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:	Interim report, September 2008
Previous report	None
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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 ……

CONTENTS

Grower Summary

Headline

- The design and installation of a ducted air heating and ventilation system in a commercial greenhouse in the UK has been successfully completed.

Background and expected deliverables

This report summarises the findings of the first year's work 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 work is being carried out to investigate a technology which can potentially address grower concerns that high energy costs and greater awareness of climate change issues are threatening the viability of glasshouse horticultural production in the UK.

The project follows on from the recently completed 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 indentified that the application of one key feature of the design, the ducted air heating and ventilation system, to conventionally designed glasshouses offered significant advantages including:

- Reduced energy consumption.
- Improved crop yield.
- Reduced pest and disease problems.

One of the major advantages of a ducted air system is that it allows lower temperature water to be used for glasshouse heating. For example, 50°C water can satisfy all the heating requirements of a greenhouse. This has the potential to reduce losses in the hot water distribution system, increase boiler efficiency and increase the working capacity of heat storage systems. In addition, the opportunities to use alternative energy sources such

as low grade heat from CHP, heat pumps and waste heat sources also increase significantly.

It is also common to use some minimum pipe heat even when the greenhouse temperature and humidity are at acceptable levels. Ducted air systems reduce the need for minimum pipe heat because they can respond much more quickly to a sudden increase in heat demand.

The improved air movement created by a well engineered ducted air system will lead to a more homogenous environment in the glasshouse. This will reduce energy use through more accurate temperature and humidity control.

Objectives

The overall 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 yield and quality.
- Reduce disease incidence and therefore the use of crop protection chemicals.

Summary of the project and main conclusions

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. Experiments to investigate system performance and crop response.

The project is being carried out at Mill Nursery Ltd in East Yorkshire. This report details the work carried out to complete items 1 and 2 of the above list.

Staff from FEC Services Ltd and representatives of Mill Nursery worked alongside a number of potential equipment suppliers prior to appointing the following companies as contractors/project partners:

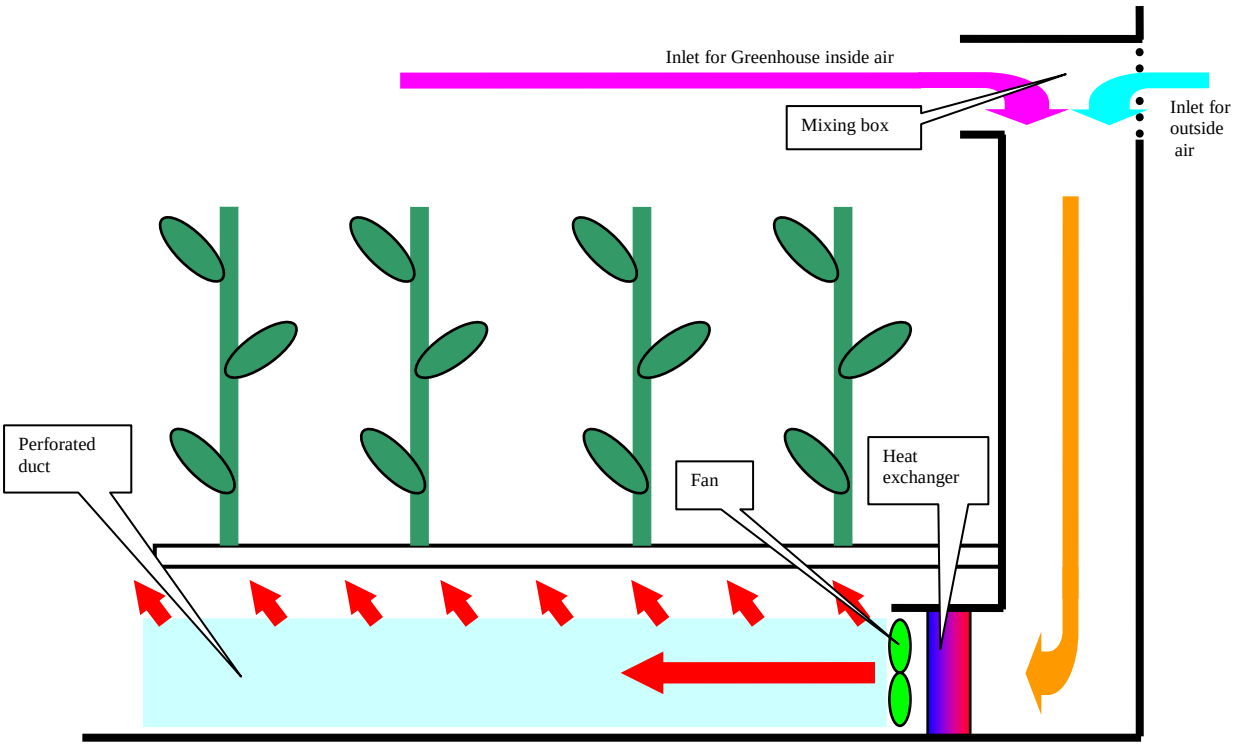
- Priva UK Ltd – responsible for the design, manufacture and installation of the fan and duct assemblies, instrumentation and control software.
- Cambridge HOK Ltd – responsible for the design and installation of a separate heating system to supply the fan and duct assemblies.

The greenhouse used for the project is split into two 1Ha blocks. This arrangement allowed a fan and duct system to be installed in one block whilst an otherwise identical 'conventional system' was retained in the adjacent block. This layout allows side by side performance comparisons of the two systems to be carried out throughout the three years of the project.

