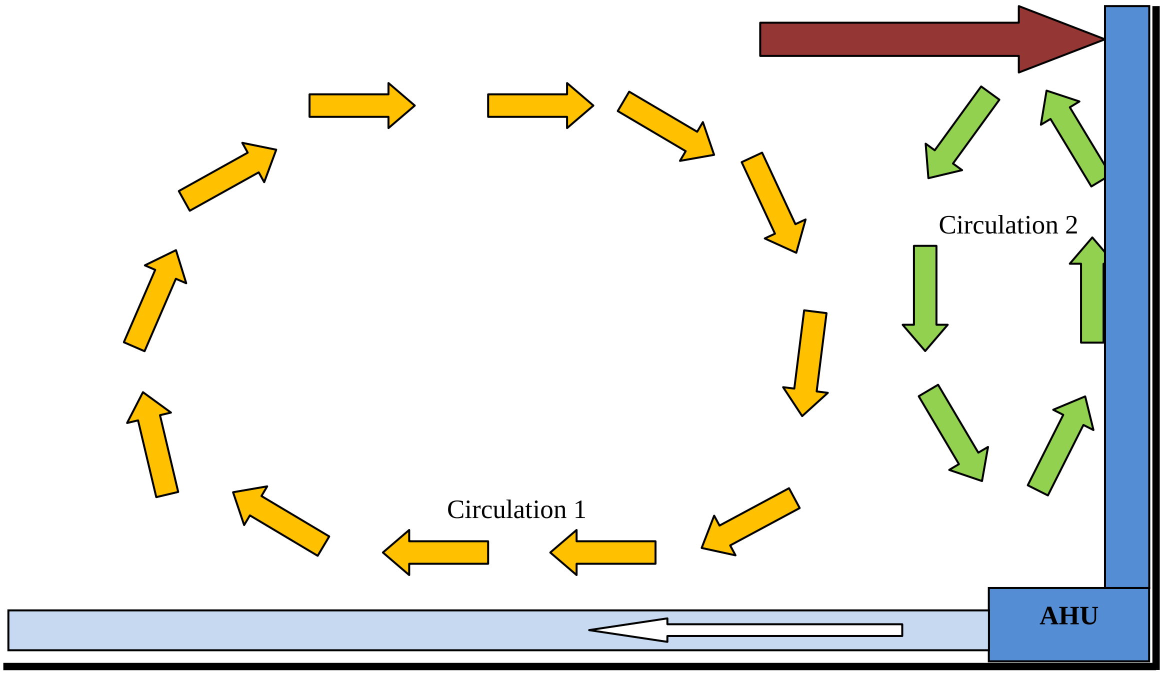

Figure 14. Original air circulation patterns

Circulation pattern 1 was established as air, exiting the duct, found its way back to the AHU. Additional momentum away from the AHU was given by the forward velocity of the air leaving the duct (Figure 15). Longitudinal circulation like this tended to promote undesirable temperature gradients along the building.

Circulation pattern 2 was established by the hot air rising from the hot water distribution pipes along the wall. Dead-zones (green triangles, Figure 15) created by the forwards motion of the air leaving the ducts were also evident.

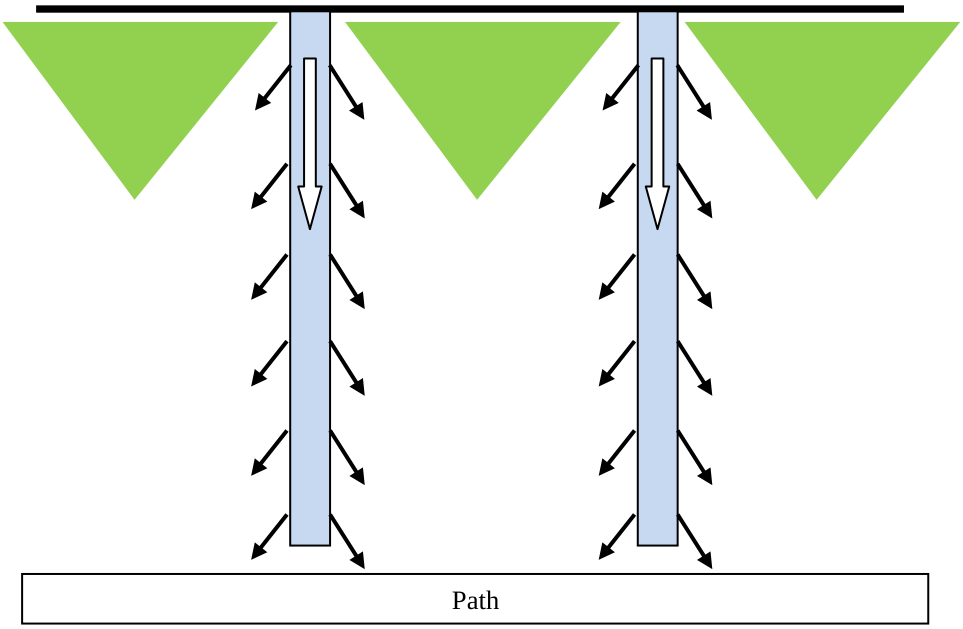

Figure 15. Plan view of airflow from the ducts

Final solution

A number of modifications were considered to reduce the effect of undesirable circulation patterns. These were:

Fitting outlet nozzles to direct air to leave the duct perpendicular to its length. The cost and complexity of this idea was deemed to be high as over 2,000 nozzles would be needed.

Fitting a second larger diameter perforated duct over the existing ducts to isolate the final air outlets from the air travelling along the inner duct. This was adopted.

Installing nozzles to blow a small amount of air back towards the wall therefore disturbing the dead zones near the wall and breaking the secondary air circulation pattern 2 (Figure 16). This was adopted.

