Project title:	Refrigeration-based dehumidification: energy performance and cropping effect on commercial nurseries
Project number:	PE 013
Project leader:	Tim Pratt, Farm Energy Centre
Report:	Final report, April 2014
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Key staff:	Tim Pratt & Oliver Coe Ronald Duyvestijn Chris Durnford
Location of project:	Red Roofs Nursery (Northmoor), E. Yorks
Industry Representative:	Nigel Bartle, North Bank Growers Ltd, Teesside
Date project commenced:	1st December 2012
Date project completed (or expected completion date):	31st March 2014

DISCLAIMER

[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

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Signature .... Date ....

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GROWER SUMMARY

Headline

Protected edible crops

Refrigerant based dehumidifiers trialled on a tomato nursery in 2013 delivered heat savings of 91kWh/m^2 (24%) compared to a conventional heating system. This was offset by electricity use of 19kWh/m^2 and a 1kg/m^2 reduction in yield. Being a single year of trials with no replicates work in 2014 aims to investigate this yield loss.

Protected ornamental crops

Extrapolation of data from the trial to cover high energy ornamental crops grown at 16^{o}C or higher indicates that quicker paybacks may be possible (less than four years) due to a reduced dehumidification capacity requirement (lower capital cost). Nurseries that use gas oil for heating should get a faster payback but this is often offset by the fact that such nurseries use relatively little heat.

Background

Controlling the humidity in greenhouses is a vital part of growing high-yielding, quality crops with the minimum use of crop protection chemicals. Traditional methods of controlling humidity involve venting warm, humid air from the greenhouse whilst replacing this with colder, outside air which carries less moisture. The consequential drop in temperature (loss of energy) is supported using heat to maintain the required greenhouse temperature. We estimate that 20% to 40% of a nursery's annual energy consumption is for humidity control.

An alternative approach is to remove the water vapour using a dehumidifier. There are a number of basic designs of dehumidifier; the most common being the refrigerant-based heat pump which has been used in this project. The heat pump design is well proven and has found many applications, e.g. grain drying and wood kilning for instance, and trials have also been carried out in greenhouses e.g. by ADAS at Stockbridge house (Bartlett D.;1991). Early investigation of the technique failed to result in significant commercial penetration but advances in the technology and increased energy costs warranted this renewed investigation.

Summary

Edible crop trials

Trial set up

Four dehumidifiers (supplied by DryGair Ltd), with a combined water removal capacity of 180 litres/hour were installed in a 6,120m^2 greenhouse at Red Roofs Nursery Ltd in East Yorkshire. Over a growing season, energy and crop performance were compared to an adjacent, conventionally heated and ventilated greenhouse compartment.

The dehumidifiers were positioned half-way along the crop rows and straddled the rows as shown in the photograph below.

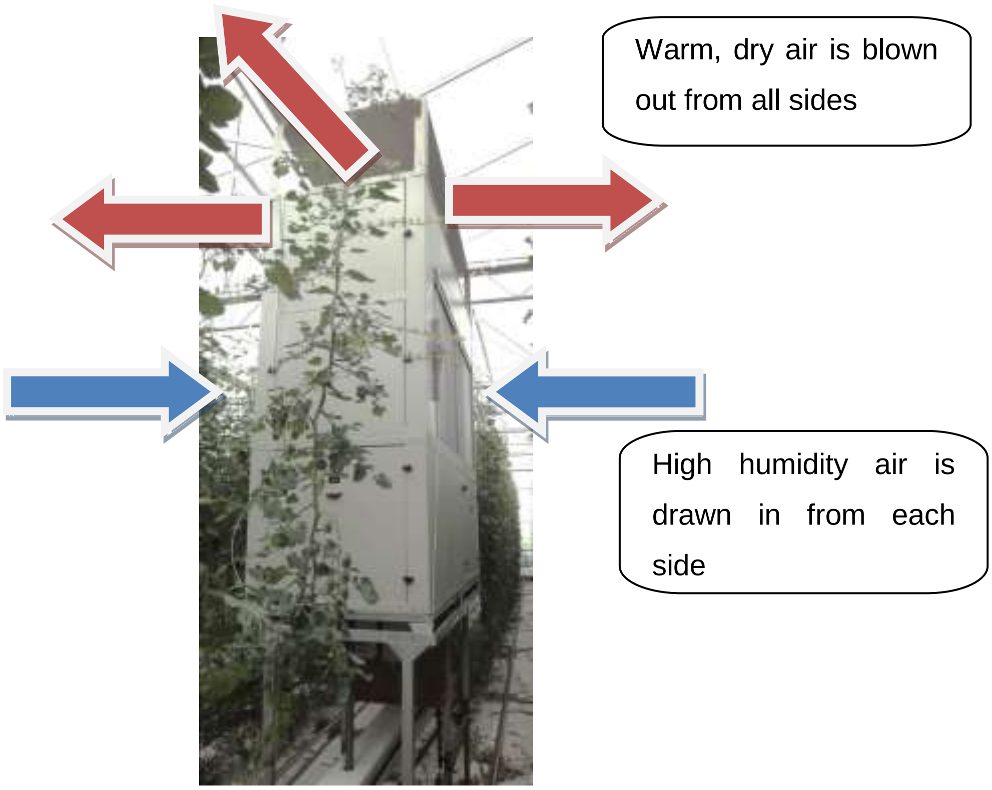

Figure 1. Dehumidifier in situ at Red Roofs Nursery

Results

After some initial problems with the dehumidifiers were resolved, they successfully performed close to specification extracting approximately 45 litres/hour of water for an energy input of 10kW of electricity i.e. 4.5 litres of water removed per kWh of electricity used. This figure is termed the Specific Moisture Extraction Rate (SMER) and is a key figure when comparing different manufacturer's equipment.

Although the original expectation was that they would only be used when the humidity was at its highest, it was soon evident that savings were possible in all but the lowest humidity conditions (<65%). Therefore as long as the RH was >65% and there was a heat demand in the greenhouse, the dehumidifiers were operated. The exception to this was when the heat produced as a by-product of CO_2 enrichment met all of the greenhouse heat demand. As a result, the dehumidifiers were not used from week 25 to week 36.

Figure 2 below shows the weekly heat saving achieved.

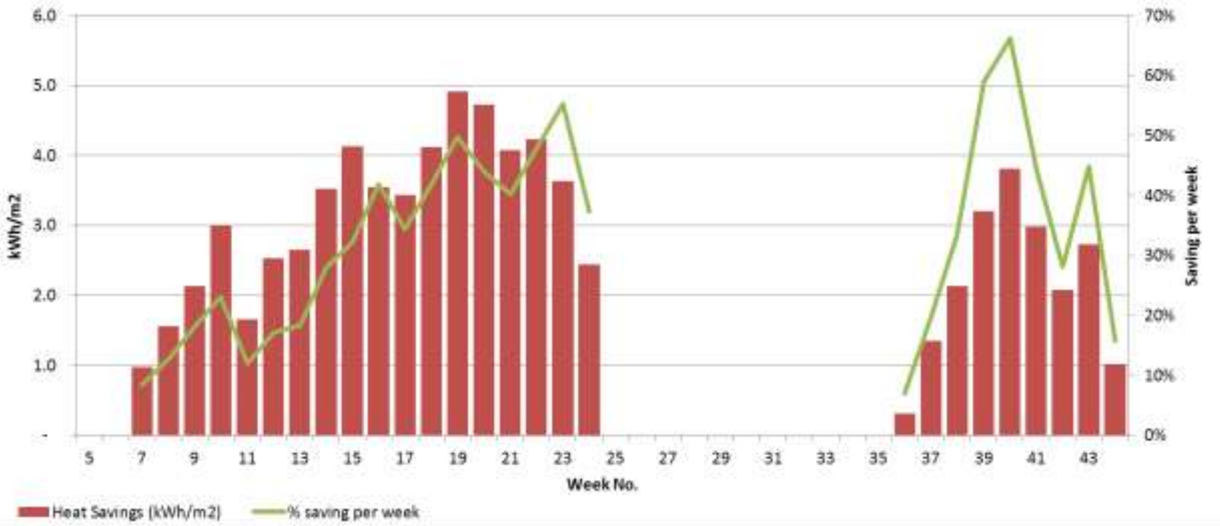

Figure 2. Absolute % (of total) weekly heat saving relating to use of dehumidifiers

Between weeks 1 to 44 inclusive, the control used 383kWh/m^2 of heat. The dehumidifier compartment used 91kWh/m^2 (24%) less and 19kWh/m^2 of electricity.

One area of concern was temperature uniformity. With the four dehumidifiers being, in effect, point heat sources compared to the distributed pipe heating source, one might have expected some degradation in uniformity. However, measurements showed there was actually a slight improvement in temperature uniformity, possibly as a result of the fact that dehumidifiers have internal fans to provide heat delivery and air mixing.

The crop in the dehumidifier compartment yielded fewer tomatoes than the control (1.0kg/m^2) as a result of the plants becoming too vegetative around week 11. Although the crop balance was corrected, the yield was not recovered. The nursery's crop advisor was confident that this could be avoided in the future. This remains to be proven in HDC funded trials in 2014 (PE 013a)

A major plus point relating to the crop is that no fungicide applications were required whereas the control crop needed two. Formal disease monitoring was not carried out.

Ornamental crop modelling

Data was collected from the pot chrysanthemum greenhouse at Double H Nurseries to allow the impact of dehumidifiers to be calculated. We measured the amount of time that heat was being used whilst the humidity was greater than 65%. Using this with the data recorded in the tomato trial we could determine the likely performance for ornamental crop.