Technology overview - ducted air heating and ventilation

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


Inlet for Greenhouse inside air
Mixing box
Inlet for outside air
Perforated duct
Fan
Heat exchanger

The system includes the following major components:

- Fan – to circulate air around the greenhouse.
- Perforated duct – this is a polythene tube with holes punched along its length. It is used to distribute the air evenly throughout the greenhouse.
- Mixing box - automatically operated louvers are fitted on both the greenhouse side and outside air side. These allow the proportion of inside and outside air to be varied according to the desired greenhouse environment.
- Heat exchanger - this allows the air to be heated to the desired temperature. It is a radiator unit that is connected to the nursery's boiler and combined heat and power (CHP) system.

Collectively these components are called an Air Handling Unit (AHU).

Although the above diagram shows the system installed in a greenhouse with hanging gutters it is equally applicable to raised benches. In practice the location of all the key components can be changed to accommodate various crop layouts and greenhouse designs.

Basic system requirements/specification

Three criteria had to be specified for the system that was installed at the trial site. These were:

1. Heating capacity.
2. Total airflow.
3. Uniformity of airflow and heat distribution.

In practice the specification of the system considered practical and commercial limitations (e.g. physical size of the equipment, capital costs and running costs) before settling on a solution that provided an acceptable compromise. In developing this solution the following performance related considerations were made.

Heating capacity

The peak heat demand of individual greenhouses varies widely depending on location, desired cropping temperature, quality of construction etc. The following describes the factors

taken into consideration for the installation at Mill Nursery. These factors are also considered to be the ones that are relevant to the majority of growers in the UK.

Peak heat demand – a modern greenhouse with thermal screens typically needs 1.25MW/Ha to maintain a greenhouse temperature of 20°C when the outside temperature is -5°C. Calculations showed that installing equipment to satisfy the peak heat demand was not commercially viable. Therefore, as the greenhouse at Mill Nursery already had an existing pipe rail heating system, it was decided that this would be retained and used during periods of high heat demand.

Heat requirements for humidity control – with a conventional heating system a pipe temperature of 50°C emits 400kW/Ha and satisfies the majority of the humidity control needs for a tomato crop.

It was therefore concluded that the heating capacity of the system should be at least 400kW/Ha.

Airflow

The size of a ventilation system is typically sized according to the number of times per hour that the air held within the greenhouse is either circulated or replaced with outside air. This is known as the air change rate.

The required air change rate for greenhouses is difficult to assess as there is currently little experience with ventilation systems of this type. However, the air change rates used in closed and semi-closed greenhouses in the Netherlands are:

- The Themato/Innogrow fully closed greenhouse – 20 air changes/hour.
- Semi-closed greenhouses – 10 to 12 air changes/hour.

If the lowest figure of 10 air changes/hour used in the Netherlands was installed at the trial site, the total power requirement of the fans would be 120kW. It was concluded that this was not practical in terms of capital and running costs and was therefore discounted.

Tests with a small scale system at Mill Nursery revealed that 2.3 air changes/hr gave acceptable air movement. Similar trials carried out by a leading tomato grower and Priva BV in the Netherlands at the same time showed that 1.4 air changes/hr gave acceptable results.

Based on these findings it was decided that the system should be specified to have a minimum air change rate of 2.0 air changes/hour.

Uniformity of airflow and heat distribution

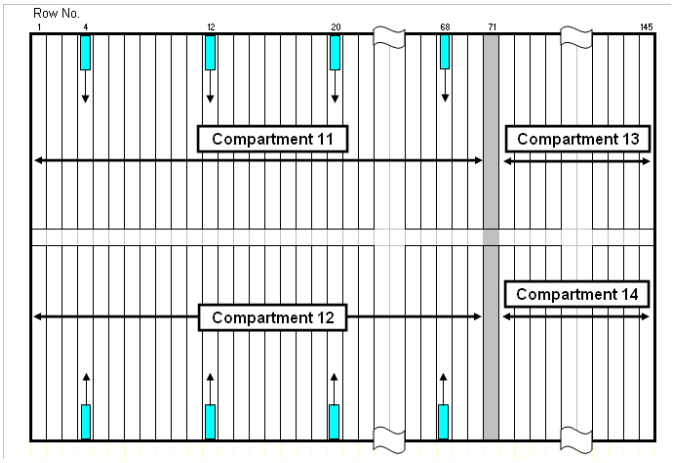
The use of hanging gutters and bench systems in greenhouses has recently become popular and this increases the opportunities for installing ducted air systems. The space under the gutter or bench can be used to house the fans and ducts, but careful consideration still needs to be given to the uniformity of airflow and heat distribution throughout the greenhouse. Areas which need specific consideration are:

- Along the duct – a perforated duct is used to ensure that air is distributed along its length. However, in a poorly designed system the holes closest to the fan can have more air leaving them than the holes at the far end. Under these circumstances the air movement and heat delivery close to the fan will be much higher than at the end of the duct.
- Between adjacent ducts – for the best air distribution a large number of ducts should be used, with the ideal arrangement being one underneath every hanging gutter. However, this arrangement is costly. Therefore, to reduce the cost the greatest possible distance between adjacent ducts was explored. Smoke tests with a small scale installation showed that one duct per 12.8m (8 rows of tomatoes) still delivered good air distribution.

The installation at Mill Nursery

Based on the specification detailed above, the installation at the trial site uses 18 x AHU's arranged as shown in Figure 2 below. Each AHU covers a floor area of 563.2m^2 (8 rows x 1.6m x 44m).

Figure 2 – AHU layout



Each AHU delivers 6,000m^3/hr of air and has a heat output of 25kW.

This gives a total heating capacity of 450kW and an air change rate of 2.0 air changes/hour (108,000m^3/hr).

The photographs below show key parts of the installation at Mill Nursery.