Figure 16. Nozzle blowing air towards the greenhouse wall

Figures 17 and 18 below show the temperature uniformity measured between 11th and 26th January 2010

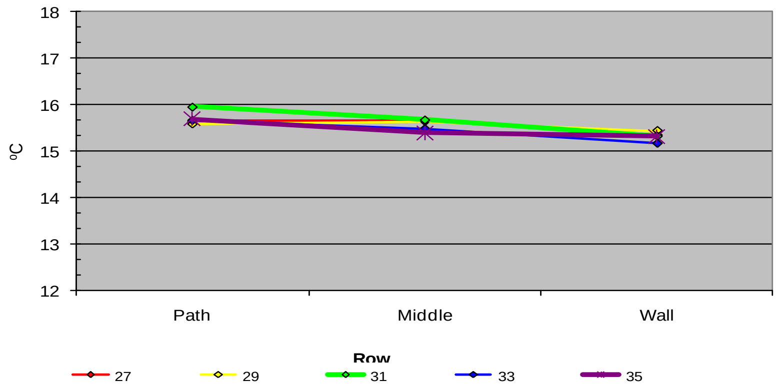

Figure 17. Fan and duct compartment (CMP12)

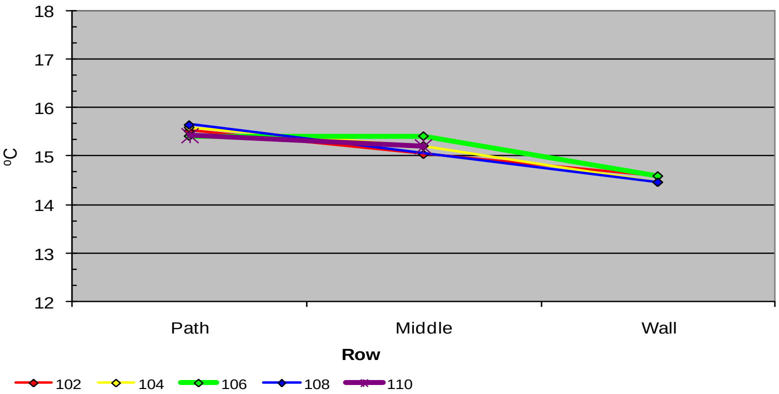

Figure 18. Conventional heated compartment (CMP14)

Uniformity of temperature in the fan and duct compartment was improved (0.4^{o}C variation) and was better than that measured in the conventional compartment (1.0^{o}C variation).

Consistency of temperature distribution over time was excellent in the conventional compartment when heat was being delivered. There were slight differences in the fan and duct compartment when heat demand was at its highest, with wall areas up to 0.4^{o}C warmer than in the middle.

During non heated periods, wall areas were up to 0.5^{o}C colder than the middle of the compartments for both treatments. Overall, these two effects cancelled each other out when considering the 24-hour average temperature.

The greenhouse environment and climate control strategy

Greenhouse environment

Climate control strategies

The underlying climate control strategies used in 2010 were similar to those used in 2009 and 2008. The greenhouse climate in each compartment was managed according to the needs of the individual crops. Clearly, there were times when the greenhouse conditions, and in particular temperatures were different in either compartment. In general, a lower humidity deficit (HD) was targeted in the compartments with fan and duct system installed.

Temperature

The grower felt that the fan and duct crop was more generative than the conventional crop for the majority of the year. Greenhouse temperature (24-hour average, day-night difference) continued to be the main tool used to manage plant development in both greenhouse compartments. During February in particular, frequent changes to set points were implemented by the grower in response to subtle changes/differences in crop development. The temperature could vary by as much as 2^{o}C between compartments albeit for periods of only a few days. From April onwards the target greenhouse temperature was the same in both compartments the majority of the time.

It was possible to apply separate heating and ventilation temperature set points to the fan and duct system, pipe rail heating and greenhouse ventilators. The basic approach taken was to use the fan and duct system as the first stage of heating:

- The pipe rail heating temperature in the fan and duct compartment was set 0.2°C lower than the fan and duct heating set point.
- The fan and duct cooling temperature was set to the same as the lee side ventilation temperature in the conventional greenhouse.
- The lee side ventilation temperature in the fan and duct compartment was set 0.5°C higher than the lee side ventilation temperature in the conventional compartment.

In addition, minimum pipe temperature set points were applied to the pipe rail heating to satisfy the base load heating demand. These were typically 30-40°C, depending on the time of year and time of day and were usually 10°C less in the fan and duct compartment.

Figure 19 shows the weekly average temperature measured at the top of the crop. This is the only temperature measured by most growers. For the sake of consistency the temperature and humidity at this point was used by the climate control computer on both greenhouses.

The effect of the combination of warm air heating, and reduced radiant heating from the pipe rail on fruit temperature was investigated in 2009. Compared to the conventional compartment, the warm air heating increased the temperature of the air around the fruit relative to the top of the crop. However, the reduction in radiant heating from the pipe rail effectively cancelled this out. The conclusion was that the air temperature at the top of the crop continued to be representative of the overall growing environment.

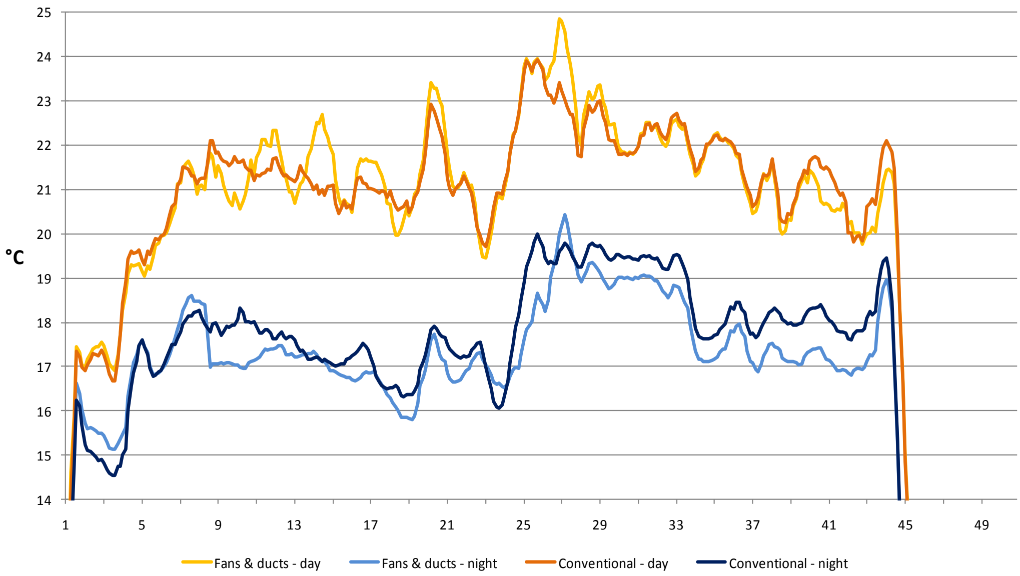

Figure 19. Weekly average temperature at the top of the crop

The greatest difference between treatments was the night time temperature. From week 9 onwards it was consistently cooler in the fan and duct compartment. Between weeks 9-12 this was due to the heating temperature set. However, during the summer months the same target temperature was used in both compartments but they were rarely achieved due to high outside temperatures. Lower energy use in the fan and duct compartment for humidity control meant that cooler temperatures were more easily achieved.

Humidity

It was possible to reduce the target HD in the fan and duct compartment, as disease risk was lower and plant activity was expected to be higher as a result of improved air movement.