Figure 3 below shows the amount of heat used (no dehumidifiers) and the likely heat saving if they had been used. The key figures are:

- Original heat use – 261kWh/m^2
- Heat saving – 97kWh/m^2
- Electricity used – 19.5kWh/m^2

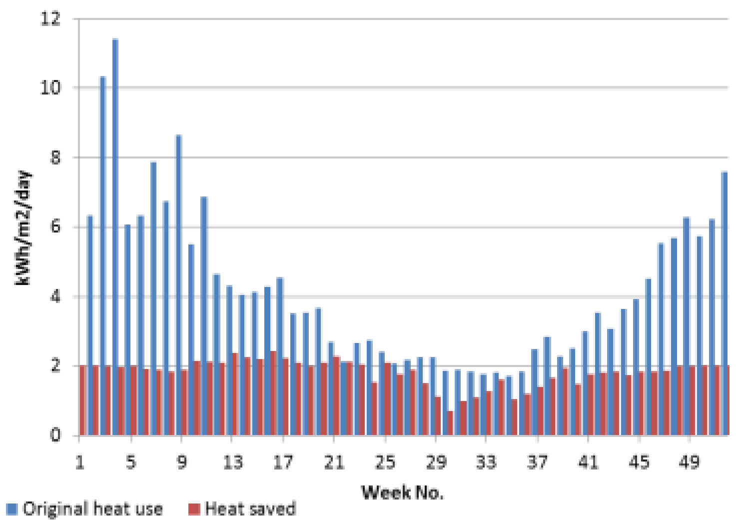

Figure 3. Ornamental crop: heat saving expected

Consultation with ornamental plant growers suggests that no negative impact on plant growth / yield is likely from the use of a dehumidifier system.

Financial Benefits

Tomato trials

Assuming, as advice suggests, the yield reduction experienced in 2013 could be avoided then it's fair to concentrate on the energy saving potential of the technique.

The figures in Table 1 below show energy savings/inputs and are based on the premises that :

- All heat saved would have been produced by a natural gas boiler (68p/Therm)
- All electricity used would have been imported from the grid (7.0p/kWh)

Nurseries that have CHP benefit from lower electricity costs which would increase the net saving by up to £0.40/m^2.

Table 1. Edible: energy saving cost breakdown

	kWh/m^2	£/m^2
Heat saving (kWh/m^2)	91	£2.48
Electricity used (kWh/m^2)	19	£1.33
Net energy cost saving		£1.14

The capital cost of an installation for an edible crop is in the order of £10/m^2 giving a return on investment in nine years. Allowing for the fact that one month of savings were missed in the figures above (equipment commissioning delays) and that simple optimisation of the control would increase performance, a return on investment in six years appears possible.

Ornamental crop modelling

Advice suggests that no impact on crop yield or quality is likely with ornamental crops. Table 2 below combines data collection from a year round high temperature ornamentals nursery with performance data from the tomato trial.

The figure in brackets is the cost of heat if gas oil is used (70p/litre).

Table 2. Ornamentals: energy saving cost breakdown

	kWh/m^2	£/m^2
Heat saving (kWh/m^2)	97	£2.65 (£7.36)
Electricity used (kWh/m^2)	19.5	£1.36
Net energy cost saving		£1.28 (£5.99)

Although net heating use is less for ornamentals, the capital cost of an installation for an ornamental crop is also lower, as the transpiration and moisture load is reduced and less dehumidifier equipment is needed per unit area. Also, with no availability of 'free' heat from a boiler which is being used to produce CO_2, the dehumidifier heat can be useful all year round. Taking these issues into account a return on investment in four years is possible (assuming natural gas as a fuel).

We must also consider here the use of the system for growers who are using gas oil as their heating fuel. As this is more expensive than gas, the payback on dehumidifiers look even better. However it's important to realise that growers who use gas oil are likely to be the ones growing lower temperature crops with lower net energy consumptions. But even taking this into account and taking the example of a grower who is using a 1/3 of the energy shown in the table above, the return on investment might still be reasonable (possibly three to four years). The only proviso to this is that our modelling has been done on a dehumidifier running in a higher temperature environment (>16^{o}C), and one would expect the dehumidifier to perform less efficiently at lower temperatures.

Capital cost is clearly a key element in the economics of a dehumidification system. As well as the hardware itself, the cost of providing sufficient electrical power to the greenhouse is often a significant issue. However, this is site specific so hard to factor into a general economic model.

Action Points

Edible crops

- The outcome of the 2014 trials will investigate if the 2013 yield reduction may be avoided. Growers are advised to delay adoption of the technology until such time as this is reported

Ornamental crops

- Dehumidifiers represent a viable energy saving option in specific circumstances.
- Any growers using gas oil to grow crops at 16^{o}C or above should compare their energy use to that of the ornamental crop nursery monitored. Even if using 1/3 of the heat the return on investment is three years
- Growers using natural gas should make the same comparison as above. The impact of lower energy cost and therefore savings potential mean that dehumidifiers are only likely to be financially viable for high energy use crops.

SCIENCE SECTION

Introduction

Good control of humidity in greenhouses is a vital part of growing high-yielding, quality crops as it optimises growth and minimises disease and the consequent use of crop protection chemicals. The normal method of controlling humidity in a greenhouse involves venting warm, humid air from the greenhouse whilst replacing this with colder, outside air which carries less moisture. The consequential loss of energy is supported using heat to maintain the required greenhouse temperature. We estimate that 20% to 40% of a nursery's annual energy consumption is for humidity control.

An alternative approach is to remove the water vapour using a dehumidifier. There are a number of basic designs of dehumidifier the most common being the refrigerant-based heat pump, and this is the one which has been used in this project. The heat pump design is well proven and has found many applications e.g. grain drying and wood kilning and trials have also been carried out in greenhouses e.g. by ADAS at Stockbridge house (Bartlett D.;1991). Early investigation of the technique failed to result in significant commercial penetration. However since then, there have been advances in the technology and energy costs are now more significant. So a renewed investigation is justified.

Some international commercial trials and applications by Israeli dehumidifier manufacturer (DryGair Ltd) and an offer of equipment for HDC trials in the UK helped to stimulate this project.

Potential benefits of dehumidification are:

- A reduction in energy use and cost for growing
- Improved yield due to reduced venting and therefore higher CO_2 levels
- Reduced fungal disease due to better humidity control

The trial objective was to evaluate these whilst identifying any downsides of the technology.

Materials and methods

Trial Site & Description

Tomato - commercial trial

The project was carried out on a commercial tomato nursery - Redroofs Nursery's North Moor Lane in Cottingham, East Yorkshire. The test compartments used were Compartment 3 (CMP3) where the dehumidifiers were situated and Compartment 4 (CMP4) which was used as a control. Each greenhouse was a typical double Venlo glass greenhouse structure with thermal screens and hanging gutters. CMP3 had a growing area of 6,120m^2, CMP4 was 9,432m^2; all the data presented in this report is per m^2 to allow for this difference in area. The most fundamental difference between the compartments was that CMP3 had a voided thermal screen (1 in 10 strips missing) whereas CMP4 had a thermal screen with no strips missing.

The crop grown in both compartments in 2013 was the mini plum tomato variety cv. *Gurrincha*. Young plants arrived on the nursery in week 1 and cropping continued through to week 45.

Ornamentals – data collection and modelling

Rather than carry out additional commercial trials, performance data collected from the tomato trial was used with energy and climate data from an ornamentals nursery to derive likely performance figures; allowing the impact of dehumidifiers on energy use to be determined. The primary objective was to provide a strategic steer on whether ornamental specific trials might be financially viable.

Data was collected from Double H's nursery in New Milton, Hampshire. The monitored compartment was approximately 18,000 m^2 and is a state of the art all year round pot chrysanthemum greenhouse.

Dehumidifier Equipment

The dehumidifier units used in the trial were refrigeration-based heat pump type dehumidifiers. With these, air is drawn over the cooling coil of a refrigeration unit and its temperature is reduced to below dew-point. At this temperature water vapour starts to condense from the air.   The cooled air is then passed over the hot condenser coil picking up the energy lost in the cooling/condensing process so that it's humidity is now lower and its temperature is typically 6-8°C warmer than when it entered the unit.

Below is a simple schematic showing the operation of the units with the key indicative performance figures:

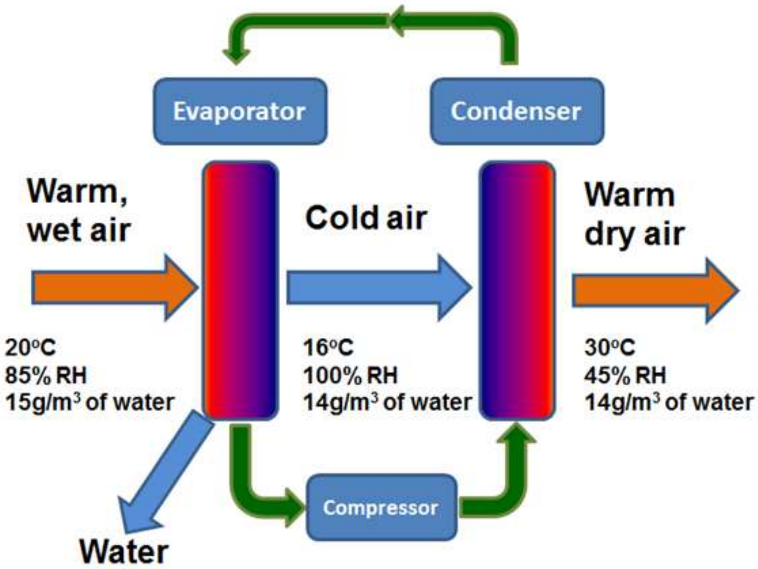

Figure 4. Refrigerant dehumidifier schematic

This technology is well established in the heating, ventilation and air-conditioning industry. Although applied in a different way, the principle of condensing water on a cold surface to deliver humidity control was used most recently prior to this project in closed greenhouse projects in the Netherlands. This was reviewed in HDC project PC 256 (2007).

An AFRC Institute of Engineering Research project (Bailey B.J, Chalabi Z.S; 1989) and further work carried out by ADAS at Stockbridge House (Bartlett D.; 1991) confirmed that the technology could be applied to greenhouses. However, at the time when energy costs were relatively low, the savings did not justify the investment required.

The supplier of the equipment for this project, DryGair, has carried out trials at the Volcani Institute of Agricultural Research in Israel. Although published reports are not available, a Coefficient of Performance (CoP) of 8.0 has been quoted (ratio of heat saved to electrical energy in). If this could be replicated in UK conditions, the heat equivalent costs would be around 0.78p/kwh (23p/Therm); compared to gas prices during 2013 of 2.22p/kWh (65p/Therm). The key specifications of the equipment supplied were:

- Energy input – 10kW of electricity
- Water removal rate – 45 litres per hour
- Airflow – 2 fans with a combined capacity of 40,000 m^3/hr

According to the manufacturer a single dehumidifier is suitable for 1,400m^2 of tomatoes. With CMP3 being 6,120m^2 , DryGair chose to supply five dehumidifiers with a view to only running four if they proved to be adequate. The dehumidifiers were installed in a ‘domino’ pattern as shown in Figure 5 below. In practice four were proven to be adequate.