Figure 3 – Fan box

Figure 4 – Fan box with side removed

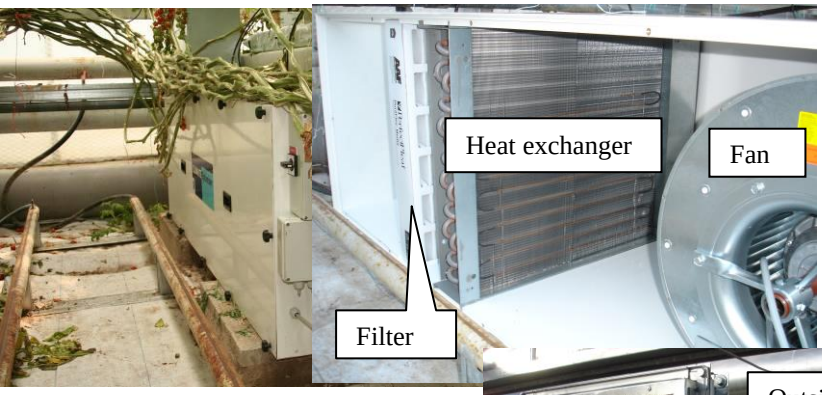
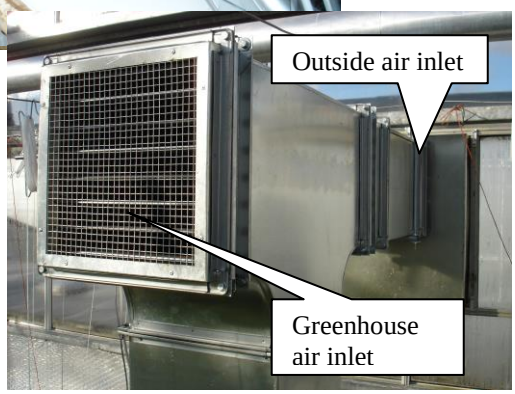
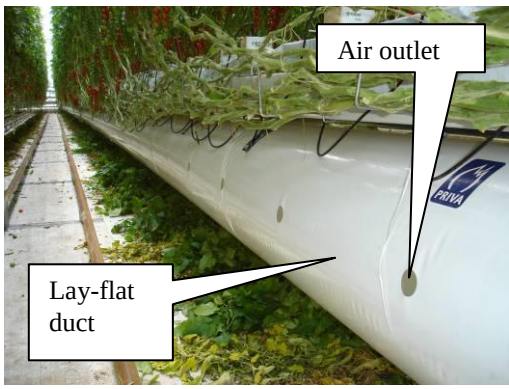


Figure 5 – Mixing box

Figure 6 – Air distribution duct





Financial benefits

Costs

The total installed cost of the installation at Mill Nursery was equal to £159,000 (£15.90/m^2). However, it should be noted that this is unlikely to be an accurate indication of the cost of a commercial installation in the future because:

- Some of the features installed at the project site (e.g. variable speed drive for the fan units and high levels of instrumentation) are likely to be proven to be unnecessary for commercial installations following experience gained during this work.
- More cost effective ways of delivering the same effect may become apparent.
- The layout of the trial greenhouse (particularly row length) had a significant impact on the cost.
- Economies of scale in the manufacture of the equipment will reduce costs if/when more systems of this type are sold.

At this early stage in the project the financial benefits have yet to be determined.

Conclusions

A fan and duct based heating and ventilation system has been successfully installed and commissioned in a 1Ha commercial tomato greenhouse at Mill Nurseries, Keyingham, East Yorkshire. The outline specification of the system is as follows:

Heating capacity	450kW/Ha
Ventilation capacity	108,000m^3/hr
Air change rate	2.0 air changes/hour

This specification is considered to be a compromise which meets technical and economic constraints which are acceptable to growers in the UK.

Action points for growers

Because this is an interim report further information is needed by growers before the system can be commercially adopted. This specifically relates to the energy saving and crop performance that is achieved when using the system. Growers should therefore wait for the results of the next two years work on this project when data relating to energy use, crop performance and pest and disease levels will be available.

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 was 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 offered considerable benefits if applied to conventional glasshouses, including:

- Reduced energy cost.
- Reduced CO_2 emissions.
- Reduced disease incidence and therefore use of crop protection chemicals.
- Increased yield/quality.

It is also widely accepted that improved air movement in glasshouses will improve the performance of a wide range of crops. PC 226 (2005) reviewed the existing knowledge of 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 wide 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.

