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:	Annual report, April 2009
Previous report	Interim report, September 2008
Key staff:	Jon Swain, FEC Services Ltd Chris Plackett, FEC Services Ltd Tim O'Neill, ADAS UK Ltd
Location of project:	FEC Services Ltd, Warwickshire & Mill Nursery, 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, heat exchangers, carbon dioxide

The results and conclusions in this report are based on an investigation conducted over a one-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 could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are 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

First year commercial trials of a ducted air greenhouse environmental control system have been successfully completed. Yields in the ducted air system greenhouse have been virtually identical to the control area but heating energy savings of 5% have been achieved. Disease levels have been significantly higher due largely to a range of early teething problems with the system.

Background and expected deliverables

This report summarises the findings of the first year of commercial trials of a three year project to investigate the performance of a ducted heating and ventilation system installed in a 1Ha tomato production greenhouse in the UK. The project follows on from PC 256 which examined the potential for using closed glasshouse technology in the UK. The main conclusion of this work was that the closed glasshouse concept could not be used in its entirety because of technical and financial constraints. However, the project identified that the application of one key feature of the design, the ducted air heating and ventilation system could offer significant advantages including:

- 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:

- Reduce energy use 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 comprises three parts:

1. Research, development and design of a commercially acceptable ducted air heating and ventilation system for the trial greenhouse at a commercial nursery in the UK.
2. Installation of the selected system at the trials site.
3. Commercial trials to investigate system performance and crop response.

The project is being carried out at tomato growers Mill Nursery Ltd in East Yorkshire. A previous report (PC 278 Interim report, September 2008) covers items 1 and 2. This report details the first year of commercial trials carried out in 2008.

Trial site and equipment

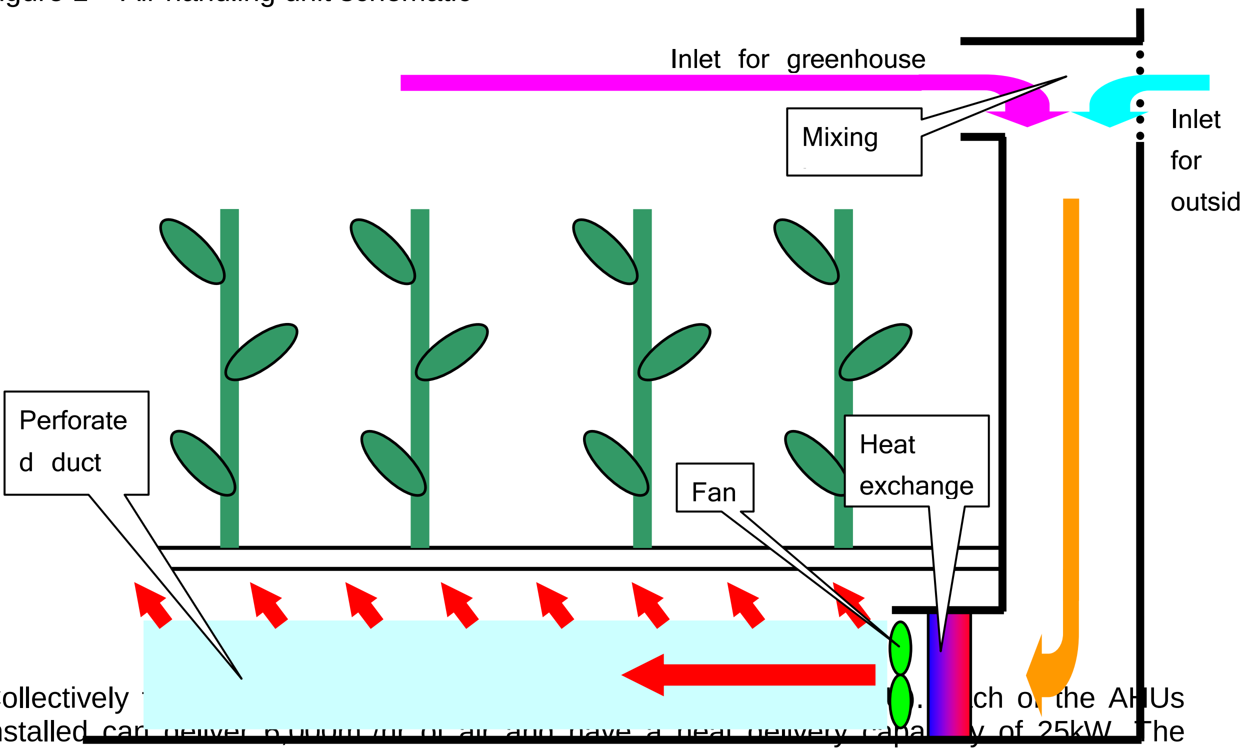
Site

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

Equipment

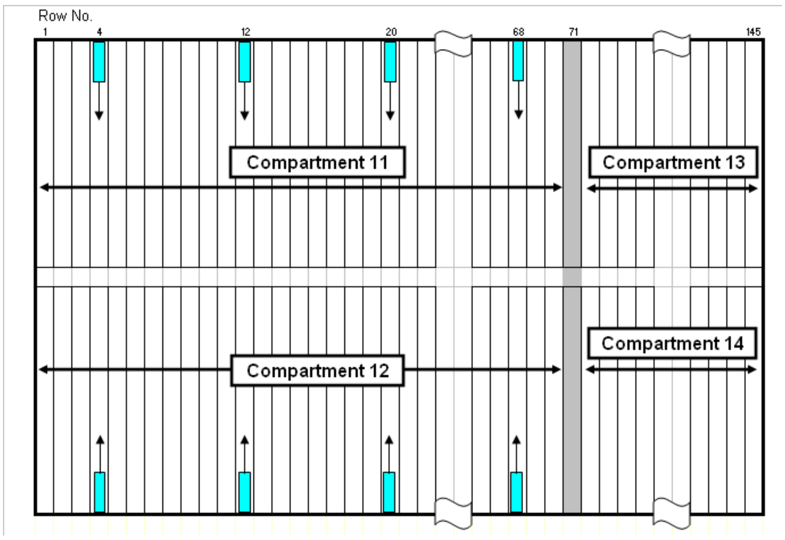
Figure 1 below is a schematic showing a single air handling unit of the type installed at Mill Nursery.

Figure 1 – Air handling unit schematic



Collectively [illegible]ch o[illegible] the AHUs installed can deliver 6,000m^3/hr of air and have a heat delivery capa[illegible]y of 25kW. The installation at Mill Nursery used 18 of these AHU's arranged as shown in Figure 2 below.

Figure 2 – AHU layout



The fan and duct installation as a whole 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 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

As this report covers the first year of three years of commercial trials in which such a radical change in greenhouse heating and ventilation technology is being investigated, few firm conclusions or findings have been reached regarding crop yield, disease levels and energy performance.

System characteristics

Specific areas investigated included:

- Airflow and heat distribution along the ducting
- Uniformity of temperature and CO_2 within the greenhouse
- Speed of response – from zero to maximum heat output

Figures 3 to 5 below show the airspeed at the outlets along the duct, the air temperature at maximum heat output and the heat distribution all with the fans running at full speed.

Figure 3 – Outlet airspeed along a duct

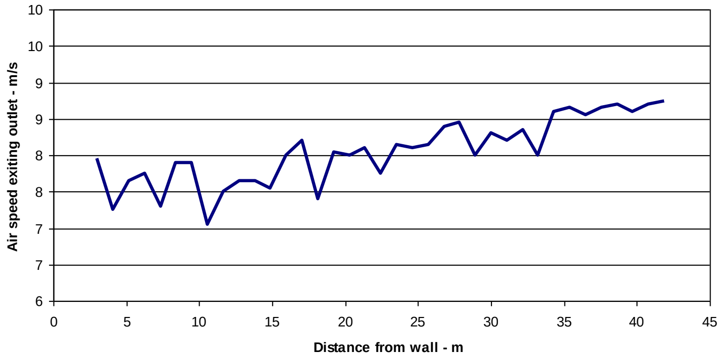


Figure 4 – Outlet air temperature along a duct

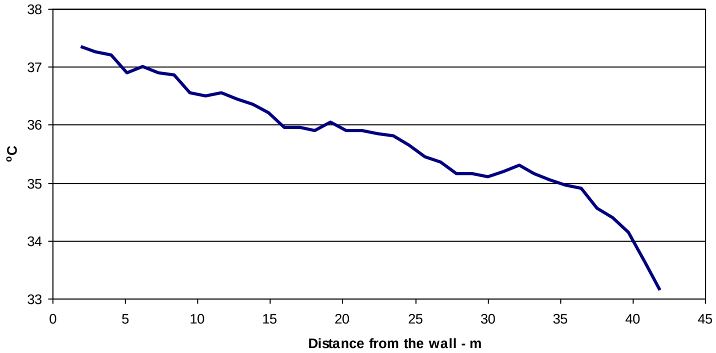
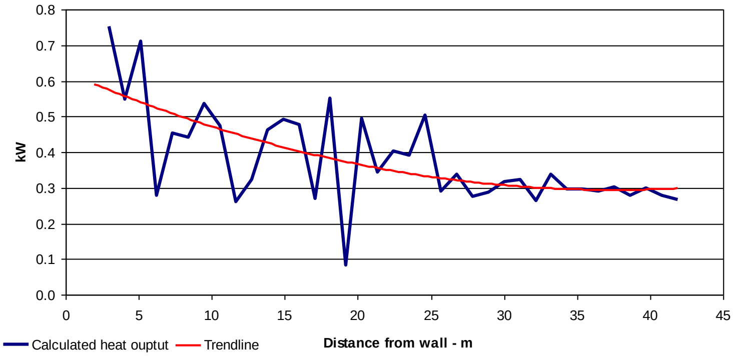


Figure 5 – Heat energy output along a duct



The significantly higher heat output close to the end wall of the greenhouse (next to the fan) is appropriate as heat losses are higher in this area compared to the middle of the greenhouse (next to the path). In spite of this temperature uniformity measurements carried out in late September 2008 showed that there was tendency for the compartment with fans and ducts to be colder at the wall. However, the difference between the coldest and hottest point was small at only 0.6°C. In the conventional compartment the wall was slightly warmer, however the difference between the coldest and hottest point was also 0.6°C.

Better air movement was expected to improve the uniformity of greenhouse temperature. Further work is required especially during the winter when the heat demand is high and differences in temperature are likely to be exaggerated.

An assessment of CO_2 uniformity showed that this was considerably worse in the fan and duct compartment. However, problems with the host nursery's CO_2 enrichment system meant that it was only possible to take a single set of measurements. As replicates of these measurements are not available their significance must be treated with caution.