As a general rule, a minimum pipe rail temperature of 30^{o}C was set in the fan and duct compartment whenever the HD was at or below target. During the night, if the HD fell below target there was no further increase in pipe temperature; any further humidity control actions were delivered using the fan and duct system. During the daytime, if the humidity deficit was less than 2.5g/m^3 the minimum pipe rail temperature was increased to 40^{o}C with any further humidity control actions carried out by the fan and duct system. In the conventional compartment, humidity influences increased the minimum pipe temperature to a maximum of 55^{o}C. These minimum pipe temperature 'limits' were increased when poor weather conditions (leading to low HD) persisted for more than two days. This was to ensure good root development/health and to reduce the likelihood of blossom end rot.

Humidity deficit

The target HD during the daytime was 3.0g/m^3 in the conventional compartment and 2.8g/m^3 in the fan and duct compartment. During the night time it was 2.5g/m^3 in the conventional compartment and 2.0g/m^3 in the fan and duct compartment. The difference between treatments during the night time is most obvious in Figure 20 especially between weeks 30-40.

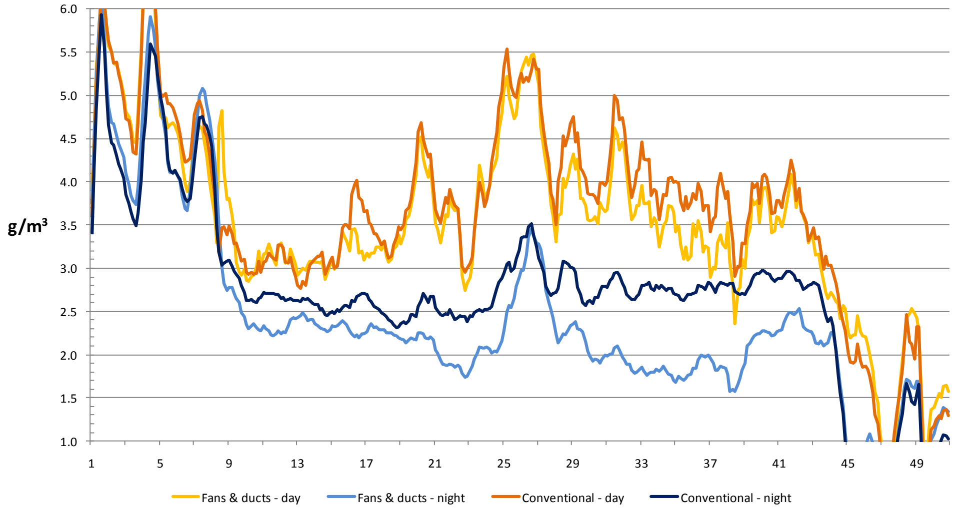

Figure 20. Weekly average humidity at the top of the crop

CO_2 enrichment

Both compartments are served by a single CO_2 enrichment system that is controlled according to the highest of the CO_2 levels measured in either of the compartments.

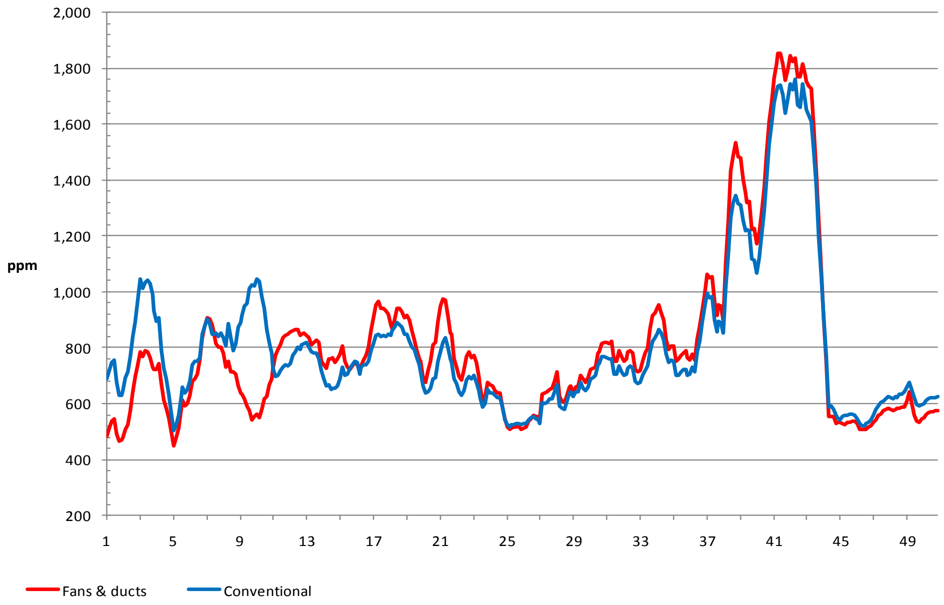

Figure 21. Daytime CO_2 concentration

Data up to week 10 are erroneous due to a fault with the Priva climate control computer. However, as there was no venting during this period it is reasonable to assume that the CO_2 concentrations were broadly the same in both compartments. As in previous years, accepting a lower humidity deficit in the fan and duct compartment led to less venting and therefore higher CO_2 levels than in the conventional compartment. Limited CO_2 availability in 2009 prevented concentrations of higher than 450ppm up to week 21. In 2010 800ppm could be achieved.

High recorded concentrations around week 42 were due to an over-supply problem with the CO_2 enrichment system.

Crop data

General crop management observations

The grower and crop consultant felt that the increased air movement from the fan and duct system resulted in better transpiration at lower HD's compared with that which would be achieved in a conventional growing environment at similar HD levels. Normally, increased transpiration is only achieved by increasing HD through greater (and more expensive) use of heat and ventilation. During the early part of the cropping year when the HD was equally good in both treatments, more generative growth took place in the fans and ducts compartment. Generally, this can be regarded as beneficial or undesirable depending on the particular stage of development of the crop. If it is felt to be undesirable, some modification of the environmental control parameters is required to "overcome" this generative effect. These modifications are no different to those used for a crop grown with a conventional heating system. They might include:

- Increasing irrigation to produce a more vegetative growth and using night watering to prevent the slab moisture content dropping too low - this should only be carried out where accurate moisture content readings are available as increased irrigation can reduce slab EC etc which can have additional undesired effects on the crop.
- Heating temperature – reducing the day night differential.