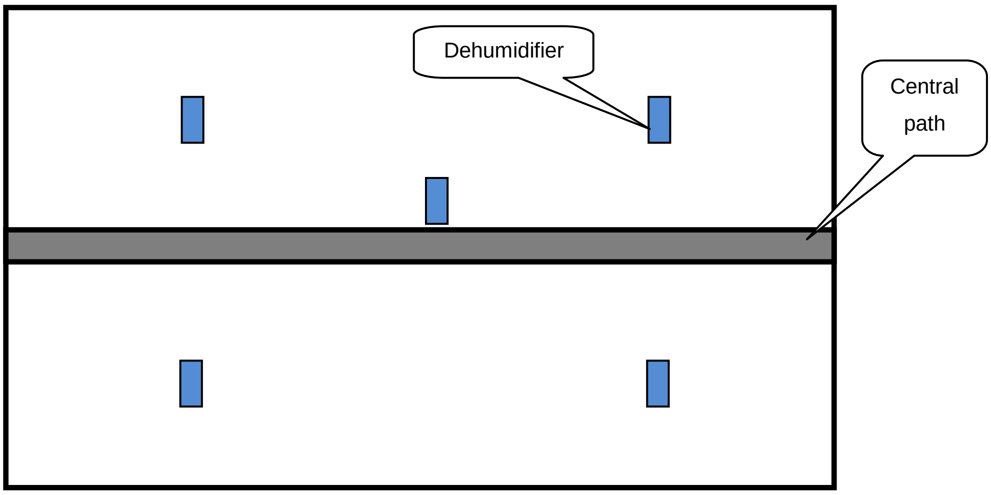

Figure 5. Dehumidifier layout

The dehumidifier’s design allowed them to straddle a row of tomatoes whilst still allowing the crop work platform to pass.

With ornamental crops being less leafy / transpiring less, the recommended installation density falls to one dehumidifier for 3,500m^2.

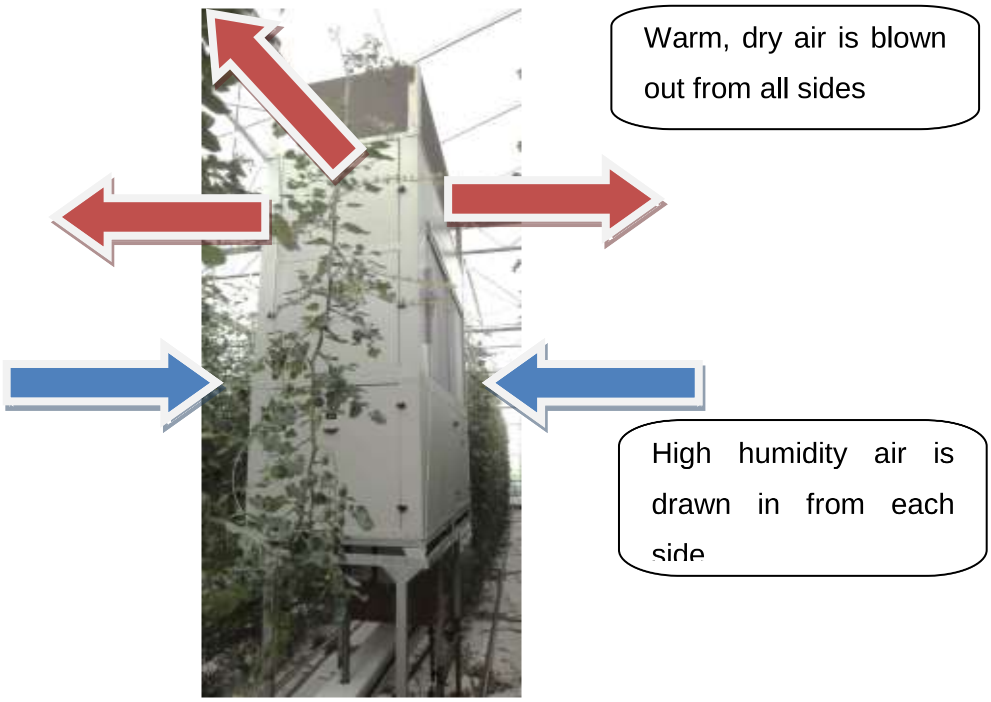

Figure 6. Dehumidifier in situ at Red Roofs Nursery

Monitoring and Data Collection

Two fundamental points had to be determined for UK growers to make well-informed investment decisions about this technology:

- The value of the net reduction in energy cost
    - Heat saved minus electricity used
- Any effect on crop performance
    - Yield and fungal diseases

To this end the following data was collected at the Red Roofs Nursery trial.

Energy and dehumidifier performance

Heat used by each greenhouse compartment

This was monitored using non-invasive flow meters and heat meter integrators installed on the hot water supplies to each compartment.

Electricity used by the dehumidifiers

An electricity meter was installed on one of the dehumidifiers and connected to the same data logger as the heat meters. As all the dehumidifiers were turned on and off together by the same control equipment, the recorded energy was multiplied by the number of dehumidifiers to give total dehumidifier consumed energy for the compartment.

Dehumidifier performance

The key performance indicator for a dehumidifier is the amount of water removed from the air for each kWh of energy used. This is known as the Specific Moisture Extraction Rate (SMER). The water recovered by a single dehumidifier (the one with the electricity meter fitted) was drained into a sump. The volume of water was measured using a calibrated pump that transferred the water into the irrigation drain water collection system.

The air temperature and humidity at the inlet and outlet of the dehumidifier were also recorded. These allowed the effect of air inlet conditions on dehumidifier performance to be determined.

Another useful performance measure is the ratio of useful heat produced compared to electricity used. This is often referred to as Coefficient of Performance (CoP). However, a better practical measure of the dehumidifier CoP is the amount of heat saved per unit of electricity used; for the purposes of this report we have referred to this as the ‘dehumidifier CoP’.

All the energy and dehumidifier data above was recorded every five minutes by a data logger which included a modem allowing remote access to the data recorded. This enabled regular analysis and feedback in response to changes in the control / operation of the dehumidifier and the greenhouse climate.

Greenhouse climate

The greenhouse climate was controlled by a Brinkman computer. This enabled all the normal greenhouse climate and equipment status to be recorded; once again in five minute intervals. Remote access to the Brinkman computer facilitated 'live' climate analysis and set point adjustments and downloading of the data for further investigation.

The following data were captured for each greenhouse compartment:

- Aerial environment
    - Temperature
    - Humidity – RH and HD
    - CO_2 concentration
- Equipment status
    - Heating pipe temperature
    - Vent and thermal screen position
    - Dehumidifiers on/off (CMP3 only)
- Weather data
    - Light level
    - Outside temperature

Simple battery powered data loggers were also laid out in a grid pattern in each greenhouse compartment to record the effect of the dehumidifiers on temperature uniformity.

Crop data

Crop registration data was collected by the nursery every week, under the guidance of their advisor (Ronald Duyvesteijn). The data collected was:

- Fruit set – per m^2
- Crop balance
    - Fruit size (visual)
    - Leaf length
    - Truss length
    - Truss height
- Yield
    - kg/m^2

Formal disease monitoring was not carried out. Feedback from the grower (Chris Durnford) and visiting tomato study groups was however noted.

Ornamental nursery data collection

The following data (recorded every 5 minutes) was exported from the nursery's climate control computer:

- Heating pipe temperature
- Vent and shade screen position
- Greenhouse temperature and relative humidity

Energy data collected included:

- Gas used by the boiler – weekly meter readings
- Heat used – heat meter connected to a GSM enabled data logger

Results

Tomato – commercial trials

Key dates / changes

- Week 1 – young plants arrive from the propagator
    - c.v. *Garrincha*, pinched and grafted on Maxifor. Starting density 2.86 heads/m^2
- Week 5 – commissioning/testing of equipment
    - Also second shoot taken, increasing the density to 4.3 heads/m^2
- Week 6 – dehumidifiers turned off
    - To benchmark greenhouse compartment energy use
- Week 7 – dehumidifiers set to run when the HD was less than 3.5g/m^3
- Week 8 – dehumidifiers set to run 19:00-16:00 all days (no humidity based control)
    - To allow the dehumidifiers to 'work hard' and accelerate the understanding of their operation
- Week 15 – compressor replaced on a single dehumidifier
    - Due to poor performance
- Week 16 – dehumidifier control based on HD and vent position
    - Turned off when the HD > 3.5m^3 AND the lee side vent was >10% open
    - To avoid running the dehumidifiers when there was no benefit
- Week 24 – dehumidifiers turned off
    - Due to low heat demand and the need to burn natural gas for CO_2 enrichment satisfying all the heat demand
- Week 37 - dehumidifier control based on HD and vent position
    - Due to increasing heat demand and reducing CO_2 demand
- Week 45 – end of cropping

Dehumidifier performance

Specific Moisture Extraction Rate (Litres of water removed per kWh of electricity used)

Figure 7 shows the SMER through the year. Dehumidifiers perform better with higher temperature, higher water content air. Therefore, a gradual improvement was expected as the crop got bigger and the challenge of maintaining acceptable humidity conditions within the greenhouse increased. Although the graph shows the average performance each week, the data collected allowed shorter periods (a few hours) of operation to be analysed. This allowed the dehumidifier performance under occasional 'ideal' conditions to be determined relatively early in the project and indicated that SMER was not up to specification. The cause was found to be a problem with the compressor which was replaced in week 15. The impact of this is demonstrated by the step improvement in performance in week 16. Following this, the dehumidifier performed at/around its specification.

The dehumidifier was turned off during the summer; hence no data for this period is shown.