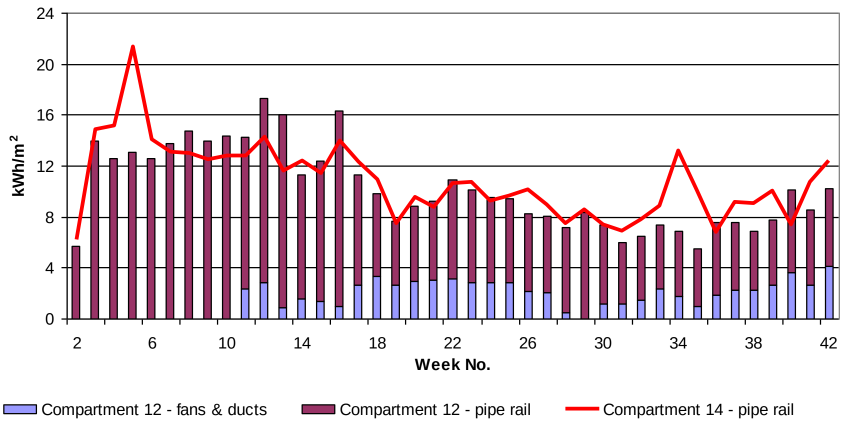
Speed of response tests showed that the fan and duct system could go from zero to maximum heat output at the farthest point of the greenhouse within 6 minutes. This is compared to 17.5 minutes for the pipe rail heating system. A high speed of response can be regarded as a benefit as it avoids having to hold residual heat in the system as 'insurance' – a common requirement with pipe rail systems.

Energy and crop data

Energy

The fan and duct installation was commissioned in week 11. The differences between the energy use in compartments 12 and 14 up to this point was due to a number of unrelated site problems. In week 5 there was a problem with the thermal screen in compartment 14 and it did not close. From week 7 to 11 there were also problems delivering sufficient heat to compartment 14. From week 30 onwards when many of the initial teething problems had been resolved energy savings of around 15% per week were achieved.

Figure 6 shows the weekly energy use in compartments 12 and 14.

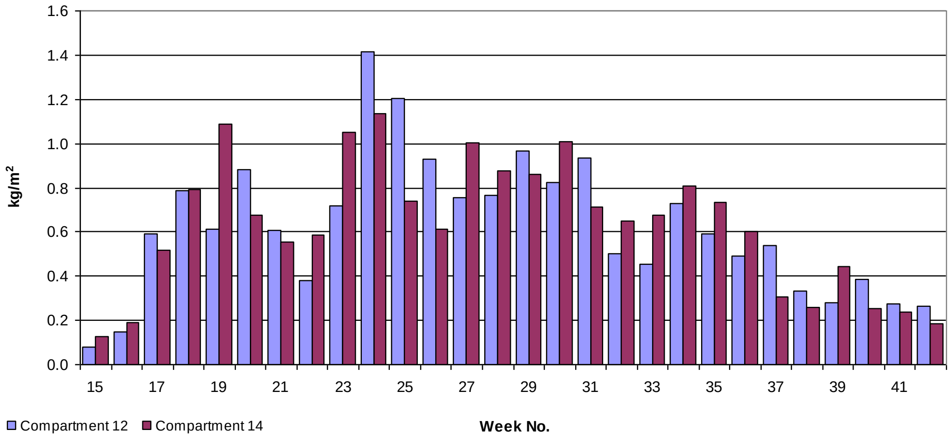


Over the whole year the total amount of heat used (as gas) in the fans and ducts compartment was 419kWh/m^2, compared with 443kWh/m^2 in the conventional compartment i.e. 24kWh/m^2 less (5%). However, the fans used 11.2kWh/m^2 which in terms of cost more than offset the saving in gas. The cost of running the fans is recognised as an important factor and as experience is gained with the system they will be turned off whenever conditions in the greenhouse allow.

Crop

The variety grown in 2008 was Piccolo. Figure 7 below shows the weekly yield from each greenhouse compartment. Up to week 23 the fan and duct compartment tended to yield less. However, this was recovered in the following weeks and the total yield for the year was only 1% less. Bearing in mind the teething problems encountered this was considered to be a good result. The lower yield early in the season was thought to be due to slower ripening of fruit and this will be monitored more closely in 2009.

Figure 7 – Weekly yield



Disease assessments carried out by Dr Tim O'Neill (ADAS UK Ltd) showed significantly higher levels of botrytis in the fan and duct compartment. Although disappointing, it was not cause for concern at this stage in the project as teething problems meant that there were prolonged periods when the fan and duct installation severely compromised the growing environment.

The greenhouse environment and climate control strategy

Temperature and humidity conditions were measured using conventional wet and dry bulb measuring boxes located at the head of the crop and 50cm above the hanging gutter. The only difference of any significance was that the humidity deficit in the fan and duct compartment was consistently lower. This was expected as humidity control set points were relaxed in this compartment in anticipation of reduced disease risk from improved air movement.

The target greenhouse temperatures were set according to the needs of the crop and not with the aim of achieving identical conditions. Having said this, plant development was similar in both compartments and therefore the set points were in fact the same throughout 2008.

It was possible to control the fan and duct installation independently of the existing pipe rail heating and greenhouse ventilators. For heating, the strategy employed throughout 2008 was to use the pipe rail heating to provide a low background level of heat whilst using the fan and duct installation to 'top up' as required. If the capacity of the fan and duct system was not sufficient, the pipe rail heating was then allowed to make up the difference. A similar approach was applied for both humidity control and cooling.

Achieving satisfactory control of the greenhouse climate with the fan and duct system proved to be a challenge throughout 2008. This was due in part to the complexity of the control system and other unforeseen conditions. One significant fault was that the control system allowed unheated outside air to be blown in through the ducts and this is believed to have caused condensation in the lower part of the crop. This last point has since been rectified by the addition of a minimum duct air temperature set point.

Financial benefits

At such an early stage in the project it is not possible to draw any conclusions regarding the financial viability of ducted air systems for glasshouse environmental control. However, the fact that there was no yield penalty at this early stage in the project suggests that where a low cost waste heat source is available, the economics of fan and duct based heating systems may be favourable.

Conclusions and action points

Many factors have to be considered when designing and operating a fan and duct greenhouse environmental control system. It is much more complex than a traditional pipe rail heating system. At this stage in the project there are no simple recommendations that are both widely applicable to UK growers and that can be readily adopted.

This project continues into 2010 and growers are advised to await further results which will be publicised via normal HDC communication channels.

Science Section

Introduction

High energy costs and greater awareness of climate change issues continue to threaten the viability of glasshouse horticultural production in the UK. As a result growers are constantly looking for methods to both reduce their dependence on fossil fuels and increase production relative to the energy used. Growers in the Netherlands are subject to similar pressures and one of the outcomes of this has been extensive Dutch research and development into closed glasshouse systems. PC 256 (2007) investigated the potential for using closed glasshouse technology in the UK and concluded that the application of closed glasshouse concepts as a whole was not technically or financially viable. However, the project identified that ducted air heating and ventilation systems that are widely used in closed glasshouses may offer considerable benefits if applied to conventional glasshouses.

It is widely accepted that improved air movement in glasshouses will improve the performance of a range of crops. PC 226 (2005) reviewed the existing information on air movement systems for glasshouses and recommended that approaches similar to those applied in this project should be investigated. The grounds for this recommendation went as far back as PC 47 (1994). There was little doubt that ducted air environmental control systems had the potential to deliver a range of benefits to the glasshouse sector. Therefore the need to develop and test such a system on a commercial scale in the UK was viewed to be a high priority and, as a result, this project was commissioned.

Objectives

The overall aims of the project are to:

- Reduce energy use and cost 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.

The specific objectives for 2008 following equipment installation were to:

- Measure the system performance – specifically, airflow and heat distribution.
- Determine the uniformity of greenhouse environment – temperature, CO_2.
- Modify / fine tune system design if necessary.
- Understand its operation and control.
- Gain an appreciation of the climate created and its impact on plant development.

Materials and methods

The project comprises three parts:

1. Research, development and design of a commercially acceptable ducted air heating and ventilation system for the trial greenhouse at a commercial nursery in the UK.
2. Installation of the selected system at the trial site.
3. Commercial trials to investigate system performance and crop response.

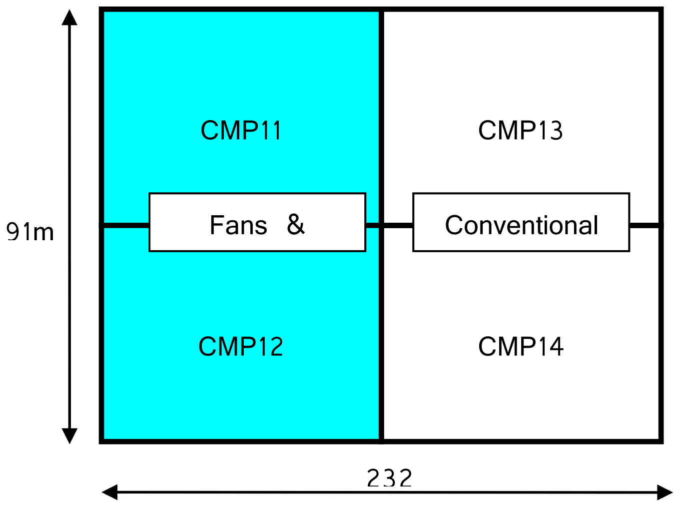
A previous report (PC 278 Interim report, September 2008) covers items 1 and 2. This report details the first year of commercial trials carried out in 2008.

Trial site and equipment

Site/greenhouse

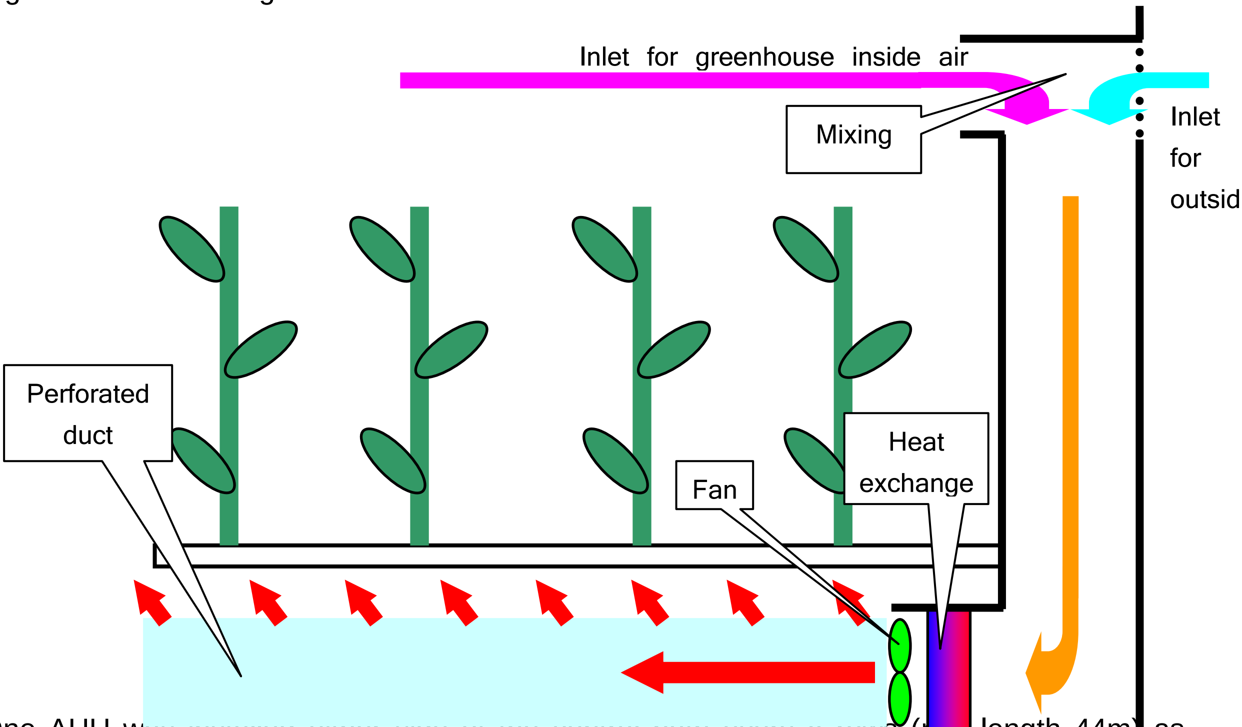
The project is being carried out in a 2.1Ha greenhouse at Mill Nursery Ltd in East Yorkshire. A fan and duct system was installed in one half of the greenhouse in March 2008 and is being compared with the other half of the greenhouse which has a conventional heating and ventilation system. A temporary partition was installed to create two separate airspaces as shown in Figure 8 below. The combined area of compartments 11 and 12 is 10,286m^2 and 11,094m^2 in compartments 13 and 14. Where appropriate, data in this and all other reports is presented as per m^2 or per Ha to take account of this small difference in the compartment areas. The greenhouse height is 5m to the gutter. Each of the four compartments has independent control of the heating, ventilation, thermal screens and irrigation. The thermal screen material is Ludvig Svensson SLS10 Ultra Plus with a 1 in 15 void strip. A Priva Integro climate computer is used to control all aspects of the growing environment on the nursery and was upgraded as part of this project to accommodate the addition of the fan and duct system.