Yield

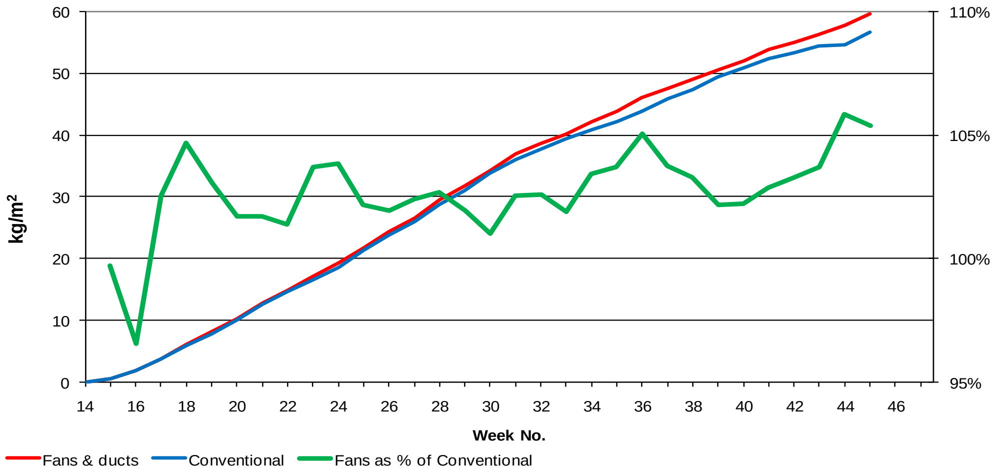

Figure 22. Total yield

Picking of the first fruit in the fan and duct compartment started 2-3 days later than in the conventional compartment. However, prior to the installation of fans and ducts the delay in this compartment was sometimes up to 7 days. Total yield was not affected by this.

Notably higher yields were evident in the fan and duct compartment from week 30 onwards. This was also seen in the 2009 season. This coincided with higher CO_2 levels in the fan and duct block.

The table below compares the final yield in 2009 and 2010:

Table 4. Yield 2009 and 2010

	2009 Total yield kg/m^2	2010 Total yield kg/m^2
Conventional compartment	48.73	56.61
Fan and duct compartment	52.41	59.63
Difference	3.68kg/m^2 (+7.6%)	3.02kg/m^2 (+5.3%)

2010 yield was higher for both treatments than those recorded in 2009. This was due to higher availability of CO_2 enrichment from the nursery's CHP installation in 2010. The reduction in the difference in yields between the two treatments in 2010 is most likely due to the wholesale increase in CO_2 levels from 2009 to 2010. As overall CO_2 levels increase the marginal improvements in yield declines from extra CO_2. With the higher overall CO_2 levels in 2010, the 'head room' for yield improvements between the two treatments was consequently less than in 2009.

Disease

The crops were assessed by Dr Tim O'Neil of ADAS UK Ltd at key stages throughout the year. A complete version of his report is included in Appendix 1. The following summarises his findings:

The effect of increased air movement using a Priva air optimiser system on tomato grey mould (*Botrytis cinerea*) was monitored in a crop of cv. Encore in Yorkshire in 2010, the third year of monitoring. It was not possible to randomise replicates, as the system used to modify the aerial environment was installed in one glasshouse only, with an equivalent area in the adjacent house.

Levels of Botrytis were much lower than in 2008 and 2009. No leaf or stem Botrytis was observed in the trial areas on 3 April or 9 July 2010. On 27 August, stem Botrytis was present at trace levels. Towards the end of the season (12 October), the incidence of botrytis symptoms had increased slightly and affected three stems per quarter row in each area. The mean number of missing or dead stem bases per quarter row was less in the house with fans and ducts (0.2) than the control house (0.5). These differences may have been due to effects on botrytis caused by:

a) A difference in the aerial environment resulting from the fans and ducts.
b) Inherent differences in the aerial environment of the two houses.
c) Differences in quality of crop work.
d) A combination of these factors.
e) An unidentified factor.

There was no difference between areas in the number of surviving heads per quarter row (29.7 and 30.5).

This result is similar to 2009 and continues to demonstrate that lower HD's and reduced energy use as a result of using the fan and duct system did not result in higher disease levels.

Energy data

Heat

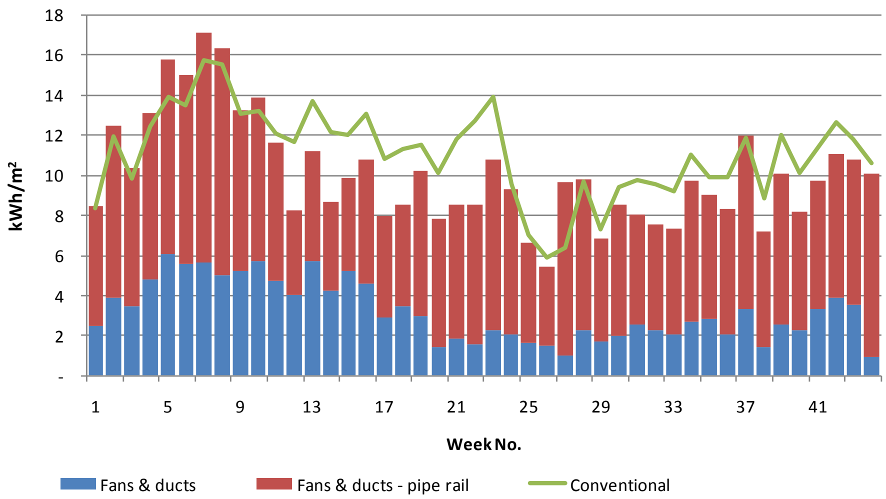

Figure 23. Weekly heat use (as boiler gas)

Up to week 10 (2010), the fan and duct compartment tended to use more heat than the conventional compartment. During this period, no venting was required for humidity control, the thermal screen set points were the same and similar greenhouse temperatures were achieved. It could be argued that increased air movement due to the fans will increase heat loss. However, the airflow delivered is relatively low and in 2009, energy use during this period was almost identical. The reason for the difference recorded in 2010 is unknown but it is not expected to be due to the fan and duct installation.

As the difference up to week 10 is not expected to be due to the fan and duct installation the figures in the table below exclude it.

Table 5. Energy usage 2009 and 2010

	2009	2010
	Total kWh/m^2	Total kWh/m^2
Conventional	458	488
Fan & duct	399	436
Saving kWh/m^2	59 (12.8%)	52 (10.7%)

The slightly lower saving in 2010 is due largely to the period between weeks 27-28 when an alternative (but unsuccessful) control strategy was used. For reference, the strategy was based around giving greater priority to the pipe rail heating with the aim of leaving more flexibility / capacity in reserve for the fan and duct system to use. Subtleties of the control software meant that the fan and duct system readily used all of the spare capacity released.

