Project title:	A computational fluid dynamics (CFD) study of flow patterns, temperature distributions and CO_2 dispersal in a tomato glasshouse.
Project number:	PC 162
Project leader:	Professor T W Davies University of Exeter School of Engineering and Computer Science Harrison Building North Park Road Exeter, Devon EX4 4QF
Report:	Annual report (December 1999)
Key worker:	ir. S Reichrath
Project coordinators:	Dr Nigel Dungey, Hazlewood VHB Mr Philip Pearson, A Pearson & Sons Ltd Mr Gary Taylor, Cantelo Nurseries Ltd
Location:	University of Exeter, School of Engineering and Computer Science
Date commenced:	1 January 1999
Date completed:	31 December 1999
Keywords:	Computational fluid dynamics (CFD), modelling, Venlo-type glasshouse, temperature, airflow, CO_2 dispersal, model crops, thermodynamics, tomato

CONTENTS

PRACTICAL SECTION FOR GROWERS

Objectives and background

Computational fluid dynamics (CFD) was used as a modelling vehicle in this work. CFD has emerged from the development stage and is now a design tool that is widely used to study the real behaviour of all kinds of processes which involve fluid flow, heat and mass transfer (transport processes). Given enough time in the hands of a skilled modeller, a modern CFD software package can be used to replicate the essential behaviour of an operational glasshouse and will provide excellent graphic or virtual reality descriptions of a glasshouse to any desired change in design or mode of working or external environmental conditions.

CO_2 enrichment levels in glasshouse tomato crops have exceeded current research recommendations for many years now. The number of growers affected has steadily increased as more systems have been installed and take-up has spread to other sectors, especially cucumbers, peppers and bedding plants. In the absence of official statistics for use of CO_2 in glasshouses it is reasonable to assume that the majority of mainstream long season tomato nurseries will have systems installed and this project addressed some of the key questions related to this sector.

The objectives set for the CFD modelling in this project, as defined in the project description, were:

1. A description of the uniformity of CO_2 distribution in the glasshouse as affected by wind, sunlight and temperature and rates of CO_2 supply in order to answer questions relating to the correct positioning/ frequency of sampling points.
2. Determination of the relationship between pipe temperature and CO_2 concentration for the same glasshouse air temperature and rate of CO_2 addition in order to indicate when CO_2 increase by means of daytime pipe temperature increase is sensible.
3. Determination of the influence of position of layflats (height and frequency) and arrangement of holes in order to indicate if the current system layouts are optimal and if not how improvements may be accomplished.
4. A collateral objective was the analysis of the movement of CO_2 from the layflat holes as a function of hole size, orientation, spacing, supply pressure (i.e. exit gas velocity) and supply gas concentration.
5. Wherever possible, validation of all aspects of the modelling work was undertaken using available and appropriate experimental data.

The overall objective was to evaluate the usefulness and potential of CFD as a modelling tool for glasshouse research.

Summary of results

The results obtained from the CFD models are limited due to the simplicity of the models and the fact that it was only possible to develop two-dimensional simulations in the time available. However, a good first indication of problem areas and an indication of priorities for future research can now be given.

In order to be able to study the behaviour of CO_2 distribution in glasshouses, first the airflow must be described since this will mainly affect the dispersal. This study of flow patterns in multi span glasshouses has given some remarkable results. Simulation of flow in a 16-26 span house with leeward ventilation showed a main internal flow that was in opposite direction of the external wind speed and a 'dead' zone at about 0.6 X the length of the glasshouse, from the windward side. A typical flow situation is drawn in Figure 1.

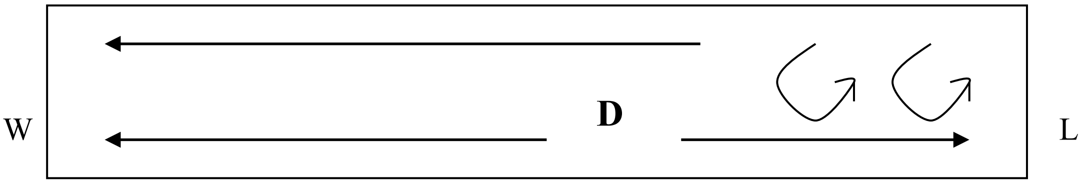


Figure 1: *Typical flow pattern in a multi span glasshouse. Arrows indicate flow direction. Left side is windward side (W), right side is leeward side (L). The 'dead' zone (D) is in the empty region at approximately 0.6 X length of the glasshouse from the windward side. The circular arrows at the windward side represent a swirling airflow.*