Figure 8 – Layout and dimensions of the trial greenhouse



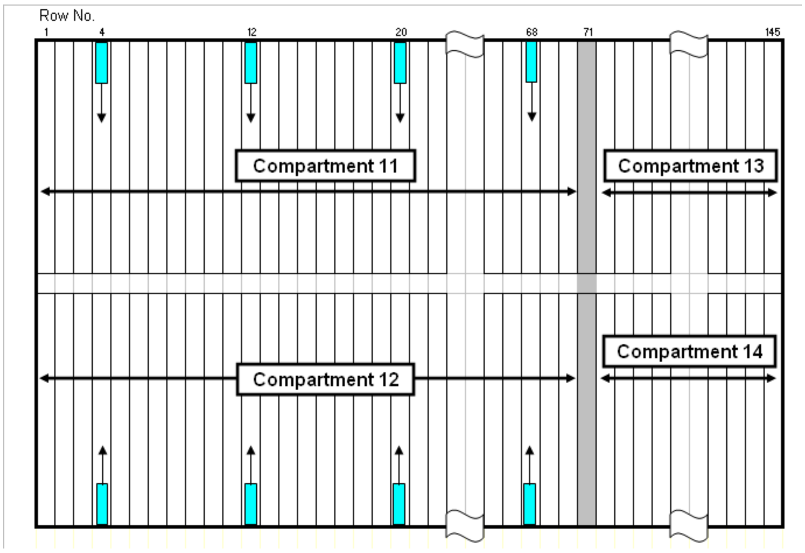
Equipment
The installation comprises 18 air handling units (AHU). Figure 9 below shows a single air handling unit of the type installed at Mill Nursery.

Figure 9 – Air handling unit schematic



One AHU was installed either side of the central path every 8 rows (row length 44m) as shown in Figure 10 below.

Figure 10 – AHU layout



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.

Greater detail describing the design of the installation and the design criteria that were considered is provided in a previous 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 1 below lists the measurements taken in each compartment.

Table 1 – Greenhouse environment measurements

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

General greenhouse equipment status

- 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.

Irrigation

The water uptake by the plants in compartments 12 and 14 was calculated using grow-scale and drain measuring equipment combined with the Priva Integro which controls the irrigation system.

Energy use

Heat

Heat use was measured using a non invasive ultrasonic flow meter connected to a heat meter integrator. In this and subsequent reports the heat used was converted into an equivalent amount of gas by assuming a boiler efficiency of 85%.

In CMP12 the heat used by the pipe rail heating system and the fan and duct installation was separately metered. Only a single heat meter was required in CMP14 to measure the heat used by the pipe rail system.

Electricity

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

Data specific to the fan and duct installation

The following data was also recorded, primarily to aid development of the control system:

- Outside air temperature and absolute humidity
- Greenhouse – outside air mixing ratio
- Temperature and relative humidity of the air entering the duct

Crop data

Crop registration data formed the basis for numerical comparison of the development of the plants in each compartment. Measurements were taken every week by nursery staff and returned to FEC for analysis. The measurements taken included:

- Stem diameter
- Weekly and total growth
- Number of leaves per plant and leaf length
- Number of trusses formed and harvested
- Distance of the youngest truss from the growing point

Yield was recorded as the total kilos of fruit harvested each week in compartments 11 and 12 for comparison with the yield from compartments 13 and 14.
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 - carried out by Dr Tim O'Neill, ADAS UK Ltd.

Results

System characteristics

Airflow and temperature distribution along a duct

To gain a more complete understanding of the characteristics of the fan and duct installation the airspeed and temperature of the air were measured in a range of defined operating conditions. These included:

- Fan speed – 100%, 80% and 60%
- No air mixing (outside air) and vents open to ensure stable airflow
- Maximum design heat output (50°C heating water) to highlight any potential effects

A single duct was approximately 42m long, 0.45m diameter and had 40mm diameter holes equally spaced along its length (0.54m apart). The airspeed shown in Figure 11 below shows the variation in airflow delivered into the greenhouse along the length of the duct. Clearly the slower the speed of the fan, the lower the total airflow delivered by it and therefore the airspeed at each hole along the duct is also lower. However, changing the speed of the fan from 100% to 60% had little effect on the distribution of air along the length of the duct. At each fan speed the air speed was relatively constant for the first 15m and then increased by 10-15% over the remaining 25m with the highest air speed always being at the end of the duct farthest from the fan and end wall of the greenhouse. This may seem illogical however engineering theory shows that it is correct.

Figure 11 – Outlet airspeed along a duct

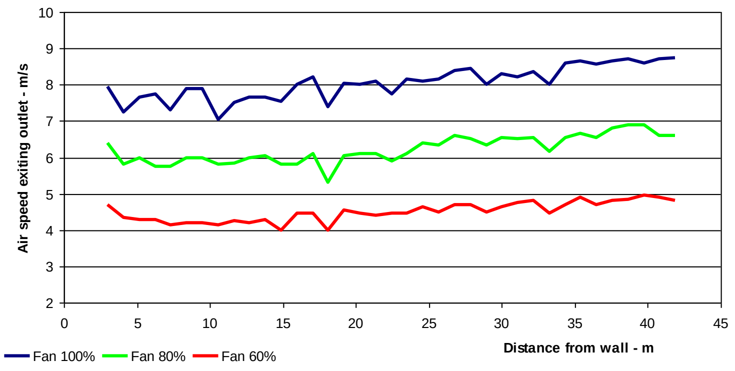
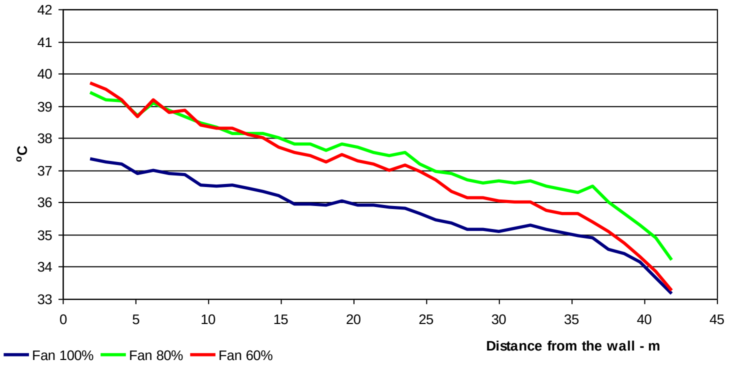


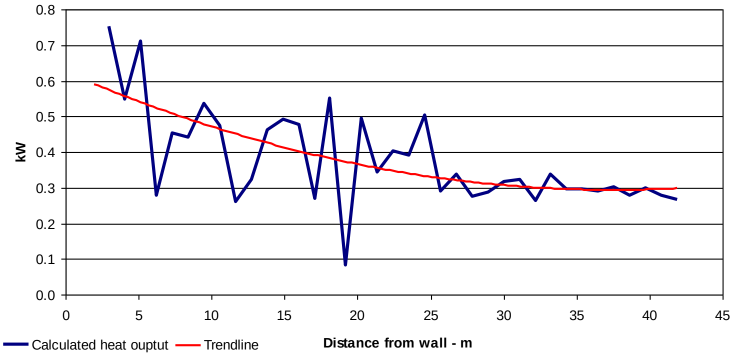
Figure 12 below shows the temperature of the air leaving the holes in the duct. At each step down in fan speed, the temperature of the air leaving the air handling unit could be expected to increase. This is not shown clearly in Figure 12 due to changes in the greenhouse temperature during the period when the measurements were carried out. The general trend in outlet air temperature is similar for all fan speeds. The temperature falls almost linearly for the first 30-35m of duct due to heat loss through the wall of the duct. However, the rate of decrease in temperature over the last 5m of duct is significantly higher than for the first 35m. This pattern is consistently the case, regardless of the fan speed. This can be explained by considering the air speed within the duct. Towards the end of the duct the majority of the air has exited the outlets leaving a relatively low airspeed within the duct. The air within the duct therefore has a relatively long residence time at this point and so the heat loss from the wall of the duct has a much greater effect compared to the start of the duct where the air is moving much faster.

Figure 12 – Outlet air temperature along a duct



Combining the airflow and temperature of the air from each duct outlet with the temperature of the greenhouse allowed the amount of heat delivered along the length of the duct to be calculated. Figure 13 overleaf shows the heat output along a duct with the fan running at full speed. There appears to be a significant amount of variability in measured heat output. This is due to the sensitivity of the calculation to relatively small measurement errors. However, there is a clear trend towards higher heat output closest to the fan (greenhouse wall).

Figure 13 – Heat output along a duct (fan speed 100%)



Speed of response

One of the expected benefits of a fan and duct heating system was its ability to change output much more quickly than a traditional pipe rail heating system. To test this, a step increase in heating water temperature was set on each heating system. The time from the first movement of the mixing valve to the point at which a stable return water temperature was measured at the farthest air handling unit and pipe rail loop was recorded.

This showed that the fan and duct system delivered the step increase in heat output to the whole greenhouse compartment within 6 minutes whereas it took 17.5 minutes for the pipe rail system to stabilise.

Uniformity of greenhouse temperature

Fifteen data loggers were installed in compartment 12 (fan and duct) and a further fifteen in compartment 14 (conventional) at a height of approximately 30cm above the hanging gutter. They were placed half way along each compartment in a grid pattern to enable any variation in temperature both across and along rows to be identified. The data loggers were set to record every fifteen minutes. Figures 14 and 15 below show the average temperature recorded by each data logger during September 2008.