Electricity

In 2009 the fans ran continuously throughout the year whilst the temperature uniformity problem was resolved. As the amount of electricity consumed by the fans is significant, one of the specific objectives of 2010 was to reduce the amount of electricity used.

In 2010 a simple control regime was employed to reduce fan running hours when the greenhouse conditions were favourable. These conditions were typically; turn the fans off during daylight hours when the HD was >4.5g/m^3 and the lee side vents were >15% open.

The last condition was set following smoke tests which showed that, once the lee side vents were open by more than 15%, the air movement created by the fans became insignificant against the influence of air moving in/out of the vents.

Figure 24 below shows the amount of electricity used by the fans during 2010. The fans ran continuously up to week 17 after which consumption reduced due to lower running hours during a period of good weather. A turn in the weather around week 28 was followed by a steady increase in electricity consumption through to the end of the year.

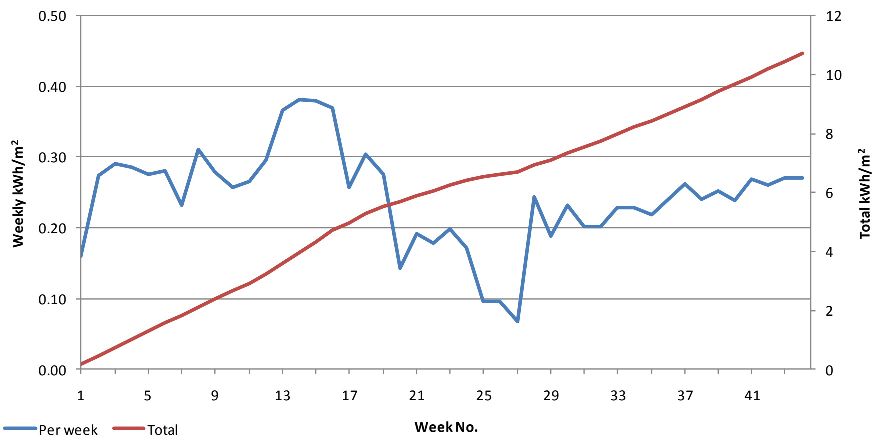

Figure 24. Electricity used by the fans

The significant increase in electricity use around week 13 was caused by replacement of the filters with a different type. The new filters allowed much higher air flow to be delivered which, due to the characteristics of the fan, meant that the power consumption increased.

The total amount of electricity consumed by the fans in 2010 was 10.7kWh/m^2. This compares to 11.0kWh/m^2 in 2009 in spite of the lower running hours in 2010. This was without doubt caused by new filters and higher airflow. Calculations show that had the same airflow as in 2009 been delivered the total amount of electricity consumed would have been 8.1kWh/m^2.

Financial

Energy

Heat

The amount of heat energy saved through the use of the fans and ducts system over the conventional system in 2010 was 44.2kWh/m^2.

The value of this saving depends on the fuel and system used for heating. At Mill Nurseries Ltd heating water comes from a CHP system. However, the majority of growers still rely on mains gas fuelled boilers. Assuming the latter, and allowing for boiler and system losses, 44.2kWh/m^2 of heat would be associated with the use of 52kWh/m^2 of gas. The value of this would depend on the cost of gas. Based on a gas price of 2.4p/ kWh (typical projected price for 2012) this would be worth £1.25/m^2.

When the 2009 annual report was written gas costs for a 12-month contract were around 1.7p/kWh (50p/therm). At the time of writing this report gas costs for a 12-month contract were around 2.4p/kWh (70p/therm). So, although the volume of gas saved was less in 2010, the financial saving was greater than in 2009 and is worth £1.25/m^2.

A major issue underpinning this need for this project was to expand the opportunities to use alternative heat sources by enabling lower temperature heating water to be used. The potential to do this was proven in 2009 and this has been reinforced by the results from 2010. The particular value of this will vary from site to site depending on available heat source and heat utilisation. Quantifying this value is complex and beyond the scope of this project, but nevertheless it is a real and tangible benefit of fan and duct systems and in many cases might itself justify the adoption of the system.

Electricity

The recorded electricity use of the fans was 10.7kWh/m^2 but a fairer future projection allowing for efficiencies realised by the filter system might be nearer 8.1kWh/m^2. At current, mains electricity prices this would cost about £0.69m^2.

This leaves a net energy cost saving of £0.56/m^2 (£0.50/m^2 in 2009).

Maintenance

Since initial teething problems were resolved in 2008, the fan and duct installation has been reliable. To date, maintenance costs have been almost exclusively associated with the fans. Three required replacement bearings which, due to their construction, were relatively easy to fit and cost around £50/fan. Two fan motors burnt out which required a re-wind costing £350 each.

The only ongoing maintenance items to date have been air filters in the air handling units. Alternative filter media have been identified which cost £1/fan unit (18 in total). Filters are replaced every six months.

Crop

A yield increase of 3.0kg/m^2 was achieved. This occurred from week 27 onwards and as such coincides with typically lower prices for the fruit. As the crop was of the loose round variety Encore, additional yield in terms of kilos will deliver additional income. The same may not be the case with tomatoes on the vine. However, if consistently overweight vines are produced, this would provide the opportunity to produce more vines by increasing the crop density or to reduce levels of CO_2 enrichment and associated energy use.

Assuming a value of £0.50/kg, the extra yield would be worth £1.50/m^2.

Capital cost

The capital cost of the installation was £15.90/m^2. It should be remembered that this technology is very much in its early adoption stage and costs are expected to come down. Since this installation was completed (March 2008) several other suppliers have brought similar products to the market. Growers who are interested in this technology are therefore advised to obtain quotes for a fan and duct installation specific to their own circumstances as significant variance is expected.

Taking the specific example discussed above, the total financial benefit (net energy saving plus yield increase) has been worth £2.06/m^2. This gives a simple payback on investment of 7.7 years.

Discussion

Temperature uniformity

Following extensive testing of a number of potential solutions the problem of poor temperature uniformity during the winter months has now been solved. The generally accepted and simplistic assumption that all air movement is beneficial is incorrect. Undesirable air circulation patterns can lead to unacceptable temperature gradients within large greenhouse and can be difficult to predict.

Energy

A similar net financial benefit was achieved in 2010 as in 2009. Further improvement is expected but, on its own, the energy saving achieved is unlikely to justify investment in a fan and duct installation unless it allows a lower cost heat source to be used.

The total air movement capacity of the installation is a key factor when considering electricity use. This is currently equal to two air changes per hour but equipment suppliers now suggest that one air change per hour is sufficient. The application of this figure would reduce the electricity consumption by 50% with, one would assume, the same level of heat energy saving. Although a reduction in capital cost might be expected, it will be relatively small with savings coming from smaller fans and heat exchangers which only represent a small part of the total cost.