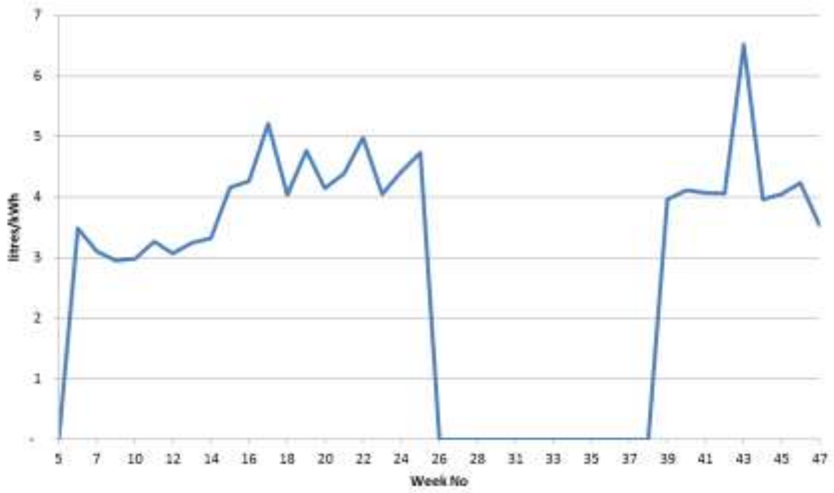

Figure 7. Dehumidifier performance as litres of water extracted per kWh of electricity

Dehumidifier CoP

This is the ratio of heat saved vs. electricity used. The relatively poor performance during the early weeks was due in part to low greenhouse humidity (small, plants, low outside temperature) and the compressor problem previously discussed. The impact of the former was exaggerated by the unseasonably cold weather during weeks 10 – 16 in particular.

The CoP from week 37 onwards appears abnormally low especially when the litres/kWh data for the same period were similar to the weeks leading up to the summer shutdown. Late in the cropping year there were differences in the crop that may have contributed to this apparent poor performance but this was not proven. A CoP of 5.0, reducing to 4.0 by week 45 was expected rather than the achieved average of 3.0.

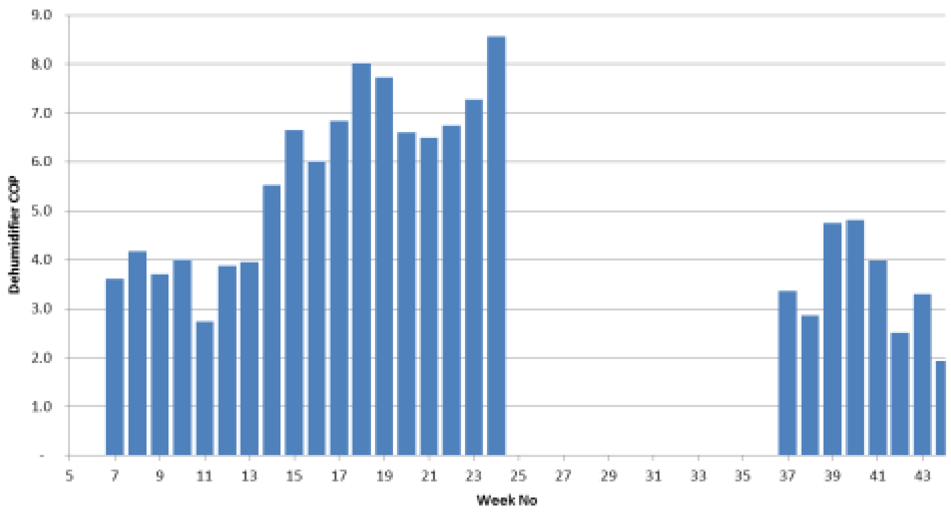

Figure 8. Dehumidifier CoP

Dehumidifier running hours

The dehumidifiers ran for a total of 3,411 hours during the 2013 cropping year. Excluding the summer period when they were turned off, they were used for an average of 19 hours / day.

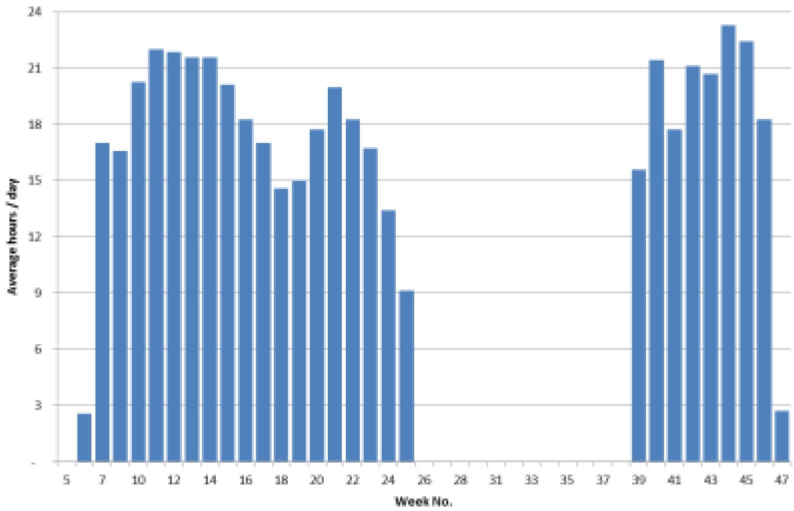

Figure 9. Dehumidifier running hours

Energy data

The greenhouse compartments were not identical and were therefore likely to use different amounts of heat even when operated in the same way without dehumidifiers. To assess the underlying difference, the dehumidifiers were not run during week 6 and the heat used by each compartment was compared. On average, CMP3 (containing the dehumidifiers) used 6% more heat than CMP4 (control). All the data that follows was corrected to take account of this difference to facilitate a direct comparison.

Prior to the trial, we postulated that the dehumidifiers would only deliver savings when the humidity was high. In such instances they would be used as the first line of 'action' to lower humidity i.e. before gapping the screen, opening the vents or increasing the minimum heating pipe temperature. During the early weeks of the trial the dehumidifiers were, in effect run on a timed basis (19:00-16:00). The off hours coincided with both high electricity prices and when a rapid drop in greenhouse temperature was required for the pre-night temperature strategy. The reason for running them such long hours when there was potentially no benefit was to produce data so we could learn about their characteristics quicker. We relied on the underlying physics of the process to provide immediate feedback:

- Total heat output comprised two elements
    - Heat recovered = the energy released by condensing the amount of water produced in 1 hour
    - Electrical energy input via the compressor and fans

Valuing the heat produced at the equivalent cost of producing it from a boiler vs. the cost of electricity used gave a simple 'is it worth running' answer.

Prior to the faulty compressor being identified, our assumption on economic operation was correct. However, once the compressor was repaired the data suggested that running the dehumidifiers at lower humidity's could also deliver savings.

Experience with this project has led us to conclude that dehumidifiers can be run economically :

- Whenever there is a heat demand

But NOT

- When the greenhouse humidity (RH) is especially low as the ability to remove water is restricted and the efficiency of the dehumidifier is poor.
    - The cut-off humidity below which the dehumidifier should be turned off depends on many factors but as a guide an RH of 65% or less seems sensible

Figure 10 below details the weekly heat and electricity use and each compartment. Figure 11 overleaf details the amount of heat saved each week.

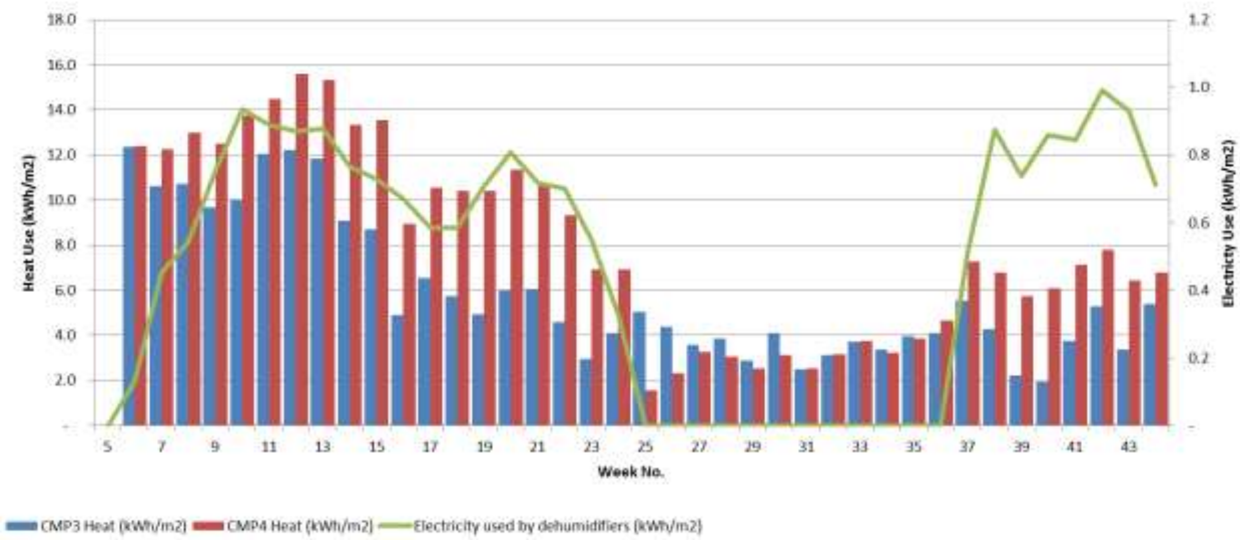

Figure 10. Weekly energy use

When the dehumidifiers were not used, CMP3 used more heat than CMP4 especially between weeks 25 to 30. This is even though the heat use data was corrected following the benchmarking adjustment as described earlier in this report. This was, in part, due to tuning set points in CMP3 after turning off the dehumidifiers. From week 31 onwards there was little difference in heat use. When calculating the heat saving, zero saving was assumed for weeks 25 to 36

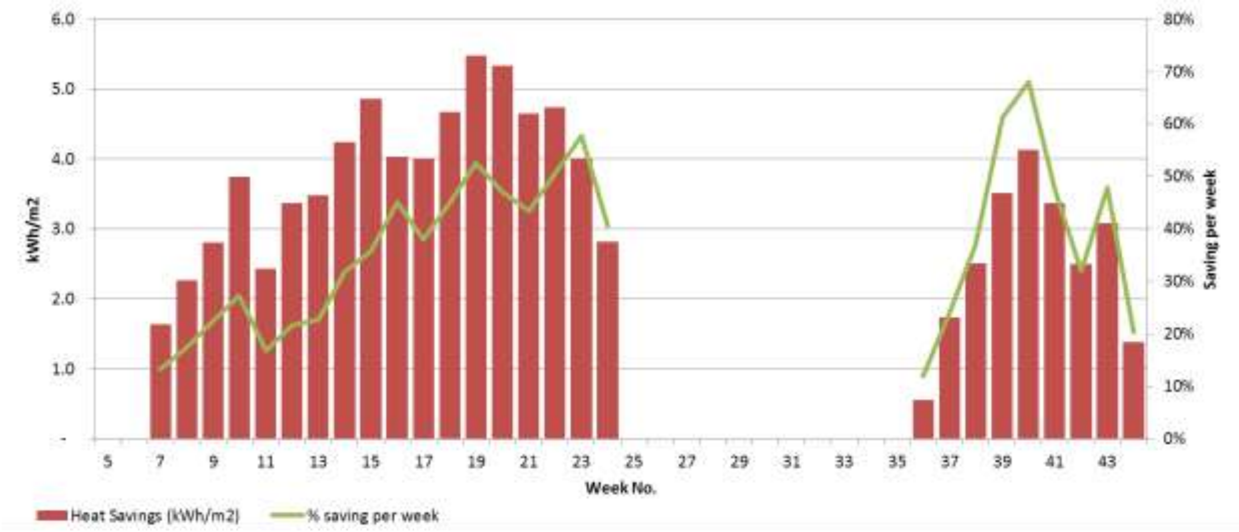

Figure 11. Weekly heat saving in the dehumidifier compartment compared with the control compartment

Table 3 below summarises the total amount of energy used / saved over the whole cropping year from weeks 1 to 44 inclusive. As heat data was not available for week 1-4 a figure of 11kWh/m^2 was assumed for both compartments during this period.