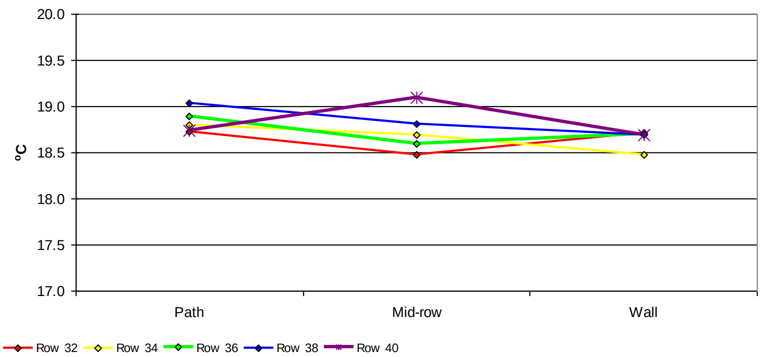
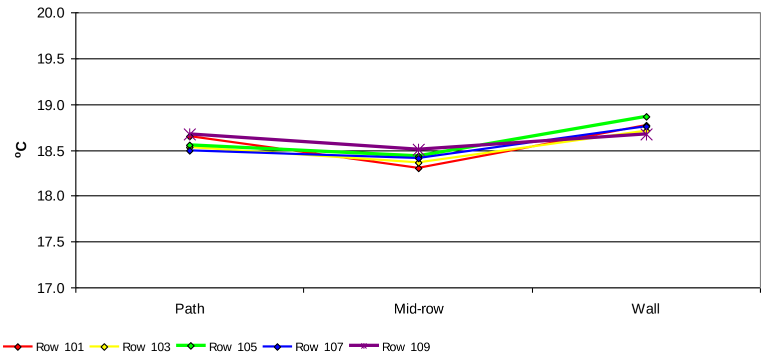


Figure 14 – Temperature uniformity in compartment 12

Figure 15 – Temperature uniformity in compartment 14



The temperature uniformity in the conventional compartment was very good as demonstrated by the tightness of the lines in Figure 15. Although there was greater row to row variation in compartment 12, the variation in temperature (maximum – minimum) was the same as in compartment 14 (0.6°C). As a starting point this is considered to be good when compared to ducted air heating systems used in the past, where temperature variation of several degrees was the norm.

However, even with the heat output of the duct being highest at the wall end this area was still consistently the coldest area in compartment 12. Better air movement was also expected to improve the uniformity of greenhouse temperature but this was not evident. Further work is required to refine heat distribution and air movement especially during the winter when the heat demand is high and differences in temperature are likely to be exaggerated.

Uniformity of CO_2 within the greenhouse

A hand held CO_2 meter was used to measure the CO_2 concentration on a grid pattern within compartments 12 and 14. The sampling point was 50cm directly above the hanging gutter close to the leaf line. To ensure the best possible comparison the following procedure was followed:

- Greenhouse vents in all compartments were closed during the test period.
- Once 1,000ppm was reached the CO_2 enrichment system was turned off and remained off during the test period.
- The fan and duct system was set to recirculate greenhouse air and not use any outside air.

It should also be noted that a single CO_2 enrichment system supplied compartments 11 to 14.

The concentration of CO_2 within each greenhouse compartment was also measured using electronic CO_2 sensors connected to the nursery's climate control computer. This allowed the gradual reduction in CO_2 levels during the test period to be recorded. The CO_2 measurements taken manually were then corrected to take account of the natural decline that occurred. The results are shown in Figures 16 and 17 below.

Figure 16 – CO_2 uniformity in CMP12 (fans & ducts)

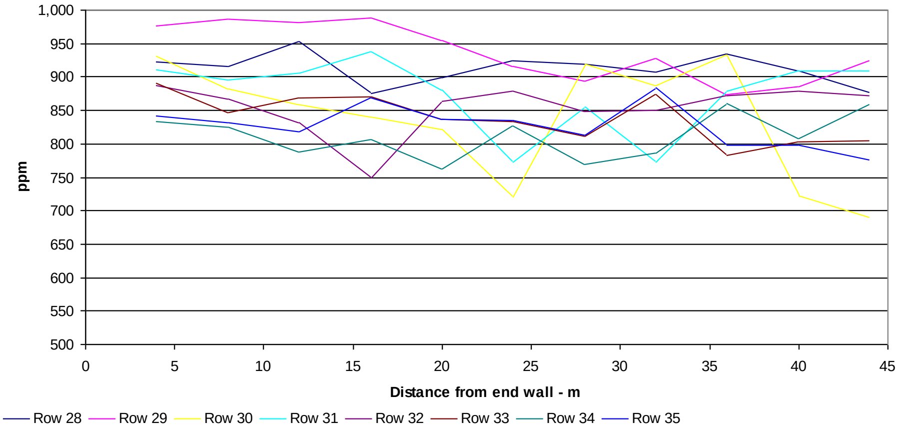
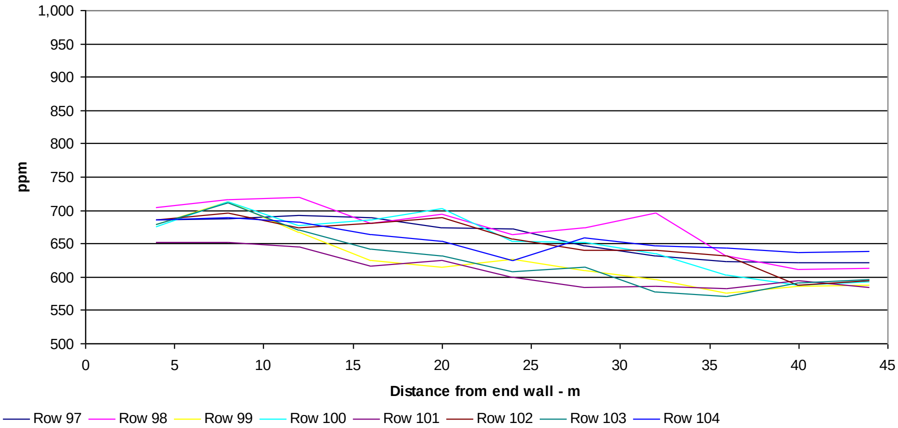


Figure 17 – CO_2 uniformity in CMP14 (conventional)



First impressions from Figures 16 and 17 suggest that the uniformity of CO_2 distribution within the fan and duct compartment is significantly worse than in the conventional compartment. However, these represent the results of a single set of measurements. These measurements were started in the fan and duct compartment first, followed by measurements in the conventional compartment. This would have given the CO_2 in the conventional compartment more time to disperse before assessment. Due to persistent problems with the CO_2 enrichment system at the host nursery it was only possible to complete one set of measurements. It was therefore not possible to repeat these measurements and reverse the order of assessment to identify whether this had an influence on the uniformity measured.

Mechanical reliability

There were a number of mechanical failures shortly after the fan and duct installation was commissioned.

Louvers

Gears within a number of the louvers broke within the first 6 weeks following installation. As a result all of the louvers were replaced. A gear on one of the replacement louvers cracked later in the year and was replaced but this appears to have been an isolated incident.

Fan / variable speed drive failure

Two weeks after the installation was commissioned one fan motor failed. This was believed to have caused the failure of a variable speed drive. Both were replaced.

Following the repair of these faults the mechanical reliability of the installation was good.

Energy and crop data

It should be noted that 2008 was the first cropping year of a three year project; where the focus was to test, refine and where necessary modify the installation to ensure that it delivered the best growing environment. There were prolonged periods when the installation did not perform as required and as such no long term conclusions can be drawn from the following energy, plant and disease data. At best it gives an indication of the range of data being collected and the occasional indication of future performance.

Energy

Heat

The fan and duct system was commissioned in week 11. The lack of a consistent relationship between the energy use in compartments 12 and 14 up to this point was due to a number of site related factors. For example in week 5 there was a problem with the thermal screen in compartment 14 which prevented it from closing. From week 7 to 11 there were also problems in delivering sufficient heat to compartment 14. In weeks 28-29 the commissioning of a major control software upgrade prevented heat being used by the fan and duct system.

Figure 18 - Weekly energy use in compartments 12 and 14.

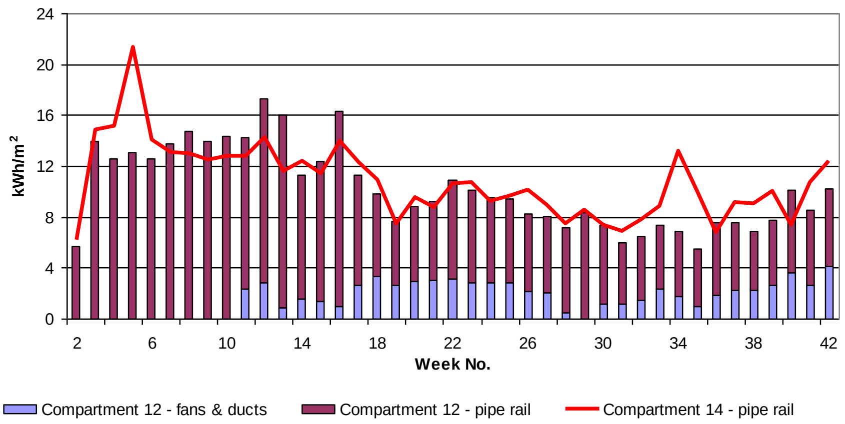


Figure 19 below shows the total amount of heat energy used in compartment 12 as a percentage of compartment 14. In general, following the software upgrade in week 27, compartment 12 used 15% less heat per week than compartment 14.

Figure 19 – Weekly energy use; compartment 12 as a % of compartment 14

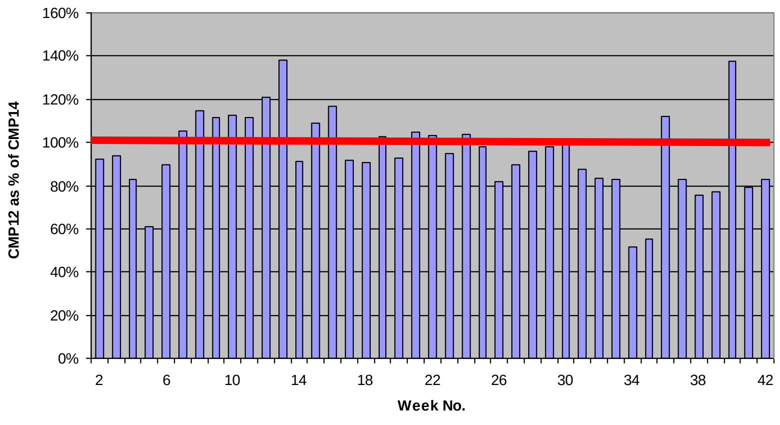
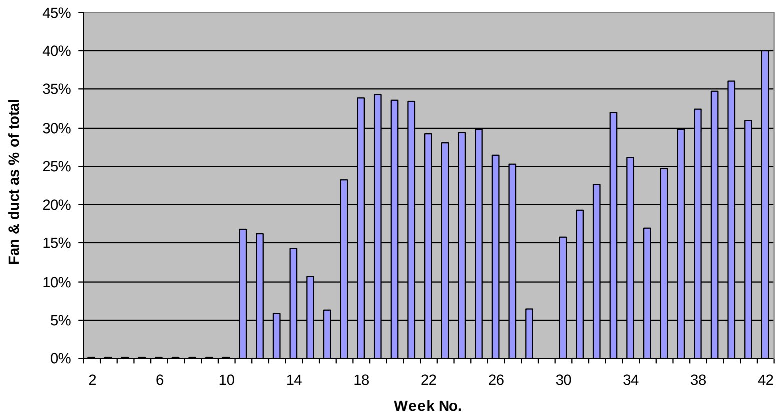


Figure 20 below shows the amount of heat delivered by the fan and duct installation as a percentage of the total amount of heat used in compartment 12. This is affected by both the heating capacity of the fan and duct installation and the way in which it is controlled. During the summer weeks when energy use was dominated by the need for humidity control the fan and duct installation was responsible for around 30% of the heat used.