Climate control / crop management

As in previous years, the same 'rules' of tomato growing were employed, so adopting this technology should not present significant crop management challenges to growers. The climate control computer software and set points associated with the fan and duct installation are complex and require considerable attention to detail. However, these are subject to continued development by the supplier (Priva).

Disease

As in 2009, there was no difference in disease levels. This suggests that we have yet to reach the energy saving limits of a crop grown with a fan and duct installation and that additional savings may be possible.

Yield

As in 2009, the fan and duct installation enabled the grower to accept lower HD's in the greenhouse. This resulted in a reduction in the requirement for ventilation and consequently, higher CO_2 levels. This is important at a time when CO_2 enrichment capacity is a limiting factor to production. This is believed to be the primary cause of the yield increase. The increase in 2010 was slightly less than in 2009 (5.3% vs. 7.6%). This is thought to be due to the generally higher CO_2 levels in 2010 and the consequently lower potential for CO_2 influenced yield increase.

General

Discussion at the project review meeting (September 2010) focussed on whether the installation of a lower cost air movement system would deliver some of the benefits achieved to date but, by virtue of its lower cost, might provide a better return on investment.

Systems which circulate greenhouse air using fans and ducts, but that have no heating or air mixing facility are available (see photograph opposite). A small number of installations of this type have been completed in the UK. However, these installations have been mostly in response to a specific problem in a greenhouse. In other cases their installation has 'been an act of faith' driven by the belief that they could deliver a better crop environment and hence better yields. At an installed cost of around £2.00/m^2, a net benefit of £0.50/m^2 (25% of that achieved to date) would make them an attractive proposition. An extension to the current project was therefore proposed to include commercial trials of this lower cost system.

Reducing the air change rate of the existing installation from 2.0 to 1.0 changes/hour to reduce electricity consumption was also discussed. This will not improve the economics sufficiently to make it viable proposition for growers with conventional heat sources. However, it was felt that the extra work required was justified as it would provide a more complete/definitive 'blueprint' for the design of such systems in the future.

Both of the above points have resulted in a project extension being approved and the project continues in 2011.

Conclusions

- Yield - the average increase achieved over 2-years attributable to the use of a fan and duct system has been 6.5% (3.4kg/m2). This is largely as a result of the achievement of higher CO_2 levels from reduced venting for humidity control.
- Disease – reducing energy use and accepting a lower humidity deficit with fans and ducts did not result in higher incidence of disease levels.
- The average heat energy saving over the 2-year project was 56kWh/m2 (11.8%) - gas.
- The lowest electricity consumption to date was 10.7kWh/m2. However, lower airflows are expected to be possible which could reduce this by 50% without reducing the heat energy saving.
- Low temperature/waste heat sources – the existing installation satisfied 95% of the total greenhouse heat demand with water that was 50oC or less compared to only 60% with a conventional heating system.
- Reliability – since early teething problems were resolved, the installation has been very reliable. Total repair costs after 3-years of operation have been £900.
- The interaction between fan-based air movement systems and natural air movement patterns in large scale commercial greenhouses is complex. Simply 'adding a few fans' can just as easily make temperature uniformity worse as make it better.
- Further investigation to reduce capital/operational costs and of lower airflow systems is required.

Technology transfer

The following technology transfer activities were carried out in 2010:

- Hampshire Isle of Wight tomato study group site visit – May 2010
- TGA Technical Committee update – June 2010
- Commercial Greenhouse Grower – July 2010
- Project Review meeting – September 2010
- Project open day – September 2010
- HDC energy News – December 2010

Glossary

Air handling unit (AHU)

The combination of fan, heat exchanger and mixing box that delivers conditioned air to the greenhouse.

Air changes per hour

The airflow delivered per hour divided by the total volume of air held within the greenhouse structure.

Combined heat and power (CHP)

Typically, a gas fuelled reciprocating engine that is used to generate electricity for local use or export to the national grid. The heat produced (engine cooling water and exhaust gases) is captured and used to heat the greenhouse.

Mixing box

A chamber, typically including two automatically controlled louvers that allow varying proportions of outside air and greenhouse air to be mixed and delivered to the greenhouse.

Heat exchanger

In relation to this project it is a means of transferring heat from the hot water supply to air that is drawn through it by the fan.

Variable speed drive (VSD)

An electronic device that allows the speed of 3-phase motors to be varied.

Humidity deficit (HD)

The amount of additional water that air is able to hold before reaching saturation. Typically measured in g/m^3.

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Appendix 1

Disease assessment carried out by Dr Tim O'Neill, ADAS UK Ltd

Summary

The effect of increased air movement using a Priva air optimiser system on tomato grey mould (*Botrytis cinerea*) was monitored in a crop of cv. Encore in Yorkshire in 2010, the third year of monitoring. It was not possible to randomise replicates as the system used to modify the aerial environment was installed in one glasshouse only, with an equivalent area in the adjacent house.

Levels of Botrytis were much lower than in 2008 and 2009. No leaf or stem Botrytis was observed in the trial areas on 3 April or 9 July 2010. On 27 August, stem Botrytis was present at trace levels. Towards the end of the season (12 October), the incidence of botrytis symptoms had increased slightly and affected three stems per quarter row in each area. The mean number of missing or dead stem bases per quarter row was less in the house with fans and ducts (0.2) than the control house (0.5). These differences may have been due to effects on botrytis caused by: a) a difference in the aerial environment resulting from the fans and ducts; b) inherent differences in the aerial environment of the two houses; c) differences in quality of crop work; d) a combination of these factors; e) an unidentified factor. There was no difference between areas in the number of surviving heads per quarter row (29.7 and 30.5).

Introduction

The use of a ducted air system suspended beneath hanging gutters is currently being examined as a method for energy saving in tomato crops through greater uniformity of air temperature and the use of lower grade heat. The objective of this study was to examine the effect of a climate management system (Priva air optimiser) which increases air movement by fans and ducts and controls air temperature and humidity, on tomato grey mould (*Botrytis cinerea*). The trial ran from planting to the end of cropping. Full details of the system are given elsewhere in this report.

In 2008, when the system was being installed and optimised, severe leaf and stem Botrytis occurred in both the crop area with the air optimiser units and in the control area (see Annual Report, April 2009). At the end of the season, the number of live heads remaining in the monitored rows was 29% fewer (i.e. Botrytis was probably greater) in the area with the air optimiser units than in the control area. In 2009, at the end of cropping the mean numbers of girdling stem Botrytis lesions and missing stem bases were less in the house with fans and ducts than the control house. After the 2009 crop the distribution of air holes along the ducts was altered in order to produce more uniform air movement along rows.