Table 3. Total energy use

	Heat used (kWh/m^2)	Electricity used by dehumidifiers (kWh/m^2)
CMP3 (dehumidifiers)	292	19
CMP4 (control)	383	-
Difference	91 (24%)	19

This gives a whole of season dehumidifier CoP of 4.8, including a period when the dehumidifier was not operating correctly.

It is worth noting that CMP4 used the equivalent of 450 kWh/m^2 of gas (assumed boiler efficiency of 85%). This is already a low figure compared to most tomato nurseries; making a further reduction of 91kWh (gas equivalent) even more significant.

Greenhouse climate

Humidity

Dehumidifiers enabled humidity control to go further than would have normally been the case with using heat venting. As energy savings were possible in all but the highest HD conditions (low RH), it was rational to use the dehumidifiers to achieve energy savings in these conditions. As such lower overall humidity conditions were achieved in the compartment with the dehumidifiers.

Looking at the average weekly daytime HD achieved (figure 12), this effect was relatively small especially between weeks 20 to 24. Even though the dehumidifiers did run during the daytime their water removal capacity (294 litres / hour / Ha) was relatively low compared to the transpiration of the crop. The poor performance of the dehumidifiers early in the year likely ‘lost’ any difference there would have been before they were repaired in week 15.

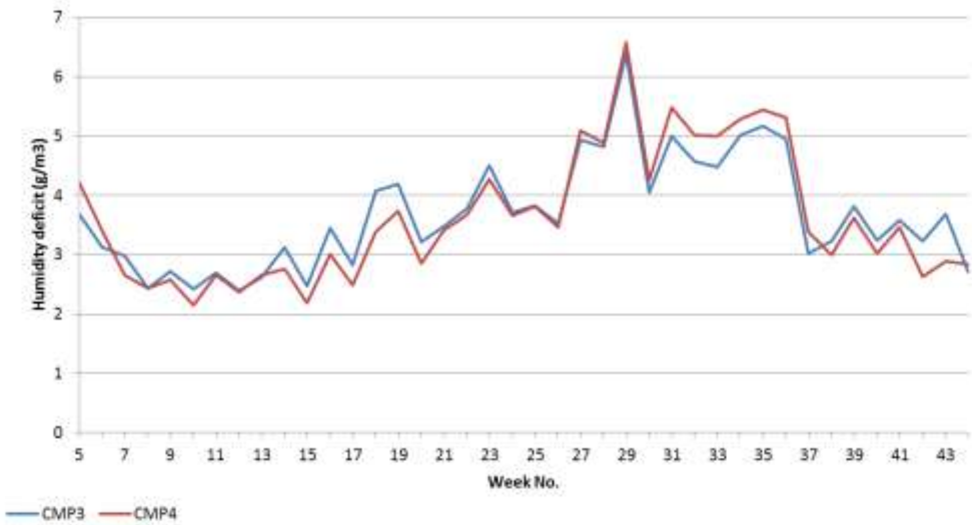

Figure 12. Average daytime humidity deficit

With the crop transpiring much less overnight the dehumidifiers had a bigger impact on the night time HD achieved (figure 13).

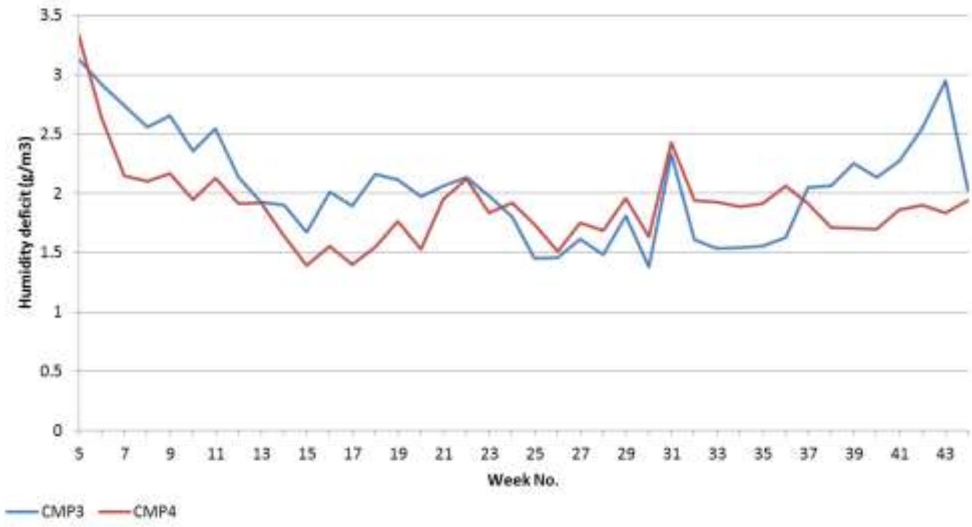

Figure 13. Average night time humidity deficit

CO_2

With the dehumidifier achieving a slightly better HD during the daytime in CMP3 with less venting better CO_2 levels might be expected. However, as previously discussed in relation to the impact on daytime HD, their impact on daytime HD levels and therefore venting was relatively small. In addition, their greatest impact on venting tended to be when the daily heat demand was still high and therefore CO_2 supply was not a limiting factor. Overall, the dehumidifiers had no measurable impact on the daytime CO_2 level achieved.

The dehumidifiers did however have a notable impact on the night time CO_2 level. This ties in with more screening hours and less gapping / venting overnight. Although the night time CO_2 level has no direct consequence / impact on yield, there was thought to be a potentially negative impact through the greater retention of flue gas pollutants such as NO_x and ethylene.

Thermal screen operation

With the dehumidifiers running almost all the time when the thermal screen was closed, and delivering a better humidity control, the screens were gapped less and closed for longer compared to CMP4 (figure 14).

Over the whole cropping year the screens in CMP3 were closed for 2,091 hours compared with 1,867 hours in CMP4 (12% more).

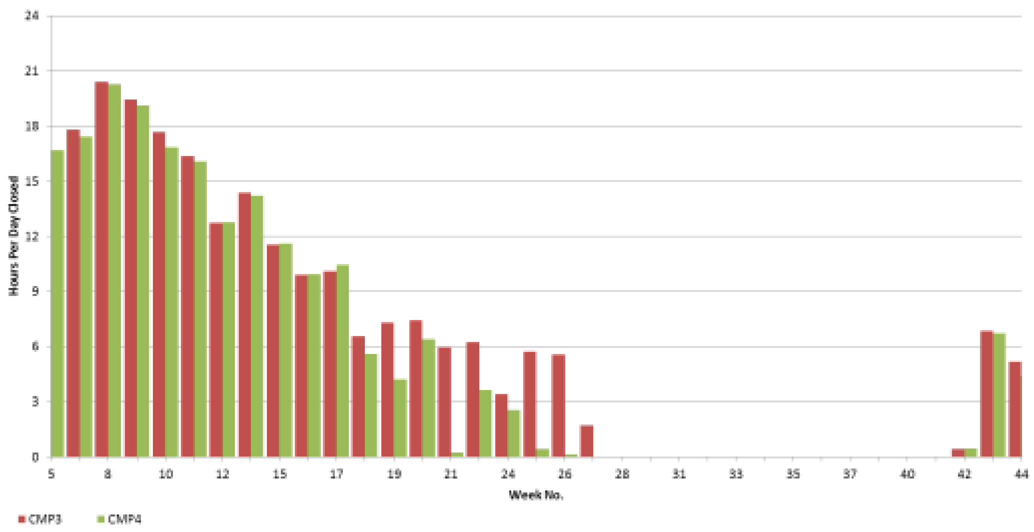

Figure 14. Thermal screen hours

Temperature uniformity

An area of concern with the dehumidifiers was their possible adverse impact on temperature uniformity. We considered that, as a less distributed form of heat, regional areas of higher temperature might be evident. Figure 15 below shows the average temperature achieved on a grid of 15 data loggers over a 3 day period in February when the dehumidifiers were turned off. Figure 16 shows data from the same loggers under comparable conditions one week later when the dehumidifiers were turned on.

With the dehumidifiers off the highest temperature was 1.9^{o}C above the average and the lowest was 2.0^{o}C below the average. With the dehumidifiers on the highest temperature was 0.4^{o}C above the average and the lowest was 1.7^{o}C below the average. This result was validated / confirmed by comments from the grower pertaining to the comparative evenness of the crop compared with previous years.