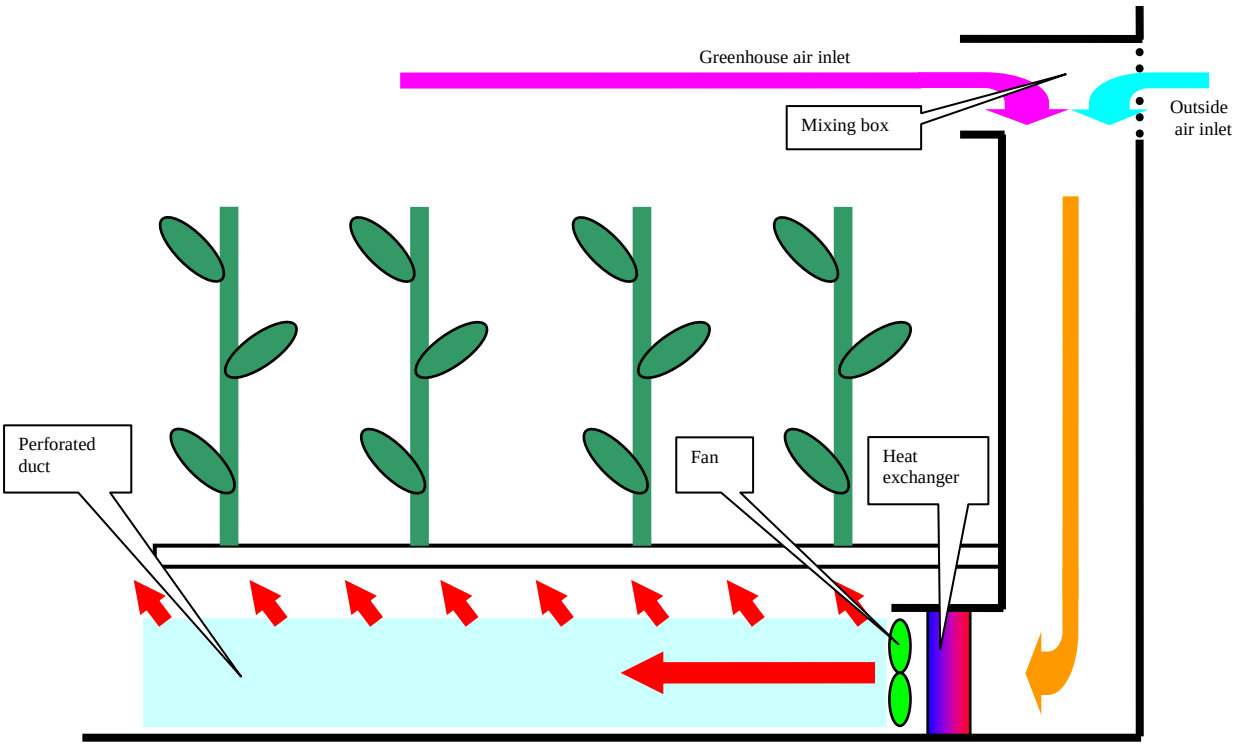
The specific objectives are to:

- Develop a cost effective ducted air environmental control system for installation in existing glasshouses.
- Determine the impact on the uniformity of the internal environment in a commercial glasshouse.
- Quantify the energy savings delivered.
- Demonstrate that low grade heat can be used to heat a glasshouse.
- Quantify the effect on both crop yield and disease levels.
- Provide recommendations on the design of ducted fan heating systems for growers.
- Effectively communicate the results to HDC members.

Technology overview – ducted air heating and ventilation

Figure 7 below shows the typical layout and key components of a single air handling unit (AHU) in a greenhouse growing a vine crop on hanging gutters. It should be noted this system is equally applicable to other greenhouse layouts such as raised benches for ornamental crops, as the location of the component parts is not restricted to those shown in this figure.

Figure 7 – Ducted air heating and ventilation schematic



The system consists of the following main components:

- Fan – to circulate air around the greenhouse.
- Perforated duct – this is a polythene tube with holes punched along its length. It is used to evenly distribute air throughout the greenhouse.
- Mixing box - this allows a mixture of greenhouse and outside air to be drawn in by the fan. Automatically operated louvers are fitted on both the greenhouse side and outside air side. This allows the proportions of inside and outside air to be varied according to the desired greenhouse environment.
- Heat exchanger - this allows the air to be heated to the desired temperature. It is a radiator unit that is connected to the nursery's boiler and combined heat and power (CHP) system.

Collectively these components are called an Air Handling Unit (AHU). A greenhouse installation will usually require a number of air handling units evenly spaced within it

Energy cost / CO_2 emissions

In a conventional greenhouse, during periods of peak heat demand a heating water temperature as high as 90°C may be required. In practice, especially now that thermal screens are being used by many growers, peak heat demands can be met with a heating water of 70°C. Such high temperatures are needed because of the surface area of heating pipes that is available to transfer the heat to the greenhouse environment. Whilst it is possible to use lower heating water temperatures (i.e. down to 50°C or less), it is not done in practice because of the extra heating pipes that would need to be installed in the greenhouse.

This problem with conventional heating systems highlights a key advantage of a ducted air system. By utilising an air to water heat exchanger (which is similar in construction to a car radiator) it is possible to provide a large surface area for heat exchange in a package that has relatively small physical dimensions. This means that the maximum water temperature needed to satisfy the peak heat demand of a greenhouse could easily be reduced to 50°C if not less. This has the potential to reduce losses in the hot water distribution system, increase boiler and condenser efficiency and increase the working capacity of heat storage systems. In addition the opportunities to use alternative energy sources such as low grade heat from CHP, heat pumps and waste heat sources also increase significantly. This last point is viewed as a key strategic step which, if comprehensively addressed, will give growers the confidence that low grade heat sources can be reliably used when they become available at an economic cost. In addition to reduced energy costs, heat sources of this type also have the potential to reduce CO_2 emissions to the point where low/zero carbon production systems may be possible.

It is also common to use some minimum pipe heat even when the greenhouse temperature and humidity are at acceptable levels. This is because:

- It is thought to provide useful air movement.
- Conventional pipe rail heating systems can take up to 20 minutes to respond to an increase in heat demand. There is therefore a tendency to continue adding some heat as an 'insurance policy' in case the greenhouse environment suddenly changes, even though it is not strictly needed the majority of the time.

- In taller crops such as tomatoes, cucumbers and peppers high light levels combined with little venting (minimal air movement) can mean that although the temperature and humidity at the top of the crop are acceptable, the conditions at the bottom of the crop are not.

Ducted air heating and ventilation reduces the need for minimum pipe heat because:

- It responds much more quickly to a sudden increase in heat demand.
- Warm, dry air from the top of the greenhouse can be re-circulated to the bottom without the need to add any heat.

Improved air movement will lead to a more homogenous environment in the glasshouse leading to reduced energy use through more accurate temperature and humidity control. This is also expected to provide opportunities for the relaxation of humidity control set points and save energy whilst continuing to deliver satisfactory plant growth and disease control.