Methods

Site

Mill Nursery, Keyingham, Hull, East Yorkshire.

Crop production

Crops of tomato cv. Encore were grown on Rockwool slabs on hanging gutters. There were two propagation cubes per slab and two plants per cube. Usually each plant had two heads. No fungicides with activity against *B. cinerea* were applied to the monitored areas. Leaf trimmings were left on the floor beneath the hanging gutters. Air handling units (AHUs) were located every eighth row on both sides of the central pathway in one half of the house (compartments 11 and 12). Air was drawn in from outside the glasshouse at the ends of rows, temperature and humidity were adjusted by the climate optimiser, and the adjusted air was blown out under the crop as described above. The units were in operation continuously from week 1. Pipe heating was also used, with the maximum pipe temperature limited to 50^{o}C.

There were no climate optimiser units in the control area, compartments 13 and 14. The control area was heated by a conventional pipe heating system with a maximum pipe temperature of 80^{o}C, though this was rarely required.

Disease assessments

Crops were assessed for botrytis on 5 April, 9 July, 27 August and 12 October 2010. Plants were examined for missing stem bases (i.e. where a dead plant had been removed), missing stem tops (i.e. where a broken or dead top had been removed), botrytis stem lesions and botrytis petiole lesions. Botrytis stem lesions were assigned to one of three severity grades: limited – confined to a leaf node; spreading – extending up and down the stem; girdling – extending all the way around the stem and causing softening. Dead leaves were only considered due to botrytis when sporulating *B. cinerea* was visible on the leaf or petiole. A stem Botrytis severity index was calculated using a weighted score as follows: severity index = sum of (limited lesions x 1) + (spreading lesions x 2) + (girdling lesions x 3).

Assessments were done on five rows of crop in the area with AHUs, comprising alternate rows from one ducted row to the next ducted row (Fig 1). This resulted in assessment of two ducted rows, one row mid-way between two ducted rows, and two rows a quarter-way from the nearest ducted row. A set of rows located in the equivalent area in the adjacent glasshouse compartment, without AHUs, was also assessed. This systematic monitoring allowed examination of the effect of air management versus no air management, distance from the ducted row, distance along the row from the central path (quarter 1), and face of the row.

Botrytis levels were low and there was rarely more than one leaf or stem lesion per stem. A total maximum botrytis score was therefore calculated by summing missing stems (assuming these were removed due to Botrytis), stem tops missing or affected with botrytis, stem lesions and leaf petiole botrytis. Other diseases were noted.

At the August and October assessments, the number of surviving heads was counted. Shoots which originated below head height and were more than around 1 m long were considered as separate heads. Botrytis stem lesions were assessed on green stems only, examining both the bundle of layered stems and the upright stems.

A record of the total numbers of plants and heads removed each week was also maintained by nursery staff in the monitored areas (rows 31-45 and 101-115).

Experiment design and analysis

A randomised design was not possible because there was no replication of houses containing fans and ducts. Assuming that the crops and glasshouse environment of cv. Encore in different halves of the same house were identical except for the AHUs, different rows and parts of rows in the same house were treated as pseudo-replicates. A total of 144 plants per row were examined, comprising 72 on either face and 36 per quarter length of row. Data were examined by analysis of variance using a factorial design. There were four factors (area of crop, position of row, face of row and quadrant along the row from the central pathway) at 2, 3, 2 and 4 levels respectively.

Results and discussion

Botrytis lesions

Levels of Botrytis in the monitored areas were much lower in 2010 than in the same areas in the previous two years. Botrytis levels were also generally low in many other tomato crops in 2010.

No leaf or stem Botrytis lesions were found in the crops on 8 April or 9 July. At the third assessment, on 27 August, two stem botrytis lesions were found in the fans and ducts area and three in the control area. There were no leaves with sporulating Botrytis in the fans and ducts area and just two in the control area. Most of these were near the side wall in path 107.

At the final assessment on 12 October, there was a slightly greater number of girdling stem Botrytis lesions in the fans and ducts area (2.4 per quarter row) than in the control area (1.7 per quarter row); this difference was significant at P = 0.079 (Table 1). The incidences of limited and spreading lesions were very low, totalling 1 and 18 respectively over the two areas, and are not tabulated. There was no difference between the houses in stem Botrytis lesion severity (Table 2). There were a greater number of Botrytis leaf lesions in the fan and duct area (11) than in the control area (1), although both were extremely low. When the botrytis categories were added together (dead or missing stem base, leaf lesion, limited stem lesion, spreading stem lesion, girdling stem lesion), there were no significant differences between the two houses (Table 3). Most stem lesions appeared to originate from stubs left at de-leafing.

Table 1. Effect of a fan and duct system on the incidence of Botrytis stem girdling lesions in tomato, cv. Encore – 12 October 2010.

Factors	Number of Botrytis girdling lesions/quarter row				
	1	2	3	4	Means
Fan and duct house					
Fan row	2.5	2.0	4.3	1.3	2.5
Quarter way	2.5	1.3	1.8	2.5	2.0
Mid way	1.0	2.5	3.5	4.5	2.9
Means	2.2	1.8	3.1	2.4	2.4
Control house					
'Fan' row	0.8	1.0	2.0	2.8	1.6
Quarter way	2.0	2.3	1.3	2.3	1.9
Mid way	1.0	0.5	2.0	1.0	1.1
Means	1.3	1.4	1.7	2.2	1.7

Table 2. Effect of a fan and duct system on stem Botrytis lesion severity in tomato cv. Encore – 12 October 2010.

Factors	Mean Botrytis severity[a]/quarter row				
	1	2	3	4	Means
Fan and duct house					
Fan row	9.0	7.0	12.5	4.3	8.3
Quarter way	8.0	4.3	5.3	8.0	6.4
Mid way	3.0	7.5	11.5	13.5	8.9
Means	7.4	6.0	9.5	7.6	7.6
Control house					
'Fan' row	2.3	4.0	6.5	8.3	5.3
Quarter way	6.3	7.3	4.3	8.8	6.6
Mid way	4.0	1.5	7.0	4.0	4.1
Means	4.2	4.8	5.7	7.6	5.6

[a] Stem Botrytis severity = (limited lesions x 1) + (spreading lesions x 2) + (girdling lesion x 3); a high score indicates greater stem damage from Botrytis.

Table 3. Effect of a fan and duct system on total Botrytis in tomato, cv. Encore – 12 October 2010.