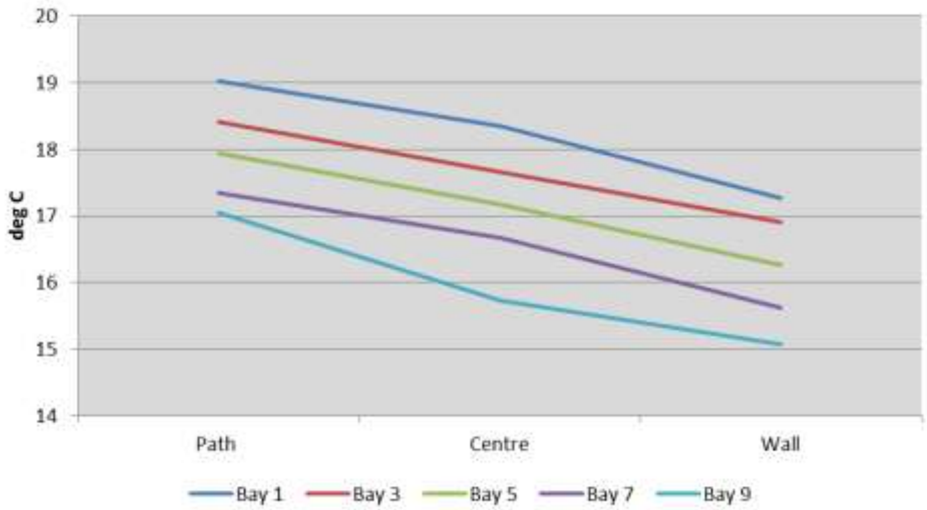

Figure 15. Temperature uniformity: dehumidifiers off

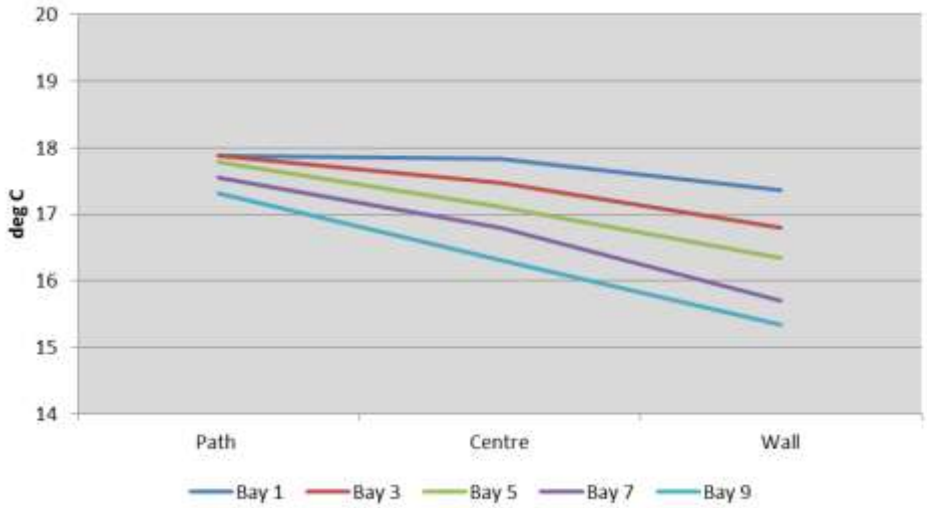

Figure 16. Temperature uniformity: dehumidifiers on

Crop data

The following data focusses on the period up to week 28 and was compiled by the nursery's crop advisor Ronald Duyvestijn. After this date other factors, principally pests and flue gas pollutants, affected crop performance and made any potential comparison misleading.

Fruit set

Fruit set was almost equal in the two compartments at the start of the season but then tended to be worse in the dehumidifier treatment during weeks 10 to 16 when the dehumidifiers had their greatest impact on the greenhouse climate (most notably HD). This trend reversed between weeks 15 and 20. During this whole period dehumidifiers treatment set a total of 1,936 fruit and the control set 1,886 fruit (figure 18).

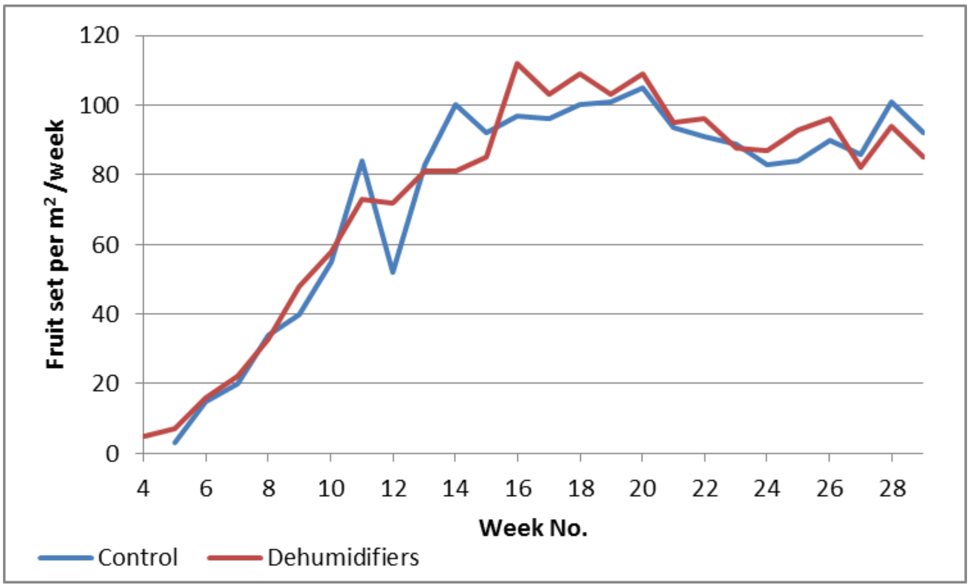

Figure 17. Fruit set per week

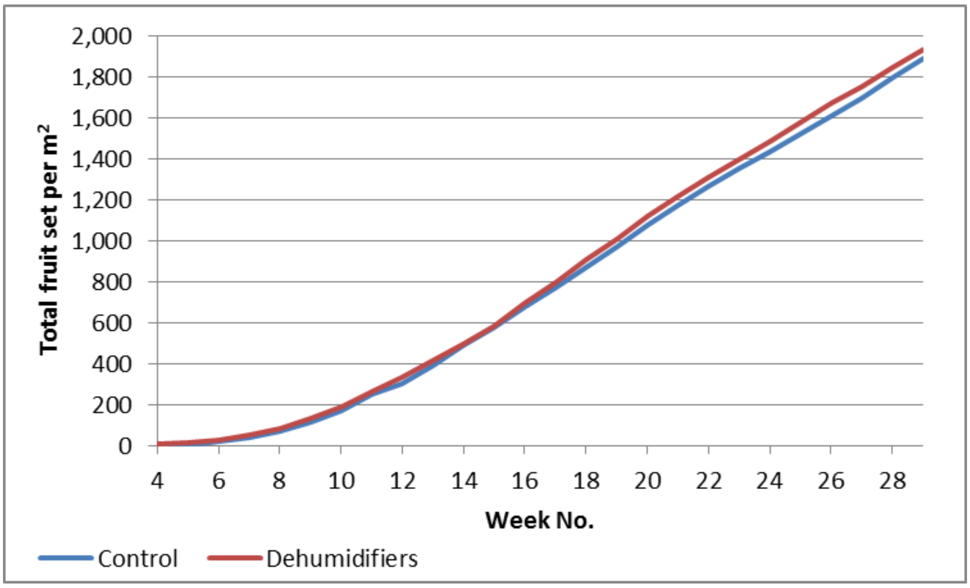

Figure 18. Total fruit set

Fruit size

Although not measured specifically for this trial, measurements in the control treatment gave an average fruit weight of 12g. The fruit size in the dehumidifier treatment was often visually less. Although the fruit set was higher, the quality of fruit set in the dehumidifier treatment was not as good.

Leaf length

Between weeks 7 to 10 the leaf length in the dehumidifier treatment was shorter, possibly caused by the lower humidity in that compartment (figure 19). Around week 11 this pattern reversed and although the trend was for shorter leaves, the leaf length in the dehumidifier treatment was always longer. Longer leaves suggest a more vegetative growth habit.

Figure 19. Leaf length

Truss length

Short truss length indicates larger fruit and a more generative growth habit. The trend was similar to the leaf length with a notable change in week 11. The longer truss length was in line with the visually smaller fruit size seen at the same time.

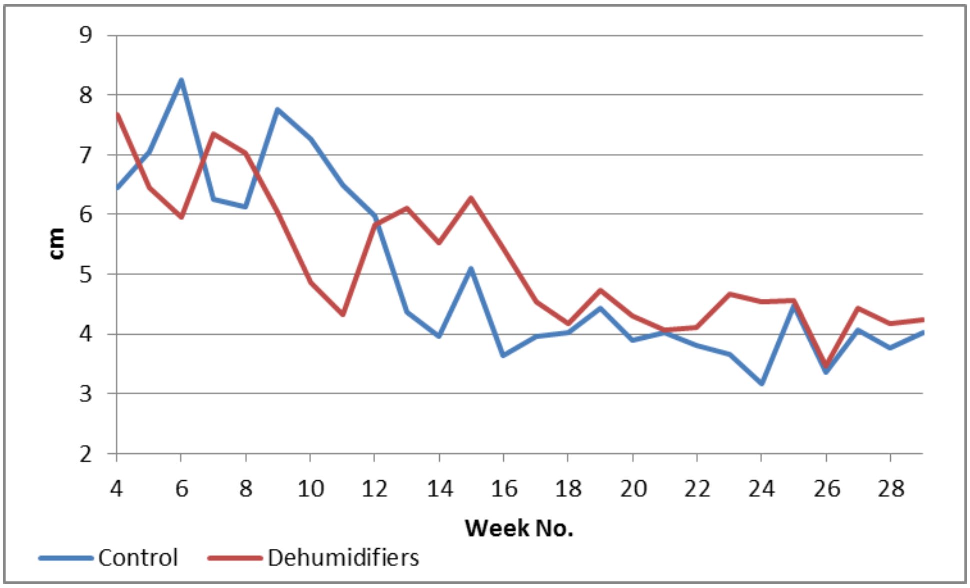

Figure 20. Truss length

Truss height

There was no clear difference between the treatments.