Reduced disease incidence/improved yield and quality

As previously discussed, enhanced air movement is expected to improve the uniformity of temperature, humidity and CO_2 in the glasshouse and within the crop canopy. This will mean that a greater proportion of the plants experience optimum growth conditions thereby increasing yield and quality. Hot/cold spots and areas of high relative humidity which serve as incubator areas for both pest and disease will also be reduced. Dependent on the airflows achieved in practice there may also be benefits relating to a reduction in the boundary layer at the air – leaf interface. However, prior research suggests that the airflow required would be impractical to achieve in a commercial installation.

Materials and methods

The project is being carried out in three parts:

1. Research, development and design of a commercially viable ducted air heating and ventilation system.

2. Installation on a commercial nursery.
3. Commercial trials.

The host site for the project is a commercial tomato nursery; Mill Nursery Ltd, Keyingham, East Yorkshire.

The work associated with parts 1 and 2 of the project delivery is described in this report. Part 3 of the project delivery will consist of trials taking place over the period January 2008 to December 2010 as follows:

1. 2008 – fan and duct system performance testing, proving and refinement.
2. 2009 – investigations into the effect of the fan and duct heating/ventilation system on the greenhouse environment, crop performance and crop management.
3. 2010 – optimising crop performance and energy savings through the application of the project results to date.

In completing parts 1 and 2 of the project, engineers from FEC Services and representatives from Mill Nursery held extensive discussions with a number of suppliers prior to appointing the following companies as lead contractors/project partners:

- Priva UK: design, manufacture and installation of the AHU's, instrumentation and control software.
- Cambridge HOK: design and installation of a separate heating system to supply the AHU's.

Trial site

The host nursery for the commercial trials is Mill Nursery Ltd, Keyingham, East Yorkshire. Key contacts at Mill Nursery and their roles in the project are:

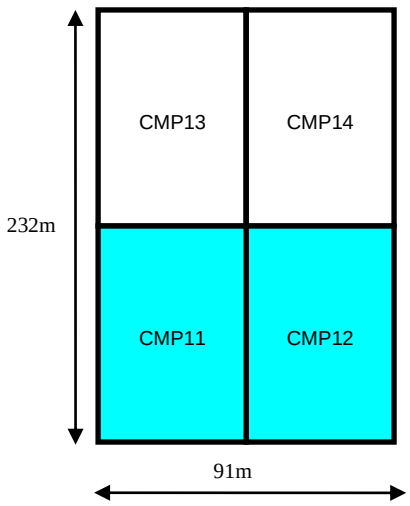
- Manus De Lang, Managing Director: input to system selection and final approval prior to installation.
- Tony Mills, Grower Manager: responsible for crop management and greenhouse environmental control decisions.
- Chris Theron, Assistant Manager: responsible for crop data recording/collection.

Both Manus De Lang and Tony Mills were closely involved in all stages of the development, design and installation of the equipment. Mill Nursery also provided a significant amount of labour to help with the installation as did CMW Horticulture Ltd (Priva UK's East Yorkshire dealer).

Figure 8 below shows the layout of the trial greenhouse. It is a single greenhouse structure split into four zones each of which 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.

A temporary partition was installed to create two separate airspaces (compartments 11 and 12, compartments 13 and 14). The greenhouse area in compartments 11 and 12 is 10,286m^2 and 11,094m^2 in compartments 13 and 14. Where appropriate, data in this and future reports will be 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.

Figure 8 – Layout and dimensions of the greenhouse compartments



Results

Basic system requirements/specification

Three main criteria had to be specified when designing a fan and duct system which met the commercial requirements set by Mill Nurseries for the installation in the trial greenhouse. These were:

1. Heating capacity.
2. Total airflow.
3. Uniformity of airflow and heat distribution.

In developing the specification of the system both practical and commercial limitations such as equipment size, capital costs and running costs were considered before settling on a solution that provided an acceptable compromise.

In developing this solution the considerations described in the following sections were carried out. It should be recognised that, as with many aspects of this project, there is no single specification that is applicable to every greenhouse in the UK. Therefore the following sections outline a methodology by which a similar specification can be developed for an alternative facility.

Heating capacity

The factors considered included:

- Does the fan and duct system have to satisfy the peak heating demand and provide 100% of the heat used by the greenhouse? If not, what is an acceptable level of heat supply from the system?
- What are the heat demand requirements for humidity control?
- How does a retrofit installation to an existing greenhouse differ from one for a new build facility?
- What heat source is being used and how does this impact on the ability of the system to deliver heat in the greenhouse?
- What is the impact of the system on the efficiency of heat production?

First the peak heat demand of the greenhouse has to be determined. A simple rule of thumb used to be that 2MW/Ha is required to maintain a greenhouse temperature of 20°C at -5°C outside. However, with the widespread use of thermal screens 1.25MW/Ha is now a more realistic figure.

Whilst it is possible to design and install a ducted air heating system that is capable of supplying 1.25MW/Ha, limitations on equipment size and the availability of capital are likely to preclude this approach. In practice the peak heating capacity is only needed for a few hours each year and therefore a better economic approach is to size a system which supplies only a proportion of the total heat demand. With this approach the existing boiler and heating pipe system is then retained for peak heating and standby purposes whilst the fan and duct system is used for 'base load' heating requirements.

This argument may not apply to new-build greenhouses as there is the ability to offset the cost of pipe rail heating against the cost of a higher capacity ducted air system. However, in edible crop production where the pipe rail provides a convenient transport system for crop work platforms and picking trolleys, it is likely that the installation of pipes on the greenhouse floor is likely to continue for the foreseeable future.

One of the many potential benefits of ducted air systems is improved humidity control. Therefore, when determining the heating capacity it is important that the system has the ability to meet the requirements in this area. Although the subject of considerable debate, adequate humidity control with conventional pipe heating systems can be achieved with a maximum water temperature of 50°C. This equates to a heat requirement of 400kW/Ha.