Factors	Total number of Botrytis symptom/quarter row				
	1	2	3	4	Means
Fan and duct house					
Fan row	3.3	2.5	4.3	1.5	2.9
Quarter way	3.3	2.0	1.8	3.8	2.7
Mid way	3.0	3.5	4.0	4.5	3.8
Means	3.2	2.5	3.2	3.0	3.0
Control house					
'Fan' row	0.8	2.0	3.3	3.3	2.3
Quarter way	2.8	4.0	2.5	3.3	3.1
Mid way	2.5	5.5	3.5	3.5	3.8
Means	1.9	3.5	3.0	3.3	3.0

Surviving plant heads

On 27 August there was a slight but significantly greater (P = 0.029) number of live heads in the fan and duct house (33 per quarter row) than in the control house (32 per quarter row) (Table 4). This was associated with a greater number of missing stem bases in the control house (15) than the fan and duct house (3).

By 12 October, the number of surviving heads per quarter row was slightly lower (Table 5). There was no significant effect from fan and duct system, distance from fan row, row quarter or row face on the number of surviving heads.

As in August, there were a greater number of missing or dead stem bases in the control house than in the fan and duct house.

The effects of all four factors (presence of fans, distance from fan row, face of row and quarter from main path) and two-way interactions of factors are summarised in Table 6.

Table 4. Effect of fans and ducts on number of live heads per quarter row face – 27 August 2010

Factor						
House and row	Face	Quarter from AHU				Mean
		1	2	3	4	
Fan and duct house						
Fan row	1	32	33	31	34	33
	2	36	33	34	32	34
Quarter way	1	32	33	31	36	33
	2	35	33	35	33	34
Mid Way	1	34	30	32	35	33
	2	38	33	31	33	34
Mean		35	33	32	34	33
Control house						
Fan row	1	31	31	31	36	32
	2	33	33	33	30	32
Quarter way	1	35	31	34	35	34
	2	32	30	33	32	32
Mid Way	1	25	27	32	30	29
	2	34	31	35	35	34

Mean	32	31	33	33	32

Table 5. Effect of a fan and duct system on the incidence of live heads in tomato cv. Encore – 12 October 2010.

Factors	Number of live heads per quarter row				
	1	2	3	4	Means
Fan and duct house					
Fan row	32.5	30.8	26.8	30.8	30.2
Quarter way	29.0	31.0	29.3	31.0	30.1
Mid way	29.0	25.5	27.5	30.5	28.1
Means	30.4	29.8	27.9	30.8	29.7
Control house					
'Fan' row	29.8	31.3	30.3	30.8	30.5
Quarter way	27.3	29.8	30.0	33.8	30.2
Mid way	28.0	28.0	33.0	34.5	30.9
Means	28.4	30.0	30.7	32.7	30.5

Table 6. Effect of four factors on Botrytis in tomato cv. Encore, Yorks – 12 October 2010

Factor	df	F probability				
		No. stem bases missing	No. live heads	No. Botrytis girdling lesions	No. Botrytis leaf lesions	Total Botrytis lesions
Fan (F)	1	0.022	0.365	0.079	0.002	0.926
Distance (D)	2	0.004	0.737	0.978	0.471	0.299
Face (Fa)	1	0.430	0.511	0.062	0.051	0.071
Quarter (Q)	3	0.249	0.122	0.413	0.115	0.852
F x D	2	0.195	0.446	0.305	0.655	0.707
F x Fa	1	0.009	0.925	0.296	0.011	0.039
D x Fa	2	0.758	0.033	0.790	0.918	0.569
F x Q	3	0.115	0.169	0.718	0.524	0.493
D x Q	6	0.216	0.236	0.508	0.925	0.637

Significant effects are shown in bold; three-way interactions (most were non-significant) are not listed. The direction of significant effects is detailed in Tables 2-5.

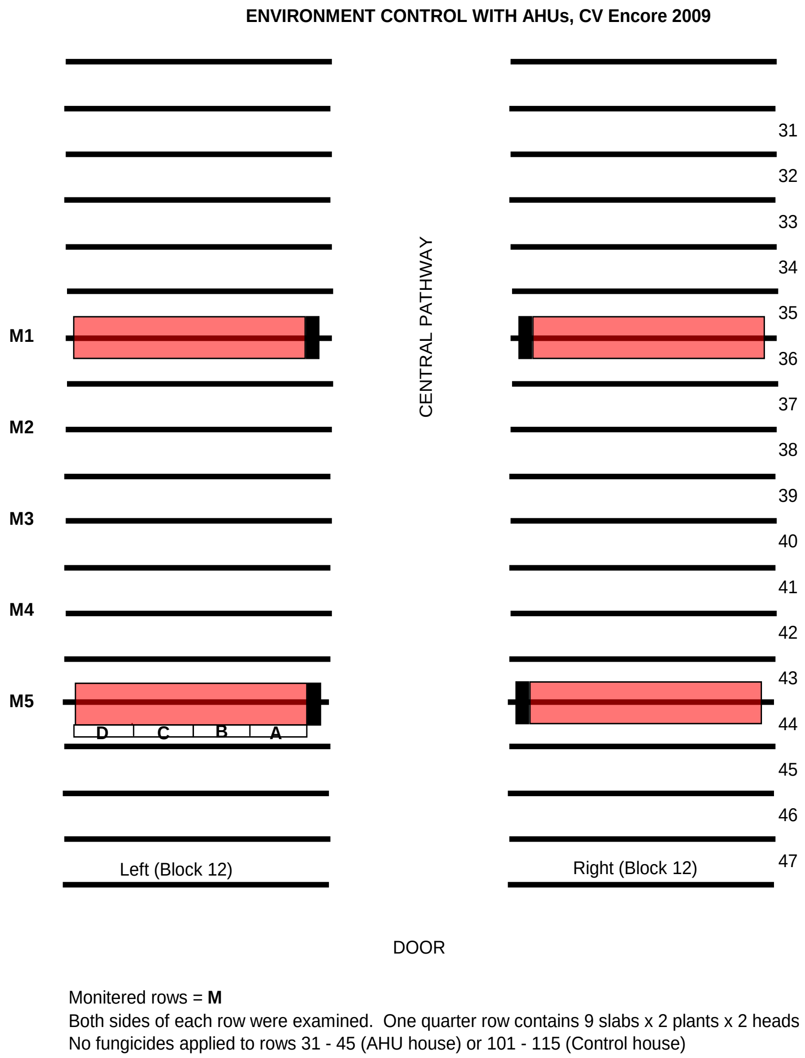

Figure 1. Detail of rows monitored for disease (M1-M5) in relation to fans and ducts