Figure 20 – Fan and duct energy use as a % of the total heat used.



Over the whole year the total amount of heat used (as gas) in compartment 12 (fans and ducts) was 419kWh/m^2. Compared with 443kWh/m^2 in compartment 14, this is 24kWh/m^2 less (5%).

Electricity

The cost of running the fans is a major consideration and could easily offset any heat energy saving. However, at this early stage in the project the decision was taken to run the fans all the time to ensure that the greenhouse climate was not compromised. It may be that this can be reduced in subsequent years when more is known about the effect of airflow on the greenhouse environment.

One positive finding was that although the rated power consumption of the fans was equal to 39 kW/Ha they only used 18 kW/Ha. This was clearly a significant saving compared to what was expected. Over the whole of 2008 the fans used 11.2 kWh/m^2 of electricity. This figure could be higher in the future as the system was only commissioned in late March, part way through the season. However refinement in control may reduce the fan speeds and energy use in the future.

Crop data

Table 2 below provides basic information about the crop grown in 2008.

Table 2 – Basic crop information

		Additional notes
Variety	Piccolo	Grafted onto Beaufort
Sowing date	Week 50, 2007	
Delivery date	Week 1, 2008	
Initial density	2 heads/m^2	
Final density	4 heads/m^2	On the first side-shoot

Crop registration data

In general, the crop registration data showed few strong trends to suggest any significant difference in the way that the plants developed in each treatment. This was confirmed by the grower's own visual observations.

One area that tied in with the weekly yield data was the total number of trusses set and the number of trusses on the plant at any point in time (see Figures 21 and 22 below). This showed that the total number of trusses set by the crops in each treatment were almost identical. However, the number of trusses on a plant was consistently higher in compartment 12 between weeks 17 to 22. During this same period the weekly yield from compartment 12 was initially lower than compartment 14 and then higher as the number of trusses on a plant became similar once again. The only explanation for this was that the ripening speed of the fruit was slower during the first part of this period.

Figure 21 – Total number of trusses set

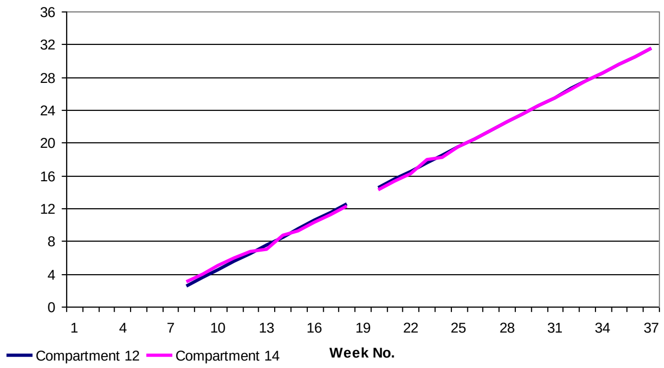
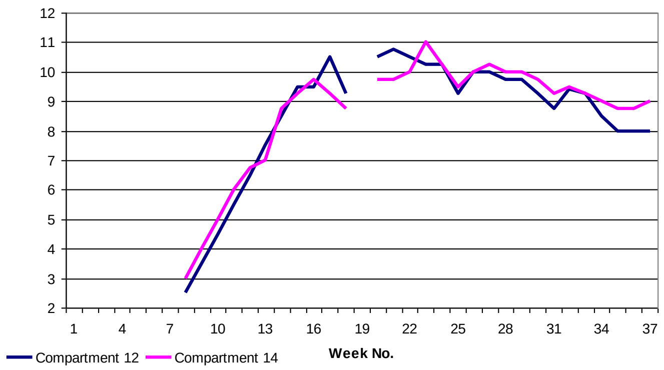


Figure 22 – Total number of trusses on a plant



Yield

Over the whole year the yield from compartment 12 was 1% less than that from compartment 14. Bearing in mind that this was the first year of commercial trials and that there were several, prolonged periods when the fan and duct installation severely compromised the growing environment, this was considered to be a positive result. The total yield in both compartments was much lower than might be expected for this variety; this was due to relatively low levels of CO_2 enrichment throughout the year. As both compartments were supplied by a single CO_2 enrichment system they were affected equally.

Early in the year (week 17 to 23) there was some concern over the yield being achieved in compartment 12 as it was consistently lower by a significant margin. However, as explained in the earlier section on crop registration data this appears to have been caused by slow fruit ripening during this period.

Figure 23 – Weekly yield

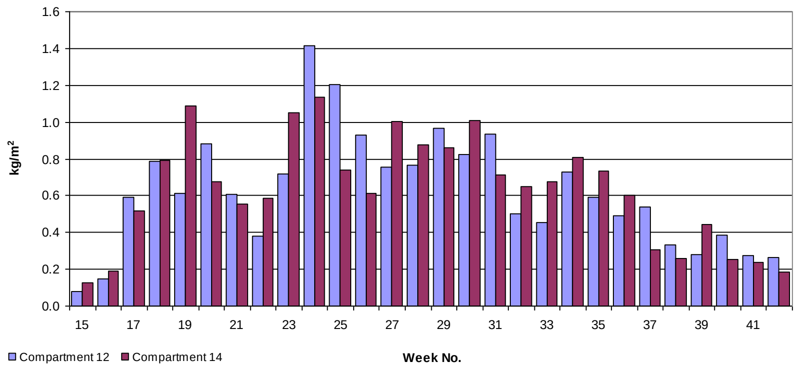
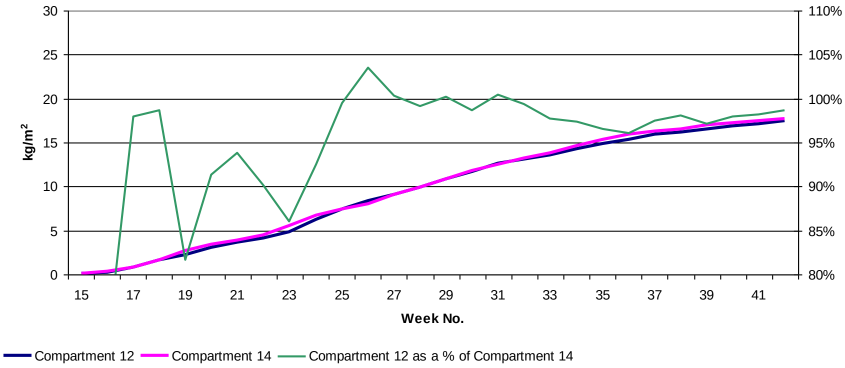


Figure 24 – Cumulative yield



Disease

The following is a summary of a report on disease levels in compartments 12 and 14 assessed by Dr Tim O'Neil of ADAS UK Ltd. A full copy of his report is included in Appendix 2.

No botrytis was observed in the trial areas on 4th March. By early July, low levels of leaf and stem botrytis and obvious powdery mildew occurred in the crop, both more commonly in the area with the fan and duct system. Leaf and stem botrytis at this time was significantly greater in the area with the fan and duct system (5.4 stem or petiole lesions/128 plants) than in the area without the system (0.4 stem or leaf lesions/128 plants). By early October, there was a significant fan x row position interaction effect on the number of live heads remaining. The number of live heads was greatest in the area without fans and ducts (86%) and differed little between rows. The number of live heads was less in the area with fans and ducts (62% overall), with least (47%) in the row midway between ducts. Nursery records of the total numbers of plants removed between weeks 11 and 38 also showed a greater incidence of plant death in the area with fans and ducts (422 plants from 15 rows) than in the control area (136 plants from 15 rows). In the compartment with the fans and ducts, there was some evidence of reduced botrytis stem lesion incidence and severity on plants close to the fan compared with those distant from the fan.

As previously discussed, there were several, prolonged periods when the fan and duct installation severely compromised the growing environment. These were due to both the mechanical failure of equipment and limitations with regard to the control software. Collectively these were not resolved until around week 30. Consequently, there were periods when the humidity in compartment 12 was significantly worse than in compartment 14 and other times when cold, unheated air was blown into the greenhouse. Although not observed on the plants, the latter coincided with condensation forming on the outside surface of the duct.

The greenhouse environment and climate control strategy

Greenhouse environment

Figures 25 and 26 overleaf show the temperature recorded by the climate control computer at the top and bottom of the crop in each greenhouse compartment. Of particular interest was any difference between each compartment in this respect. However, no difference is apparent in the Figures 25 and 26 below.

Figure 25 – Compartment 12 temperatures

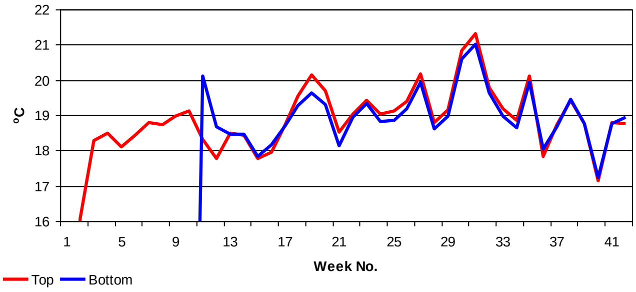


Figure 26 – Compartment 14 temperatures

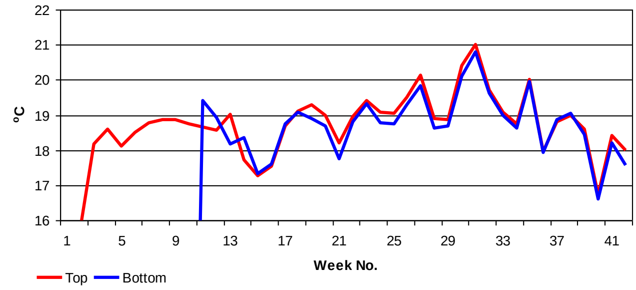


Figure 27 below compares the temperature in the lower part of the crop in each compartment. It was postulated that a lower temperature in the fan and duct area could have been the reason for the lower yield in weeks 17 to 23 by causing a delay in fruit ripening. However, Figure 27 shows that it was slightly warmer in compartment 12 during this period. A possible explanation of this contradiction may be that during the early part of the year the fruit ripens more slowly and therefore tends to be at a similar height to the hanging gutter. As a result the fruit would have been almost directly in the path of air exiting the duct which is sometimes quite cold. The only sure way to determine any such effect is to measure the fruit temperature and this will be done in 2009.