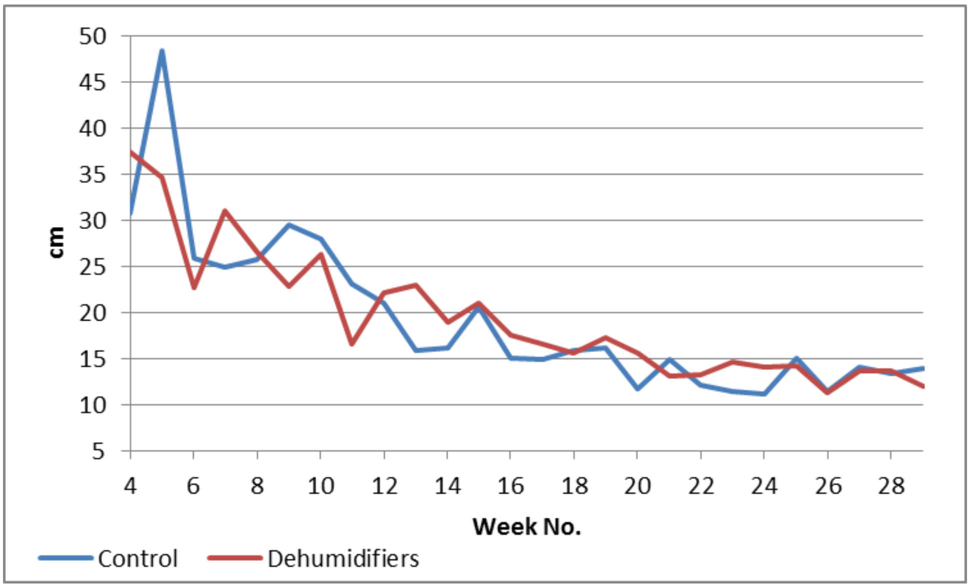

Figure 21. Truss height

Yield

The total yield up to week 30 was 17.2kg/m^2 in the dehumidifier treatment and 18.2kg/m^2 in the control (figure 22). This difference occurred mainly between weeks 17 and 20. These fruit were set between weeks 10 to 14. This coincides with the more vegetative trend in the crop noted in the leaf length and truss length at the same time.

Looking more closely at the yield between weeks 21 to 30, the total was 11.68kg/m^2 in (dehumidifier) and 11.66kg/m^2 (control). The fruit harvested in this period were set when the plants were equally in balance in both compartments and dehumidifiers had a rapidly diminishing impact on the greenhouse climate.

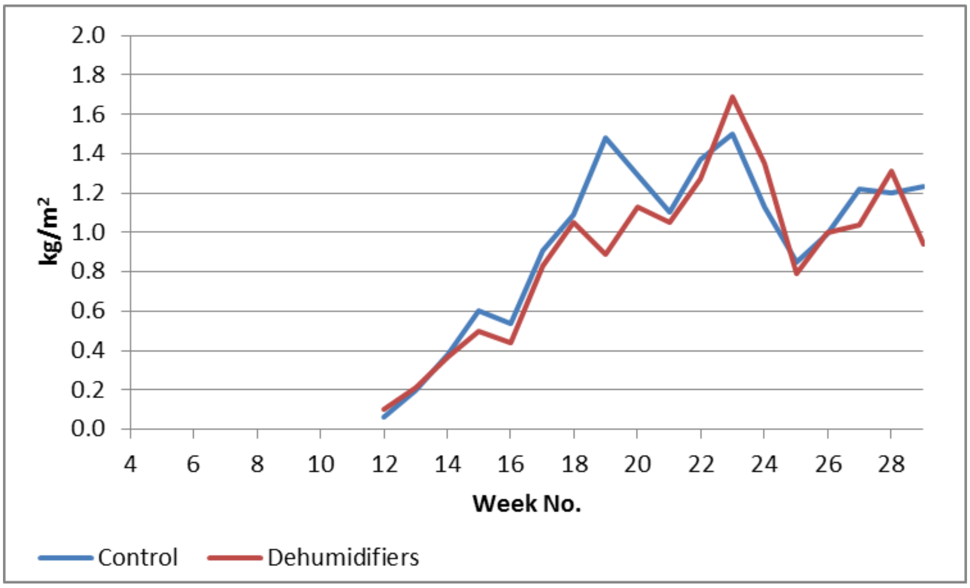

Figure 22. Yield

Disease

Formal disease monitoring was not carried out. However, the clearest indication of the impact of dehumidifiers on fungal disease such as *Botrytis* was the nursery's spray records.

Control compartment (CMP4) – two fungicide applications; one in early May and one in early October.

Dehumidifier compartment (CPM3) – no fungicide applications.

Albeit somewhat informal, tomato study groups that visited the nursery during 2013 agreed that disease levels in CMP3 were lower than in CMP4.

Summary of crop data / effects:

- The dehumidifiers had a more vegetative effect on the plants.
- There was no effect on the ripening speed; as the production started in both compartments at the same time.
- The fruit size was smaller.
- The total fruit set was higher.
- The total production was 1 kg/m^2 less.

- The production loss occurred between weeks 7 and 20. This was related to a very vegetative trend period in the plants in the dehumidifier compartment.
- To avoid the lower yield a more generative plant should be created early in the year.

Ornamentals crop – data collection and modelling

Analysis of data collected

Energy

Figure 23 shows the amount heat used each week by the greenhouse. This served as the benchmark against which savings were calculated. The total amount of heat used p.a. was 261 kWh/m^2.

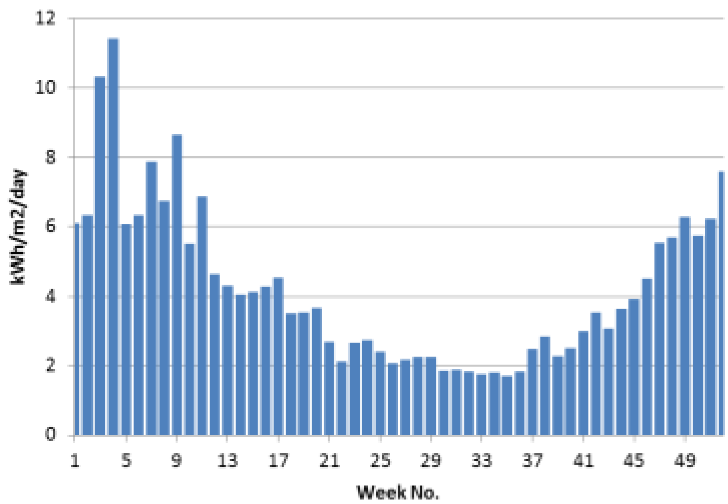

Figure 23. Ornamental crop heat use

Greenhouse climate – prediction of dehumidifiers operation

As mentioned previously, energy savings can be achieved even when the humidity is deemed to be acceptable. The saving achieved is however affected by the amount of water in the air; a lower RH resulting in a lower saving. In addition, a lower air temperature but high RH will result in a lower saving as the amount of water held in the air (absolute humidity) is low, limiting the latent energy that can be recovered. Fortunately, the temperature in both the ornamental and tomato greenhouses were broadly similar leaving the humidity as the key difference.

To determine the dehumidifier running hours with the ornamental crop the following control strategy was applied. The dehumidifier was deemed to have been running if:

- The heating pipe temperature was above a set threshold
    - Ensuring that it only runs when a heat saving would have been achieved
- The RH was above a set threshold
    - Ensuring that it only runs when it’s efficiency is acceptable

Figure 24 shows the predicted daily length of dehmidifaction operation time for RH and pipe temperature thresholds of 65% and 30^{o}C respectively. In this situation the dehumidifiers would run for 6,491 hours p.a.

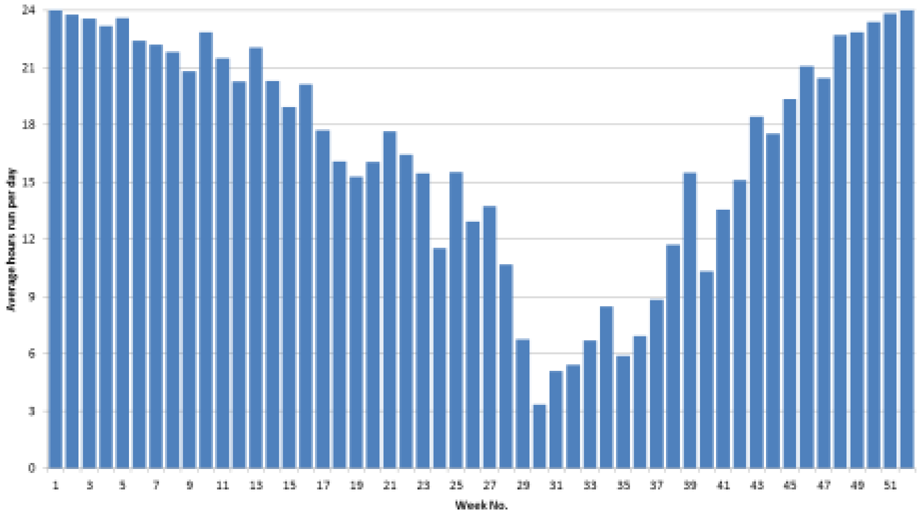

Figure 24. Ornamental crop run regime model

The modelled impact of increasing the RH threshold to 70% (the main driving factor) was relatively small, reducing the total hours to 6,401 hours p.a. (1.4% less).

Dehumidifier CoP

Multiplying the dehumidifier running hours by power rating (kW) gives the total kWh of electricity used. Multiplying this by the dehumidifier CoP gives the amount of heat saved. CoP data from the 2013 tomato trial is slightly misleading due to the compressor problem early in the year. However, with the project being extended into 2014, more recent data allowed a better assessment of the true CoP. Figure 25 shows the CoP trend used to calculate the potential savings.