The heat source determines the maximum temperature of the water that can be supplied to the ducted air system and this in turn determines the amount of heat that can be delivered by a heat exchanger of a given size. Useful guidelines for this are:

- A flue gas condenser/economiser delivers maximum benefit when the water temperature is 50°C or less.

- Current designs of heat pump deliver a maximum water temperature of around 55°C. Their efficiency increases significantly if lower water temperatures can be used.
- Low grade heat from a CHP unit is typically at a water temperature of 40-50°C.

Each of these directs us towards designing a system that operates with a maximum water temperature of 50°C. As highlighted above, the pipe rail heating system in a conventionally designed greenhouse has a heating capacity of approximately 400kW at a water temperature of 50°C. Therefore if the peak heating demand of a modern greenhouse with a thermal screen is to be satisfied (1.25MW/Ha) with 50°C water then the heating capacity of a ducted air system would need to be 850kW/Ha. This is obviously far in excess of that needed for humidity control.

Finally the possibility of using separate high and low grade heat supplies on a site should also be considered. This would deliver the benefits of using low grade heat from a CHP or the boiler flue gas condenser but retain the flexibility of being able to operate the pipe rail at higher temperatures in extreme conditions.

Total airflow

Ventilation systems are typically sized based on the number of times per hour that the air held within the greenhouse is either recirculated or replaced with outside air. This is known as the air change rate.

The total volume of air in the 1Ha trial greenhouse at Mill Nursery is approximately 55,000m^3. Therefore, if an air change rate of 1/hr is to be achieved it needs a fan capacity of 55,000m^3/hr.

The target air change rate for a greenhouse is difficult to assess as there is currently little experience with ventilation systems of this type. However, the air change rates used in closed and semi-closed greenhouses in the Netherlands are:

- The Themato/Innogrow fully closed greenhouse – 20 air changes/hour.
- Semi-closed greenhouses – 10 to 12 air changes/hour.

If the lower figure of 10 air changes/hour was installed at the trial site, the total power requirement of the fans would be 120kW. It was concluded that this was not practical in terms of capital and running costs and was therefore discounted as being impractical. To develop a solution, and because of the lack of knowledge and practical experience available to guide the project team, trials were carried out to determine the impact of a simple fan installation on air movement and distribution within the greenhouse.

Uniformity of airflow and heat distribution

Several decades ago ducting connected to warm air heaters was a common sight on many nurseries. However, these systems became unpopular because of temperature uniformity problems and poor crop quality. There was also the problem of where to put the ducting; suspending it in the greenhouse roof reduced light transmission and laying it on the floor took up room that could be used for production. In the end it was replaced by the now common pipe rail heating system.

Time and knowledge have moved on and the increasing use of equipment such as hanging gutters and raised benches now means that installing and working with ducted air systems is more straightforward. However, the distribution of air and heat along the length of the duct and between adjacent ducts still needs to be considered.

Along the length of the duct

The distribution of air along the length of a duct is affected by many factors. As previously described, the common approach is to use a duct which has holes punched along its length. This stops all of the air taking the path of lowest resistance and escaping close to the fan. However, the hole size and spacing must be determined to stop more air coming out of the holes closest to the fan and less from the holes at the end. The simplest way to overcome this is to vary the size and/or number of holes along the length of the duct.

Heat delivery along the duct depends on the temperature of the air as well as the airflow at each hole in the duct. An immediate reaction might be that perfectly uniform air distribution along the length of the duct would be a good starting point. However, heat loss through the wall of the duct means that air leaving the holes closest to the fan is warmer than air leaving the holes at the end of the duct. To compensate for the drop in temperature along the duct and deliver uniform heat distribution, the airflow from the holes at the end of the duct has to be higher than from the holes closest to the fan. There is therefore a conflict between the requirements for uniform airflow distribution and uniform heating.

Between adjacent ducts

The ideal situation would be a lay-flat duct installed underneath every hanging gutter. This would effectively guarantee that the same volume of air and heat would be delivered underneath each row of plants. However, this would increase the capital cost of the installation. The challenge is to deliver satisfactory air and heat distribution using the smallest number of ducts possible or in other words have the greatest possible distance between them. As for the total airflow capacity, knowledge and practical experience in this area is limited and investigation of this was included in the small scale trials.

Small scale trials

This comprised two parts:

1. Simple fan and duct installation at Mill Nursery.
2. Visit to the Netherlands to view a prototype on trial in a commercial greenhouse.

Three 580mm diameter axial fans, excluding heat exchangers and mixing boxes, were installed with lay-flat ducts in the greenhouse at Mill Nursery in August 2007. The ducts were 44m long and each one had 52 x 40mm diameter holes equally spaced along each side.

Figure 9 – Simple fan and duct installation

The fans and ducts were installed in the middle of the greenhouse to one side of the central path. One fan and duct was installed every 5 rows (8m). The airflow delivered by each fan was 4,400m^3/hr giving an air change rate of 2.3/hour.

The fans were set to run continuously for one hour to allow airflow patterns to stabilise. To enable airflow patterns to be observed, smoke was introduced to each fan. The speed and uniformity of distribution were observed visually by FEC engineers and Mill Nursery staff. Albeit this is a subjective assessment, this experiment established the effectiveness of relatively low air flow rates (when compared to those used in closed greenhouse designs) in providing satisfactory levels of air movement.

Independently of this project Priva BV in the Netherlands was developing a similar concept. Their first prototype air handling unit was installed in a commercial greenhouse in early September 2007 and the project team visited the Netherlands to see it on 17 September 2007. The installation was in a greenhouse that had 100m long rows and the intention was that one unit would be installed in each 8m bay (5 rows). This would deliver approximately 1.4 air changes/hour. Smoke tests showed a similar level of air distribution to that seen in the small scale trials carried out at Mill Nursery.