Figure 27 – Bottom of crop temperatures

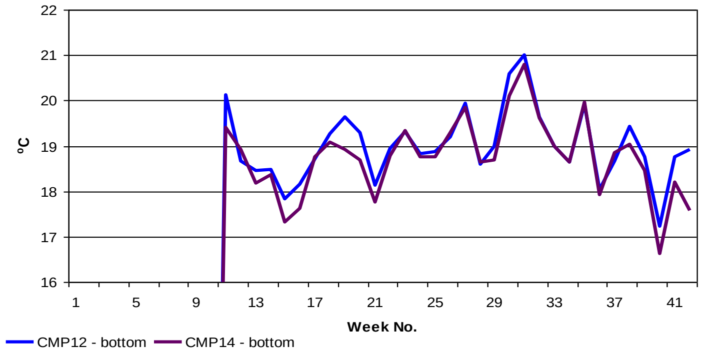
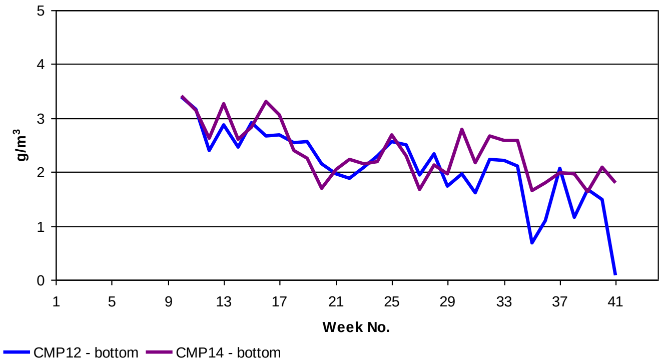


Figure 28 below shows the weekly average night time humidity deficit measured 50cm above the hanging gutter. This is when the humidity conditions are generally most likely to lead to disease development. For most of the time the humidity deficit in compartment 12 was lower than in compartment 14.

Figure 28 – Night time bottom of crop humidity deficit



Control strategy

Temperature strategies

From the point of view of managing plant development the same target greenhouse temperatures were set throughout the year as the plants in each compartment developed in a similar way. It should be noted that this decision was driven by the needs of the plants, not a desire to deliver identical greenhouse conditions. The target greenhouse environment was always dictated by the needs of the plants. If necessary, in the future, different growing strategies may be adopted to optimise plant performance.

It was possible to apply separate heating and ventilation set points for the fan and duct installation, pipe rail heating and greenhouse ventilators. In general:

- The fan and duct heating temperature in CMP11 and CMP12 was the same as the pipe rail heating temperature in CMP13 and CMP14
- The pipe rail heating temperature in CMP11 and CMP12 was 0.2^{o}C lower than the fan and duct heating set point.
- The fan and duct cooling temperature in CMP11 and CMP12 was the same as the lee side ventilation temperature in CMP13 and CMP14.
- The lee side ventilation temperature in CMP11 and CMP12 was set 0.5^{o}C higher than the lee side ventilation temperature in CMP13 and CMP14

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^{o}C depending on the time of year and time of day. The pipe rail water temperature only rose above the minimum set points if the fan and duct was at maximum heat output (50^{o}C) and unable to maintain the required greenhouse temperature.

Humidity strategies

Table 3 below shows the target humidity deficits that applied throughout the year.

Table 3 – Target humidity deficit

	Compartment 12 (fan & ducts)	Compartment 14 (conventional)
Day	3.0	3.5
Night	2.2	2.5

The target HD in compartment 12 was lower due to the reduced disease risk and increased plant activity expected as a result of improved air movement.

A balanced approach to humidity control was taken similar to that applied to temperature. As a general rule, a minimum pipe rail temperature of 30^{o}C was set whenever the humidity was at or below the target humidity deficit. During the night time any further humidity control requirements were left to the fan and duct system i.e. there was no further increase in minimum pipe rail temperature. 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.

At a ‘tier 1’ level, humidity control set points for the fan and duct installation were relatively simple. It was possible to set a target humidity deficit for different times of the day in the same way that heating set points are applied. The control software then decided the ratio of greenhouse to outside air and how much heat was required to achieve satisfactory humidity control.

In practice the outcome was often unsatisfactory, requiring constant attention to ‘tier 2’ and ‘tier 3’ set points. The original control software allowed cold, unheated outside air to be introduced via the ducts. Although not proven by direct measurement, this was thought to have contributed to the slower fruit ripening by chilling the low hanging fruit and to higher disease levels by chilling stems and making condensation on them more likely. The software upgrade installed in week 29 solved this specific problem by adding the ability to set a minimum duct air temperature.

Economics

At such an early stage in the project it is not possible to draw any conclusions regarding the financial viability of ducted air systems for glasshouse environmental control. However, the fact that there was no yield penalty at this early stage in the project suggests that where a low cost waste heat source is available the economics of fan and duct based heating systems may be favourable.

Discussion

Following some initial problems with the mechanical side of the fan and duct installation reliability was good. However, some questions remain over the design of the ducts with particular reference to the uniformity of temperature and CO_2 within the greenhouse. Temperature uniformity measurements taken in late September – early October showed that there was little difference between the trial compartments. This was disappointing as improved uniformity was expected. It should also be noted that similar tests have yet to be carried out during periods of consistently high heat demand. This will be done at the start of 2009. Due to ongoing problems with the nursery’s CO_2 enrichment system it was only possible to carry out a single set of CO_2 uniformity measurements. These showed that uniformity was worse in the compartment with the fan and duct installation. However, with such a limited dataset firm conclusions cannot yet be drawn from this. As with temperature uniformity, additional measurements are required in 2009 to confirm any effect.

Towards the second half of 2008 energy use data showed heat savings of around 15% per week. This was of the magnitude expected / targeted in the original project proposal and was therefore encouraging. Overall though, the compartment with fans and ducts used 5% less heat than the conventional compartment. However electricity used by the fans (11.2kWh/m^2) more than offset the heat saving in terms of cost and CO_2 emissions. It was encouraging to see that the heat energy used in the conventional compartment (443kWh/m^2 gas) compares favourably with industry best practice. Therefore any savings achieved by using the fan and duct system were genuine and not simply the result of poor energy performance within the conventional compartment.

Although disappointing, the higher disease levels in the fan and duct compartment were understandable due to the various teething problems through a large part of the year. It was encouraging that, despite all the problems encountered, the yield in the two compartments was almost identical. The lower yield early in the season, thought to be due to slower ripening of fruit, requires further investigation to identify the cause.

Overall a number of significant challenges remain before we can focus on fine tuning the fan and duct system and thereby learn how to optimise plant performance. These are:

- To determine the uniformity of greenhouse temperature delivered in winter operation and if necessary modify the installation to deliver a satisfactory result.
- To work with Priva to develop a control system that delivers satisfactory climate control.

We expect the latter to be a continuous process throughout the project as we learn more about the effect of the fan and duct installation on the crop and therefore what we need to control. For example the need for a maximum and minimum duct humidity set point has already been discussed.

Conclusions

Many factors have to be considered when designing and operating a fan and duct greenhouse environmental control system. It is much more complex than a traditional pipe rail heating system. This project continues into 2010 and growers are advised to await further results from this project that will be publicised via normal HDC communication channels such as HDC News.

It is unwise at this stage to try to draw firm conclusions from this first year of trials. Teething problems and the ‘pain’ from having to go though the steep learning curve for everybody involved in the project has clearly detracted from obtaining optimum performance. It is hoped that as experience is gathered then more definite recommendations can be made on the design, operation and suitability of such systems.

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 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 though it by the fan.
Variable speed drive (VSD)	An electronic device that allows the speed of 3-phase motors to be varied.

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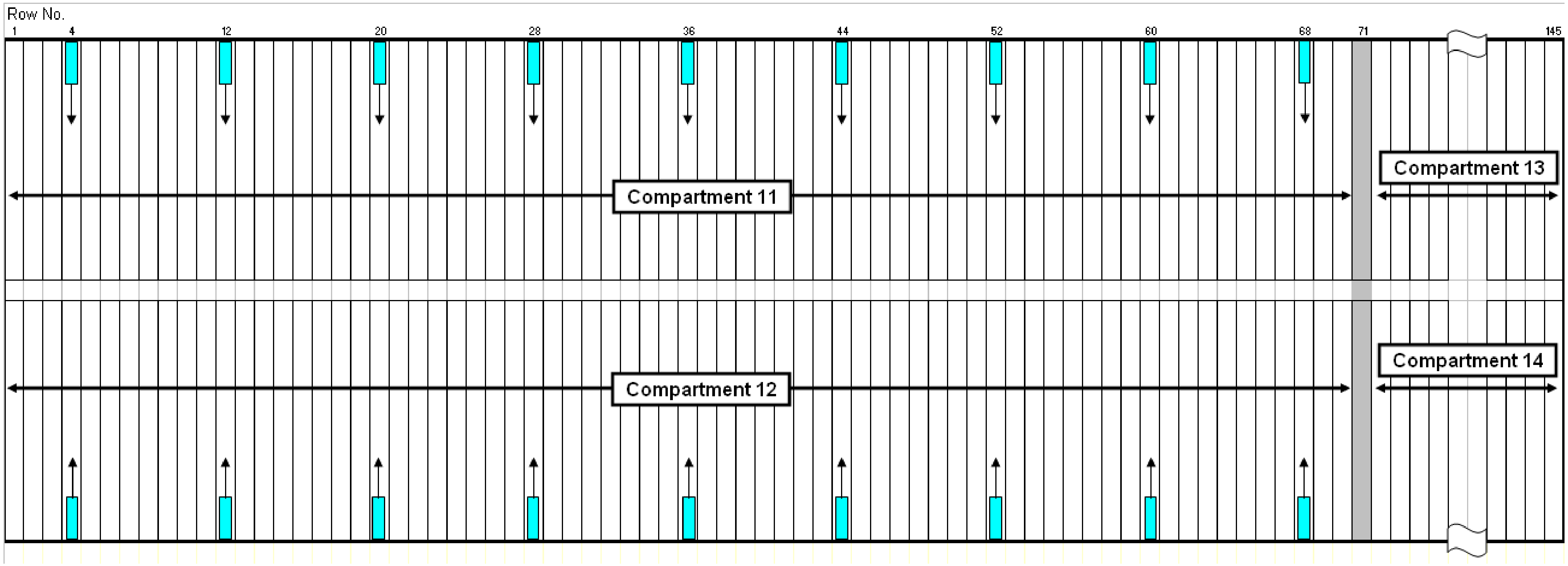
Pratt T. (2008). The development and commercial demonstration of ducted air systems for glasshouse environmental control. Interim Report of HDC Project PC 278.

Appendix 1

Greenhouse & AHU layout



Appendix 2

Effect of assisted air movement and climate control using fans and ducts on grey mould (*Botrytis cinerea*) in protected tomato – 2008 (PC 278)

Summary

The effect of increased air movement using fans and ducts on tomato grey mould (*Botrytis cinerea*) was monitored in a crop of tomato cv. Encore in Yorkshire in 2008. In a separate glasshouse at the same site, the effect of a Priva air optimiser system using air handling units (AHUs) was monitored in a crop of cv. Piccolo. It was not possible to randomise replicates as the two systems used to modify the aerial environment were each installed in one glasshouse only, with untreated control areas in the adjacent compartments; observed differences in levels of botrytis may therefore have been due to inherent differences between compartments rather than the effect of the fans and ducts systems.