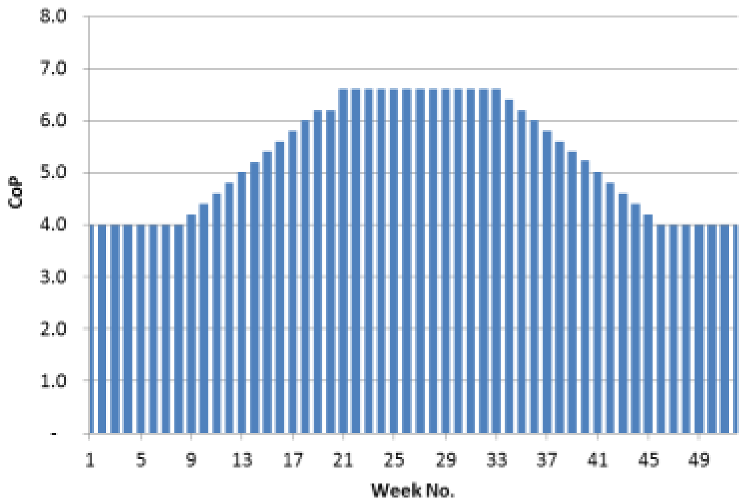

Figure 25. Ornamental crop: CoP expected

Energy saving

Combining all the information above produces the data forming Figure 26 below. The model produces a potential anomaly around week 30 in particular; the impact of the dehumidifier seems disproportionately low. However with energy used in this period being small and considering the limitations of the model, the effect on indicated annual performance is deemed insignificant. The projected annual energy data were:

- Heat saved 97kWh/m^2 (37%)
- Electricity used 19.5kWh/m^2

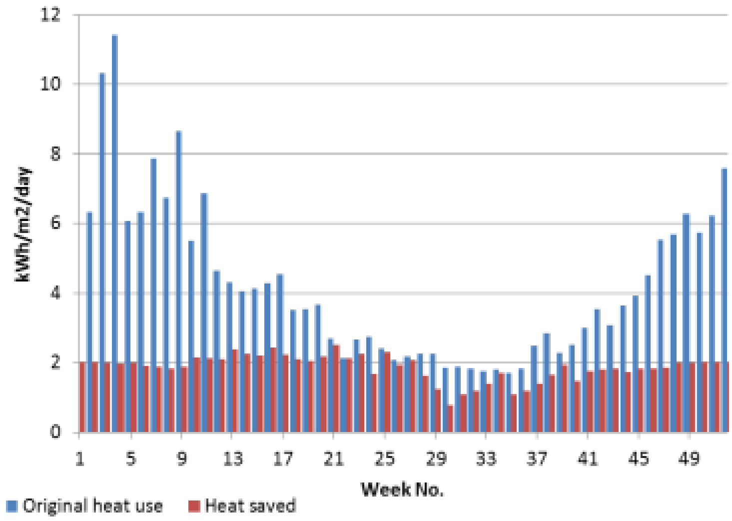

Figure 26. Ornamental crop: calculated heat saving relating to use of dehumidifiers

Financial impact

Crop effect

A lower yield was recorded in the tomato trial in 2013. However, advice suggests that this can be resolved and this is being scrutinised in the 2014 trial.

No such effect is expected on ornamental crops.

The figures that follow assume no crop related benefit or loss.

Capital cost

The current list price of the equipment supplied by Drygair is £17,000 per unit. Normal purchasing discounts plus the possibility of competition in the market could reduce the price down to around £14,000 per unit.

The cost to install the dehumidifiers can be significant. One area that could be overlooked is the cost of providing electricity to each unit. This comprises both cabling within the nursery plus the possible need to reinforce the grid connection to a nursery. Both are relatively unique to a specific site.

For the purposes of the following calculations we have assumed:

- Tomato crop (broadly applicable to all high temperature edible crops)
    - 6 dehumidifiers per Ha – total cost £84,000
    - Electrical installation including controls - £15,000
    - Total installed cost £99,000/Ha (£9.90/m^2)
- Ornamental crop
    - 3 dehumidifiers per Ha – total cost £42,000
    - Electrical installation including controls - £10,000
    - Total installed cost £52,000/Ha (£5.20/m^2)

Energy saving

Cost of electricity used

Red Roofs Nursery benefit from having CHP. In 2013, the average cost of electricity used was around 6.0p/kWh. If the electricity was all imported from the grid the average would be in the region of 7.0p/kWh.

Value of the heat saved

With Red Roofs having CHP it could be argued that the heat saved is worth less than if it had been produced by a boiler. However, the CHP rarely satisfied all of the heat demand so the heat saved by the dehumidifiers would have reduced boiler operation in most instances.

For the purposes of this assessment, prices broadly indicative of those in 2013 were used (assumed boiler efficiency of 85%):

- Natural gas – 2.7p/kWh (68p/Therm)
- Cost of electricity
    - Imported from the grid – 7.0p/kWh
    - From CHP – 6.0p/kWh
- Gas oil – 7.5p/kWh (70p/litre)

Table 4 below shows detailed results for each scenario considered. Table 5 shows the net financial saving.

Table 4. Energy saving cost breakdown relating to use of dehumidifiers

	High temperature edible crops	Ornamental crop
Heat saving (kWh/m^2)	91	97
Electricity used (kWh/m^2)	19	19.5
Value of heat saved (natural gas)	£2.48	£2.65
Value of heat saved (gas oil)	£6.98	£7.36
Cost of electricity used (CHP)	£1.14	£1.17
Cost of electricity used (100% import)	£1.33	£1.37

Table 5. Energy saving summary

	Saving £/m^2	
	High temperature edible crops	Ornamental crop
Natural gas heat source / CHP electricity	£1.33	£1.48
Natural gas heat source / 100% import electricity	£1.14	£1.28
Gas oil heat source / CHP electricity	£5.74	£6.19
Gas oil heat source / 100% import electricity	£5.55	£5.99

Edible crops

In practice most nurseries have natural gas. In this case the simple return on investment would be 9 years based on the trial results as measured. However, with experience gained during this project additional savings of 30kWh/m^2 seem possible. This would bring the simple return on investment down to 6 years.

Ornamental crops

Very few (if any) ornamental nurseries in the UK have CHP i.e. all electricity used would be imported from the grid. Furthermore high energy ornamental crops tend to use natural gas. Therefore a saving of £1.28/m^2 is most likely to apply to high energy ornamentals nurseries. This being the case, a simple return on investment in 4 years is expected.

Due to the cost of gas oil, ornamental nurseries that use it tend to grow lower energy requirement crops. Therefore the potential energy saving (kWh) will be les; so the comparison in the above table is less likely to occur in practice. In this situation, a simple pro-rata of the savings based on total current heat use compared with the data from Double H Nurseries is useful. For example, if a nursery used 1/3 of the heat p.a. the savings would be in the order of 1/3 (£1.82/m^2). Even so, with the high cost of gas oil the simple return on investment would then be 3 years.

Discussion

Tomato trial

Energy

Albeit compromised to some degree by poor performance of the dehumidifiers early in the trial the total heat saving achieved was still significant (22%). Interestingly, this is of a similar magnitude to the first year savings obtained when thermal screens were first trialled in the UK (PC 198, 2003) and thermal screens are now accepted as standard equipment in a modern glasshouse. With the experience gained during 2013 it is also clear that savings could have been realised before week 7 when the dehumidifiers were not used in 2013. Additionally, the unusual cold March and April in 2013 will have resulted in smaller savings than would have been obtained in an average year. There is therefore little doubt that energy savings recorded for the tomato crop in 2013 can be beaten. A target saving of 100kWh/m^2 seems realistic.

Beyond the impact of the dehumidifiers in isolation, they have potential to change other aspects of greenhouse construction/equipment. The most obvious is thermal screens where there is often a compromise between energy saving and humidity control. There is a particular focus by thermal screen manufacturers on developing materials that are well sealed with regard to air exchange but that have an inbuilt 'wicking' action to allow moisture to pass through them. However, even allowing water vapour to pass through is allowing energy to be lost. Dehumidifiers both remove the need to allow moisture to pass through screens, thereby allowing higher energy saving materials to be used, and recover the energy contained in the water vapour. This provides the opportunity for a second tier of energy saving through the use of different thermal screen materials and/or the addition of a second thermal screen (whether moveable or temporary). We believe that there is the potential to save a further 20-40kWh/m^2. This would bring the total annual energy use of a modern, but far from state of the art greenhouse, down to the same levels as those being achieved at the Improvement Centre (NL) using the 'New way of Growing'.

As with many energy saving technologies and/or alternative heat sources, the need for CO_2 in edible crops in particular limits the savings they can deliver for as long as growers are reliant on natural gas as their source of CO_2.

Greenhouse climate

The greatest concern about the dehumidifiers used for the trial was their heat distribution characteristic. Warm air discharge was delivered over the top of the crop contrasting with warm air rising from heating pipes with a conventional hot water system. One impact of this could have been slower ripening of the fruit, but this was not evident in the crop data.

One theory was that the warm air being blown across the top of the crop contributed to the vegetative shift of the crop around week 11. However, the crop advisor did not believe that this was the case.

A second concern was whether four point sources of heat, albeit with built-in fans to deliver increased air movement, would deliver good temperature uniformity. A network of data loggers showed that, if anything, there was a slight improvement in temperature uniformity when the dehumidifiers were used.

Crop

Although there was a negative impact on yield, the nursery's crop advisor is confident that it can be avoided in the future. This does however remain to be proven and will be tested in the follow up HDC funded project PE 013a.

The most positive finding in relation to the crop was that no fungicides were applied to the crop with dehumidifiers whereas the control crop had two applications.

Note – these results are from one year of trials and there were no replicates.

Ornamental crop modelling

The need for less dehumidifiers per Hectare reduced the capital cost compared to an edible crop. Combined with the fact that they can be operated all year (not restricted due to the need for CO_2) the end result financially is reasonably attractive.

Lower energy use ornamental nurseries that use gas oil for heating have less to save in energy (kWh) terms. However, the substantially higher unit cost of gas oil means that dehumidifiers could still represent a good investment.

Dehumidifier performance with lower temperature crops (less than 16^{o}C) will be less than detailed above. The effect of this could not be quantified.

Conclusions

Edible crop trial

- Heat savings of 91kWh/m^2 p.a. (24%) were achieved.
    - Note this excluded 1 month of potential savings
- Dehumidifier electricity use of 19kWh/m^2
- No fungicides were applied to the dehumidifier crop compared with two applications to the control crop
- Yield in the dehumidifier crop was 1kg/m^2 less
    - Advice suggests that this can be avoided in the future
- Return on investment
    - 9 years based on current performance (excluding yield loss)
    - Reduces to 6 years if experience gained from 2013 trials is proven in 2014
- The need for CO_2 (from burning natural gas) during the summer significantly limits the savings that are possible.

Ornamental crop modelling

- Savings of 97kWh/m^2 (37%) were calculated vs. electricity use of 19.5kWh/m^2
- The need for less dehumidifiers means that a return on investment within 4 years appears possible.
- Nurseries that use gas oil for heating tend to be lower energy users. However, the high cost of gas oil offsets the lower kWh saving and could deliver a return on investment within 3 years.

Knowledge and Technology Transfer

- Tomato Working Party – nursery visit, April 2013
- HDC Energy News – July 2013
- Tomato Growers Association – Technical Committee meeting, September 2013
- Tomato Growers Association – Annual Conference, September 2013
- British Protected Ornamentals Association – Technical Committee meeting, October 2013

Glossary

CO_2	Carbon dioxide
CoP	Coefficient of Performance
Ha	Hectare
HD	Humidity deficit
KPI	Key performance indicator
kWh	Kilowatt hour
NO_x	Nitrogen oxides
RH	Relative humidity

References

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Bartlett D. (1991). DAG dehumidifier performance assessment in a cucumber house