Few large air handling units versus many smaller units

At each extreme it would be possible to consider the installation of:

- One large air handling unit for each side of the greenhouse, requiring a total of two units;

or

- One small air handling unit per row in the greenhouse, requiring a total of 144 units.

Two large AHU's might be expected to be the more cost effective solution because of:

- Economies of scale; for example installing two large heat exchangers is theoretically cheaper per kW of heating capacity than many smaller ones. However, this is not necessarily the case in practice as larger heat exchangers tend to be made to order whereas smaller ones are mass produced.
- Savings on installation costs; for example the supply and connection of heat, power and controls to two units will be cheaper than connections to many units.

However, to ensure satisfactory air distribution in the greenhouse, the preliminary trials had concluded that a lay-flat/air distribution duct was required every 5 rows (8m). Therefore, if a small number of large AHU's was to be used, an expensive and potentially complex manifold would be required. In addition to the cost issues, a number of practical issues/questions also needed to be addressed such as:

- Should the AHU's be installed inside or outside the greenhouse? If the installation was outside, should the manifold be insulated?
- Should the manifolds be installed at high level or low level? If installed at high level the shading effect must be considered plus support would be needed for a large diameter and relatively heavy pipe network. If installed at a low level the amount of room required close to the side-wall must be considered.

These factors are of greatest significance to retro-fit installations, so much so that it would have been extremely difficult to fit large AHU's and the associated manifolds to the trial greenhouse at Mill Nursery. This is also expected to be the case in the majority of retro-fit installations in the UK.

New-build installations provide the opportunity to consider a much wider range of options. A significant divergence from the scenarios already discussed could be accommodated and solutions such as the construction of an air chamber along the whole length of each greenhouse side-wall (within which the fans, heat exchangers etc. can be integrated) would be possible. A similar concept to this was seen at the Hortifair in 2006 where the air chamber was simply an additional greenhouse bay and the airflow control louvres were modified greenhouse vents.

The installation at Mill Nursery

Hardware

After the completion of preliminary investigations the basic requirements for the installation were set as:

- Between 2 and 5 air changes per Ha per hour.
- A minimum heating capacity of 400kW/Ha and if possible up to 850kW/Ha.
- Multiple smaller AHU's installed inside the greenhouse rather than a small number of large units.

By this stage the decision had been taken to use the AHU package developed by Priva. This solution had the additional benefit of guaranteeing compatibility with the nursery's existing climate control computer (Priva Integro). Figure 10 overleaf shows one of the fan boxes in its final position. The height of the unit had to allow it to be fitted underneath the hanging gutter and the width had to ensure that the picking trolleys and crop work platforms were not impeded. This restriction on its physical size affected the heat and airflow that could be delivered by a single unit due to the physical size of off-the-shelf fans and heat exchangers that were available.

The final specification of each of these units was:

- Airflow – 6,000m^3/hr.
- Heating capacity 25kW when supplied with 50°C water.

Figure 10 – Fan box

The original design had all the motorised louvers built into this box so that it could be assembled and pre-wired off-site. This would have allowed simpler installation and ongoing maintenance. It was also intended to have two air inlet ducts, one connecting the outside air inlet through the side wall at ground level and a second duct going straight up to the height of the crop wire to draw in greenhouse air at high level. As can be seen in the above photograph, the CO_2 distribution pipe, header for the pipe rail heating and hanging gutter support make access to the side wall difficult at ground level. Installation of the outside air duct at ground level would have required all of these existing greenhouse services to be moved and/or modified. This was considered to be impractical and therefore the decision to mount the mixing box at high level as shown in Figure 12 was taken.

Figure 11 below shows the fan box with its side removed. A filter was added primarily to avoid fouling on the heat exchanger as cleaning them can be difficult and time consuming.

Figure 11 – Fan box with side removed

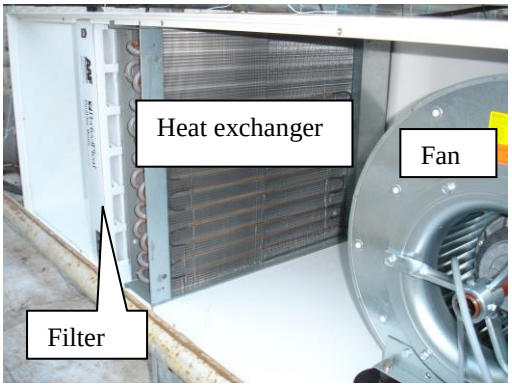
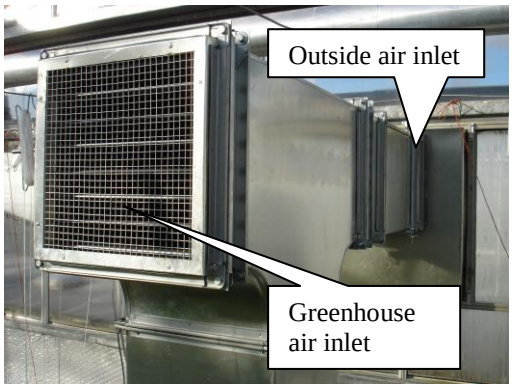


Figure 12 below shows the mixing box that was installed at a similar height to the crop wire.

Figure 12 – Mixing box



How many AHU's

The installation of one AHU in each 8m bay (5 rows) would have required a total of 28 units giving a combined heating capacity of 700kW/Ha and an air flow of 168,000m^3/hr (3 air changes per hour). This satisfied the upper end of the heat requirement and was 50% more than the minimum airflow requirement. However, the total installed cost of 28 units was significantly over budget. This was to some extent a consequence of the relatively short rows in the trial greenhouse (44m) which meant that the greenhouse area covered by each AHU was 352m^2. Exactly the same unit would have satisfied the minimum air change rate (2.0) whilst covering 544m^2 (68m long rows) thereby reducing the AHU cost per square meter by 45%. However, there are few greenhouses in the UK with rows of this length so a solution had to be sought that offered a more commercially realistic proposition for UK growers.