No botrytis was evident in the trial areas of cv. Encore on 4 March. By early July, severe leaf and stem botrytis had developed in the trial. The use of fans and ducts had no significant effect on levels of the disease at this time, although there appeared to be greater levels in the area with ducted fan ventilation. The fans were switched off on 1 September. By early October, stem botrytis had resulted in widespread plant death. The number of surviving heads was slightly but significantly greater in the area with fans and ducts (26%) than in the corresponding control area (20%).

No botrytis was observed in the trial areas of cv. Piccolo on 4 March. By early July, low levels of leaf and stem botrytis and obvious powdery mildew occurred in the crop, both more commonly in the area with the air optimiser system. Leaf and stem botrytis at this time was significantly greater in the area with the air optimiser system (5.4 stem or petiole lesions/128 plants) than in the area without the system (0.4 stem or leaf lesions/128 plants). By early October, there was a significant fan x row position interaction effect on the number of live heads remaining. The number of live heads was greatest in the area without AHUs (86%) and differed little between rows. The number of live heads was less in the area with AHUs (62% overall), with least (47%) in the row midway between AHUs. Nursery records of the cumulative numbers of plants removed between weeks 11 and 38 also showed a greater incidence of plant death in the area with AHUs (422 plants from 15 rows) than in the control area (136 plants from 15 rows). In the compartment with the AHUs, there was some evidence of reduced botrytis stem lesion incidence and severity on plants close to the fan compared with those distant from the fan.

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 objectives of this study were to examine the effect of a ducted air system which increases air movement within a glasshouse, and a climate management system (Priva air optimiser) which additionally controls air temperature and humidity, on tomato grey mould (*Botrytis cinerea*). Full details of the two systems are given elsewhere in this report.

Methods

<u>Crop production</u>

Crops of tomato cvs Encore and Piccolo were grown in separate glasshouses on rockwool slabs on handing gutters in 2008. 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 except for Switch (cyprodinil + fludioxonil) to rows 11-30 of the control area of cv. Encore on 4 March (applied in error), and to all the monitored rows of cv. Encore on 10 July (due to visible botrytis development). Thiovit Jet (sulphur) was applied for control of powdery mildew in cv. Piccolo on 29 May, 28 June and 20 September. Leaf trimmings were left on the floor beneath the hanging gutters.

In the crop of cv. Encore, ducts and fans were located beneath every tenth row on one side of the central pathway. Air was drawn in from the central pathway by the fans and blown out horizontally beneath the crop from 4 cm diameter holes positioned at regular intervals along both lateral sides of the ducts. The fans were in operation continuously from March to 1 September. There were no fans and ducts on the other side of the central pathway.

In the crop of cv. Piccolo, climate optimiser units 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 12 (mid-March). 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 areas of the Piccolo crop and both areas of the Encore crop were heated by a conventional pipe heating system with a maximum pipe temperature of 65^{o}C.

Disease assessments

Crops were assessed for botrytis on 4 March, 4 July and 13 October 2008. 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 severity index was calculated by summing the number of lesions using a weighted score: limited (x 1), spreading (x 2) and girdling (x 3).

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

In the crop of cv. Encore, assessments were done on six rows of crop in the area with assisted air movement and on the six equivalent rows on the opposite side of the main pathway, where fans and ducts were not present (control area). The rows assessed were two rows with fans and ducts below, two rows mid-way between ducted rows and two rows close to a ducted row, in July, and just fan rows and mid-fan rows in October.

In the crop of cv. Piccolo, assessments were done on five rows of crop in the area with air handling units (AHUs), comprising alternate rows from one ducted row to the next ducted row. 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. An equivalent set of rows in the adjacent glasshouse compartment, without AHUs, was also assessed.

For both cvs. Encore and Piccolo, assessments were done in order to examine the effect of air management versus no air management, distance from the ducted row, distance along the row from the end where air was drawn in (quarter 1), and face of the row (North or South).

At the October assessment, in cv. Encore, only the number of surviving heads was counted due to the high incidence of plant death in the monitored area of crop. In cv. Piccolo, the number of surviving heads was calculated by deducting dead and missing plants (x 2 heads per plant), wilting heads and heads with botrytis at the top from the theoretical maximum number of heads in an area. 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 of the Piccolo crop (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 or climate optimiser units. Assuming that the glasshouse environment and crops of cv. Encore on opposite sides of the main pathway were identical except for the presence or absence of fans, and that the crops and glasshouse environment of cv. Piccolo in different halves of the same house were identical except for the air optimiser units, different rows and parts of rows in the same house were treated as pseudo-replicates. A total of 128 plants per row were examined, comprising 64 on either face and 32 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 fan) at 2, 3, 2 and 4 levels respectively.

Results and discussion

No botrytis was found on either cultivar at the first assessment in March. By 4 July, botrytis lesions were evident in both crops, and were more common in cv. Encore than cv. Piccolo. The nursery heating system malfunctioned in June resulting in sub-optimal heating in both crops. Development of leaf botrytis was noted soon after by nursery staff. Botrytis stem lesions appeared to originate primarily from leaf petiole lesions. The occurrence of botrytis in the monitored areas of cv. Encore was reported to have been exacerbated by the use of inexperienced crop workers in this area which probably resulted in greater crop damage.

One application of the botrytis fungicide Switch (cyprodinil + fludioxonil) was applied on 4 March to rows 11-25 on the no-fan (control) area of cv. Encore by mistake. A second application of Switch was made to all the monitored area of cv. Encore on 10 July due to the high level of botrytis in the crop.

Other diseases noted in the crops were powdery mildew and root mat. Powdery mildew was obvious in both areas of cv. Piccolo. At the July assessment it was causing leaf death and at the October assessment some plants were severely affected and wilting, possibly due to the mildew. Powdery mildew was present at trace levels only in cv. Encore. Root mat occurred at a very low incidence and slight severity.

Effect of assisted air movement using fans and ducts (cv. Encore)

In July, there was no evidence that the use of fans and ducts significantly affected the incidence of missing plants, dead stem tops, botrytis stem lesions, or botrytis petiole lesions (Table 1) or stem lesion severity or total botrytis incidence (data not shown). When additional rows close to the fan row, all unsprayed with botrytis fungicides, were included in an analysis (Table 2), there appeared to be a greater incidence of botrytis stem and leaf petiole lesions in the fans area than the control area, but this was not statistically significant at p=0.05. An examination of the effects of distance from the ducted row, distance along the row, and row face, indicated no statistically significant effects on stem lesions, total botrytis, or other symptoms (data not presented).

In October, the mean number of surviving heads (out of a maximum of 36) was slightly but significantly greater in the fans area (9.4) than the control area (7.2) (p=0.007) (Tables 3a and 3b). There were also significant differences between replicate rows in the same area (p=0.012).

Table 1: Effect of assisted air movement on occurrence of botrytis in tomato cv. Encore – 4 July 2008

Treatment and row number	**Number of missing [a]:**		**Number of botrytis lesions on [a]:**	
	Stem bases	**Tops**	**Stems**	**Leaf petioles**
Fans present				
4/5 (fan row)	3	5	14	17
9/10 (mid fans)	6	2	8	3
14/15 (fan row)	0	0	4	5
19/20 (mid fans)	1	1	9	23
Total	10	8	35	48
No fans				
4/5	4	12	13	15
9/10	4	4	0	3
14/15*	0	2	4	8
19/20*	1	4	8	9
Total	9	22	25	35

[a] 128 plants assessed per row.
* One application of Switch early season, none thereafter; no botrytis fungicides applied to all other rows.

Table 2: Effect of assisted air movement on occurrence of stem botrytis in unsprayed tomato cv. Encore – 4 July 2008

Treatment and row number	Number of missing [a]: Stem bases	Tops	Number of botrytis lesions on: Stems	Leaf petioles
Fans present				
4/5 (fan row)	3	5	14	17
6/7 (close to fan row)	2	7	12	1
7/8 (close to fan row)	3	8	10	6
9/10 (mid fans)	6	2	8	3
Total	14	22	44	27
No fans				
4/5	4	12	13	15
6/7	2	6	3	1
7/8	0	3	4	3
9/10	4	4	0	3
Total	10	25	20	22

[a] 128 plants assessed per row.

Table 3a: Effect of assisted air movement on occurrence of live heads in tomato, cv. Encore – 13 October 2008

Factor Area	Position	Row face	Mean number live heads per quarter row face (out of 36 heads)				
			1	2	3	4	Total
Fans	Fan row	N	12.5	5.0	8.5	7.0	33
		S	7.5	10.5	12.5	8.5	39
	Mid fans	N	11.5	11.5	12.0	6.0	41
		S	7.0	9.5	11.5	9.0	37
	Total		38.5	36.5	44.5	30.5	150
No fans	Control fan row	N	9.0	9.0	10.5	7.5	36
		S	7.0	6.0	4.0	8.0	25
	Control mid row	N	5.5	3.5	4.5	8.5	22
		S	8.0	10.5	7.5	6.5	32
	Total		29.5	29.0	26.0	30.5	115

Table 3b: Analysis of variance of effect of assisted air movement on occurrence of live heads in tomato, cv. Encore – 13 October 2008

Source of variation	Df	F pr
Rep	1	0.012
Position	1	0.967
Fans	1	0.007
Face	1	0.900
Quarter	3	0.678
Position. Fan	1	0.299
Position. Face	1	0.339
Fan. Face	1	0.834
Position. Quarter	3	0.787
Fan. Quarter	3	0.219
Face. Quarter	3	0.265
Position. Fan Total. Face	1	0.012
Position. Fan. Quarter	3	0.841
Position. Face. Quarter	3	0.875
Fan. Face. Quarter	3	0.178
Position. Fan. Face. Quarter	3	0.061
Residual	31	
Total	63	

Effect of climate control using a Priva air optimiser system (cv. Piccolo)

In July, the incidences of stem tops with botrytis, botrytis stem lesions and botrytis leaf petiole lesions (Table 4a), stem botrytis severity and total botrytis score (data not shown), were greater in the glasshouse area with AHUs than in the area without. These differences were statistically significant (Tables 4b and 5). Distance from AHU row (position), distance along the row (quarter) and row face had no significant effect on incidence of stem lesions or total botrytis (Table 5).

In October, the overall incidence of dead and missing plants (out of 16) was 3.1 in the AHU area and 1.0 in the no-fans area (Tables 6a and b), which was significant. There was also a significant fan x row position interaction (Table 6b). In the fans and ducts area, the incidence of dead and missing plants was high in the AHU row and midway between AHU rows, and least in the rows a quarter-way between AHUs. In the control area without fans and ducts, botrytis levels were lower and there was a gradual drop across the rows. There was also a significant effect of row face, with more dead and missing plants on the south side (1.6) than the north (2.5).

There was also a significant fan x position interaction effect on the number of live heads remaining (Tables 7a and b). In the fans and ducts area, the greater mean number of live heads (23.4) was in the rows a quarter-way between AHU rows, with fewer in the AHU rows (20.3) and in the row midway between AHU rows (15.0). In the control area without fans and ducts, there was a gradual increase in mean numbers of live heads with distance from the first row (26.1, 27.0 and 29.0).

There was no significant effect of fans and ducts, row face, row position or row quarter, on the number of botrytis lesion on remaining green stems (Table 8, statistical analysis not shown). The incidence of botrytis stem lesions appeared to be less in the two quarters of row close to the fan than in those distant from the fan (Table 8). There was a significant fan x row quarter interaction effect on botrytis lesion severity (Table 9). In the AHU area, botrytis lesion severity was greater in the two quarters distant from the AHU (11.8 and 14.8) than close to the AHU (7.9 and 6.3). In the control area without fans and ducts, there was a trend of decreasing lesion severity (from 14.5 to 9.1) with distance from glasshouse side wall.

Nursery records of the number of plant heads and whole plants removed from 15 rows in the area with the air optimiser system and from equivalent rows in the control area also revealed a higher incidence of stem death in the former than the latter (Table 10).

It is possible that some of the greater incidence of plant death in the area with AHUs was due to powdery mildew, either the result of direct damage, or indirectly by causing premature leaf death which was colonised by botrytis. However, at the July assessment, when levels of powdery mildew were still relatively low, there was a clear difference in numbers of botrytis stem and leaf petiole lesions between the AHU area and the control area.

Details of fungicides used to control botrytis and powdery mildew in the non-monitored areas of both crops are shown in Table 11.

In future monitoring of botrytis on the nursery, more definitive results on the potential of ducted air systems to control the disease are likely to be obtained if: 1) information is obtained on stem wetness duration during the period botrytis is assessed, 2) there are no boiler problems, 3) experienced crop workers are used in the monitored areas, 4) powdery mildew is well controlled, 5) no botrytis fungicides are applied to the monitored areas.

Table 4a: Effect of air optimiser on occurrence of botrytis in tomato cv. Piccolo – 4 July 2008

Treatment and row number	Number of missing [a]: Stem bases	Tops	Number of botrytis lesions on: Stems	Leaf petioles
AHUs present				
35/36 (AHU row)	1	7	4	4
37/38 (quarter-way)	2	3	5	5
39/40 (mid-AHUs	2	5	1	1
41/42 (quarter-way)	1	5	4	1
43/44 (AHU row)	0	3	2	1
Total	6	23	16	12
No AHUs				
101/2 (control row)	2	2	0	1
103/4 (quarter-way)	4	2	0	0
105/6 (mid-way)	2	0	0	0
107/8 (quarter-way)	0	3	0	0
109/10 (control row)	2	1	1	0
Total	10	8	1	1

[a] 128 plants assessed per row.

Table 4b: Analysis of variance tables for selected symptoms on cv. Piccolo, July 2008

Symptom and sources of variation[a]	Df	F pr
Number of stem lesions		
Fan (fan vs no fan area)	1	0.005
Face of row (north or south)	1	0.553
Position (fan row vs not fan row)	2	0.449
Quarter of row	3	0.177
Fan x face	1	0.843
Fan x position	2	0.417
Face x position	2	0.661
Fan x quarter	3	0.087
Face x quarter	3	0.098
Position x quarter	6	0.682
Residual	32	
Total	79	
Total botrytis[b]		
Fan	1	0.029
Face of row	1	0.146
Position	2	0.666
Quarter of row	3	0.078
Fan x face	1	0.768
Fan x position	2	0.605
Face x position	2	0.468
Fan x quarter	3	0.503
Face x quarter	3	0.066
Position x quarter	6	0.371
Residual	32	
Total	79	

[a] Three factor interactions not shown; no significant effects.
[b] Sum of missing bases, dead tops, stem lesions and leaf lesions.

Table 5: Summary of factors significantly affecting botrytis and missing plants in cv. Piccolo – July 2008

Source of variation	F pr					
	Missing stem base	Dead top botrytis	Botrytis stem lesion	Botrytis leaf lesion	Botrytis total score	Stem botrytis severity
Fan (fan vs. no fan area)	NS	<0.001	0.005	0.027	0.029	0.010
Face of row (north or south)	–	–	NS	NS	NS	NS
Position (fan vs no fan row)	NS	NS	NS	NS	NS	NS
Quarter of row	0.016	NS	NS	NS	NS	NS
Fan x face	–	–	NS	NS	NS	NS
Fan x position	NS	NS	NS	NS	NS	NS
Face x position	–	–	NS	NS	NS	NS
Fan x quarter	0.006	NS	NS	0.039	NS	NS
Face x quarter	–	–	NS	NS	NS	NS
Position x quarter	0.025	NS	NS	NS	NS	NS

NS not significant at P = 0.05.

Table 6a: Effect of air optimiser system on dead and missing plants in tomato cv. Piccolo – 13 October 2008

Area	Position	Face	Mean number dead or missing per quarter row per side (16 plants)				Total
			1	2	3	4	
Fan	AHU[a]	N	6	2	2	2	12
		S	5	4	3	6	18
	Quarter-way[a]	N	1	1	3	0	5
		S	3	2	4	2	11
	Mid AHUs[b]	N	3	5	4	4	16
		S	9	4	5	5	23
	Total		27	18	21	19	85
No Fan	Control[a]	N	2	1	2	1	6
		S	1	2	2	1	6
	Quarter-way[a]	N	1	1	1	1	4
		S	1	1	2	1	5
	Mid-way[b]	N	0	0	0	1	1
		S	1	1	0	1	3
	Total		6	6	7	6	25

[a] Mean of two rows; [b] Single row.

Table 6b: Analysis of variance of effect of air optimiser system on dead and missing plants in tomato cv. Piccolo – 13 October 2008

Source of variation	D.f.	F pr.
Fan	1	<.001
Face	1	0.022
Position	2	0.008
Quarter	3	0.411
Fan. Face	1	0.103
Fan .Position	2	0.002
Face. Position	2	0.897
Fan. Quarter	3	0.510
Face. Quarter	3	0.979
Position. Quarter	6	0.448
Fan. Face. Position	2	0.946
Fan. Face. Quarter	3	0.732
Fan. Position. Quarter	6	0.625
Face. Position. Quarter	6	0.426
Fan. Face. Position. Quarter	6	0.693
Residual	32	
Total	79	

Table 7a: Effect of air optimiser system on number of live heads remaining in tomato cv. Piccolo – 13 October 2008

Area	Position	Face	Mean number of live heads remaining per quarter row (out of 32)				Total
			1	2	3	4	
Fan	AHU[a]	N	16	25	23	25	89
		S	16	18	22	19	75
	Quarter-way[a]	N	25	27	20	27	99
		S	22	26	18	25	91
	Mid AHUs[b]	N	17	18	18	19	72
		S	6	14	10	18	48
	Total		102	128	111	133	474
			1	2	3	4	
No Fan	Control[a]	N	25	24	27	28	104
		S	26	25	27	29	107
	Quarter-way[a]	N	28	27	28	28	111
		S	26	25	27	29	107
	Mid-way[b]	N	29	29	27	30	115
		S	28	28	32	29	117
	Total		162	158	168	173	661

[a] Mean of two rows; [b] Single row.

Table 7b: Analysis of variance of effect of air optimiser system on number of live heads remaining in tomato cv. Piccolo – 13 October 2008

Source of variation	d.f.	F pr.
Fan	1	<.001
Face	1	0.057
Position	2	0.029
Quarter	3	0.092
Fan. Face	1	0.089
Fan. Position	2	<.001
Face. Position	2	0.854
Fan. Quarter	3	0.218
Face. Quarter	3	0.965
Position. Quarter	6	0.536
Fan. Face. Position	2	0.417
Fan. Face. Quarter	3	0.987
Fan. Position. Quarter	6	0.655
Face. Position. Quarter	6	0.876
Fan. Face. Position. Quarter	6	0.733
Residual	32	
Total	79	

Table 8: Effect of air optimiser system on occurrence of botrytis stem lesions in tomato, cv. Piccolo – 13 October 2008

Area	Position	Face	Mean number botrytis lesions / quarter row				Total
			1	2	3	4	
Fan	AHU[a]	N	3	4	6	5	18
		S	4	4	4	7	19
	Quarter-way[a]	N	6	4	6	7	23
		S	5	3	6	8	22
	Mid AHUs[b]	N	4	4	4	4	16
		S	1	1	4	6	12
	Total		23	20	30	37	110
			1	2	3	4	
No Fan	Control[a]	N	8	5	6	3	22
		S	6	5	5	9	25
	Quarter-way[a]	N	6	6	7	3	22
		S	9	4	4	7	24
	Mid-way[b]	N	4	5	5	2	16
		S	6	2	3	4	15
	Total		39	27	30	28	124

[a] Mean of two rows; [b] Single row.

Table 9a: Effect of air optimiser system on botrytis severity index in tomato cv. Piccolo – 13 October 2008

Area	Position	Face	Botrytis severity index per quarter row			
			1	2	3	4
Fan	AHU[a]	N	6.5	8.5	15.0	13.0
		S	7.5	5.0	6.5	14.0
	Quarter-way[a]	N	12.5	9.5	16.0	18.0
		S	10.0	5.0	13.5	20.0
	Mid AHUs[b]	N	9.0	8.0	10.0	12.0
		S	2.0	2.0	10.0	12.0
	Mean		7.9	6.3	11.8	14.8
No Fan	Control[a]	N	15.5	12.0	10.0	5.0
		S	14.5	11.5	9.0	17.5
	Quarter-way[a]	N	12.5	13.0	18.5	6.5
		S	18.5	8.0	6.5	14.5
	Mid-way[b]	N	11.0	13.0	8.0	3.0
		S	15.0	5.0	5.0	8.0
	Mean		14.5	10.4	9.5	9.1

[a] Mean of two rows; [b] Single row.

Table 9b: Analysis of variance of effect of air optimiser system on botrytis severity index in tomato cv. Piccolo – 13 October 2008

Source of variation	d.f.	F pr.
Fan	1	0.631
Face	1	0.538
Position	2	0.100
Quarter	3	0.275
Fan. Face	1	0.307
Fan. Position	2	0.615
Face. Position	2	0.870
Fan. Quarter	3	0.022
Face. Quarter	3	0.064
Position. Quarter	6	0.980
Fan. Face. Position	2	0.835
Fan. Face. Quarter	3	0.663
Fan. Position. Quarter	6	0.997
Face. Position. Quarter	6	0.976
Fan. Face. Position. Quarter	6	0.838
Residual	32	
Total	79	

Table 10: Effect of air optimiser system on the cumulative numbers of plants and heads removed from cv. Piccolo, weeks 2008

Area	Cumulative number removed up to week:					
(and rows)	15	20	25	30	35	38
Plants removed						
AHUs (31-45)	18	18	25	112	121	422
Control (101-115)	8	8	11	26	72	136
Heads removed						
AHUs (31-45)	35	35	53	220	508	791
Control (101-115)	0	0	6	34	103	171

Based on records made by nursery staff; no information for weeks 15-20.

Table 11: Details of fungicide applications to the non-monitored areas of crops in 2008

cv. Encore (houses 15-18)		cv. Piccolo (houses 11-14)	
Date	Product	Date	Product
4 March	Switch (not rows 1-10)	5 March	Switch
25 April	Rovral (not rows 1-30)	3 May	Sulphur
8 June	Rovral (not rows 1-30)	29 May	Systhane 20EW
10 July	Switch	28 June	Rovral WP (11 & 14)
		2 August	Rovral WP (11 & 12)
		20 September	Sulphur