Another way of increasing the greenhouse area covered by a single AHU is to increase the distance between them. This increases the risk of poor air distribution between adjacent AHU's as previously discussed. The maximum distance between adjacent AHU's that Priva was prepared to support was 12.8m (8 rows). This required a total of 18 AHU's, 9 each side of the path with a total output of:

- 450kW/Ha when supplied with 50°C water.
- 108,000m^3/hour (2.0 air changes per hour).

Each of the fans had a rated power consumption of 2.4kW giving a total power consumption of 43.2kW/Ha. A variable speed drive (VSD) was also fitted. The main benefit of a VSD is that it allows the fan speed to be varied which could deliver savings in electricity consumption if less than 2 air changes/hr is found to be acceptable. This provided an installation at a capital cost considered to offer a commercially realistic proposition. A detailed plan of the trial greenhouse showing the location of the AHU's is provided in Appendix 1.

Heat supply

To allow the heat output of the AHU's to be controlled independently of the pipe rail system, separate pumps, mixing valves and heating pipe headers were installed to supply greenhouse compartments 11 and 12.

The source of hot water is currently the existing high temperature transport system. However, Mill Nursery has CHP on site and the low grade heat produced by it is currently destroyed. The intention is to connect to this 'free' heat source in due course.

Software/control

The AHU installation is operated in two parts (compartments 11 and 12) to match the control of the existing heating, ventilation and thermal screens. The following detail describes the control of one compartment, which is replicated in the second one.

The centre AHU within the compartment is referred to as the 'master' unit and the temperature and humidity conditions of both the inlet (outside and greenhouse) and outlet airstreams are measured only at this unit. The heating water temperature and position of the louvers of all the remaining AHU's (known as the 'slaves') are adjusted according to these measurements. The set points applied in the greenhouse climate control computer (Priva Integro) are also derived from the measurements taken at the master unit.

A new section of control software has been written for the Priva Integro computer specifically for this project. It has drawn on experience gained by Priva from the Themato/Innogrow closed greenhouse and more recently from other semi-closed greenhouse projects in the Netherlands. It supplements the existing set points that most growers are familiar with such as heating and ventilation temperature, minimum pipe temperature and vent position etc., rather than replacing them. This allows the AHU's to be used as either:

- The lead system for temperature and humidity control, or
- For fine-tuning temperature and humidity control whilst continuing to rely on the pipe rail heating system for the majority of the heating needs.

In practice it is expected that the actual operation of the system will sit somewhere between these two points. It is even possible for the AHU to be the last resort as a system for temperature control but the lead system for humidity control. However, this remains to be proven during the commercial trials which continue through to the end of 2010.

Cost

A breakdown of the cost of the whole installation excluding VAT is detailed in Table 1 below. However, these costs should not be taken as an accurate indication of a commercial cost as:

- Some of the features installed at the project site (e.g. variable speed drive for the fan units and high levels of instrumentation) are likely to be proven to be unnecessary for commercial installations following experience gained during this work.
- More cost effective ways of delivering the same effect may become apparent.
- The layout of the trial greenhouse (particularly row length) had a significant impact on the cost.
- Economies of scale in the manufacture of the equipment will reduce costs if/when more systems of this type are sold.

Table 1 – Installation costs

Description	**Total cost £**	**Cost/m^2**
Heating system modifications	20,000	2.00
Mains electrical cable and installation (excluding variable speed drives)	13,000	1.30
Supply and installation of: AHU, all ducting, variable speed drives, instrumentation and control software	124,000	12.40
Labour supplied by Mill Nursery (estimate)	2,000	0.20
Total	159,000	15.90

Discussion

The final specification and design of the AHU installation was a compromise between capital cost, running cost and performance. There was also the added uncertainty of the unknown value of the benefits that this installation will deliver. A significant factor that influenced Mill Nursery's decision to install this equipment was that they already had a free heat source in the form of low grade heat from their CHP. This meant that there was a relatively obvious energy cost saving even if there was no crop benefit or reduction in energy use.

As discussed earlier, energy savings are anticipated on nurseries with conventional boiler based heat supplies but without CHP. However, it is clear that energy savings alone are unlikely to justify the investment and crop benefits will need to be achieved for widespread uptake of this technology.

The longer-term strategic objective of this project is to provide a means by which growers can use lower grade waste heat. For example, allowing all the heating demand of a greenhouse to be satisfied by 50°C water or possibly even lower. The installation at Mill Nursery will not satisfy 100% of the greenhouse heat demand with 50°C water in the middle of winter. However, it is expected that at least 75% of the total heat use will be met with a maximum water temperature of 50°C. In a situation where say a 40°C waste heat source is available it may be necessary to install more/larger AHU's to satisfy the whole heat demand. This will clearly increase the capital cost and running cost of the fans. However, if the cost of the waste heat is low enough such an installation may well be justified.

Conclusions

A fan and duct based heating and ventilation system has been successfully installed and commissioned in a 1Ha commercial tomato greenhouse at Mill Nurseries, Keyingham, East Yorkshire. The outline specification of the system is as follows:

Heating capacity = 450kW/Ha

Ventilation capacity = 108,000m^3/hr

Air change rate = 2.0 air changes/hr

This specification is considered to be a compromise which meets technical and economic constraints which are acceptable to growers in the UK.

Because this project is at an interim stage, no reliable information on energy savings or crop performance is available yet. This additional information is needed before the economics of fan and duct systems can be assessed.

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 gasses) 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 combined.

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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Appendix 1

Greenhouse & AHU layout