To study the CO_2 distributions in more detail, a section of two spans in winter conditions was modelled. In the two span section, the layflat position clearly influenced the CO_2 dispersal in the glasshouse in a positive way if the height of the layflats was increased. Using the same injection rate of CO_2, the absolute CO_2 concentration in the house increased and the uniformity of CO_2 distribution was improved. Both pipe temperature and CO_2 temperature did not have significant effect on the dispersal of CO_2 in the glasshouse.

Studies of flow from the layflat holes have demonstrated that the effect of single holes on the dispersal of CO_2 can be neglected. Therefore, also the rate of flow of CO_2 through the nozzle is negligible.

Action points for growers

Bearing in mind the restrictions of the model only one positive recommendation can be made from the output of this part of the study:

- Use more than one sample point for glasshouse control.

Practical and financial benefits

The work has clearly shown that the flow patterns in a multi span glasshouse must be studied in more detail. This might lead to a change in positioning of the sampling points that can optimise glasshouse control. If flow patterns are known, CO_2 dispersal and layflat positioning can be studied in detail and recommendations to increase efficiency and effectiveness could follow.

This work has demonstrated the power of CFD for glasshouse research and the future potential for optimising glasshouse management, control and design. It also has indicated priorities for future research and highlighted gaps in experimental data that are currently available.

SCIENCE SECTION

Introduction

In the first year of this project, computational fluid dynamics (CFD) was evaluated as a tool to model the convective processes inside a glasshouse. After 30 years, CFD has emerged from the development stage and is now a design tool that is widely used to study the real behaviour of all kinds of processes that involve fluid flow, heat and mass transfer (transport processes). Given enough time and expertise, a modern CFD package can be used to replicate the essential behaviour of an operational tomato glasshouse and will provide excellent graphic or virtual reality descriptions of the responses in the convective processes in a glasshouse to any desired change in design or mode of working or external environmental conditions. Limitations of CFD lie in the ability to model certain physical processes to the required degree of accuracy (also dependent on available data) and the amount of computational power available.

The objectives set for the CFD modelling in this project, as defined in the project description, were:

1. A description of the uniformity of CO_2 distribution in the glasshouse as affected by wind, sunlight and temperature and rates of CO_2 supply in order to answer questions relating to the correct positioning/ frequency of sampling points.
2. Determination of the relationship between pipe temperature and CO_2 concentration for the same glasshouse air temperature and rate of CO_2 addition in order to indicate when CO_2 increase by means of daytime pipe temperature increase is sensible.
3. Determination of the influence of position of layflats (height and frequency) and arrangement of holes in order to indicate if the current system layouts are optimal and if not how improvements may be accomplished.
4. A collateral objective was the analysis of the movement of CO_2 from the layflat holes as a function of hole size, orientation, spacing, supply pressure (i.e. exit gas velocity) and supply gas concentration.
5. Wherever possible, validation of all aspects of the modelling work was undertaken using available and appropriate experimental data.

The overall objective was to evaluate the usefulness and potential of CFD as a modelling tool for glasshouse research.

Materials and methods

A reference glasshouse was used for model construction and subsequent simulation of the physical processes of the internal environment. The glasshouse chosen was the new block of Cantelo Nurseries at Taunton, which is a modern Venlo-type house of 240m * 160m with a concrete path in the centre of the house in the east-west direction, normal to the gutters. The height to the gutter is 4.3 m, the roof angle of 22 degrees and the span width is 4 m. Under every two spans five rows of crop were placed. Heating and CO_2 injection rates used were 45 degrees Celsius pipe temperature in summer conditions (open vents), 60 degrees in winter conditions (closed vents) and an injection rate of CO_2 of 49 kg/1000m^2/h with a CO_2 temperature of 30 degrees Celsius. There were two heating pipes per crop row and one layflat pipe. For the purposes of the study the external wind was assumed to be west-east and normal to the gutter and the ambient CO_2 concentration was assumed 300 ppm. When modelling summer conditions only leeward ventilation was considered.

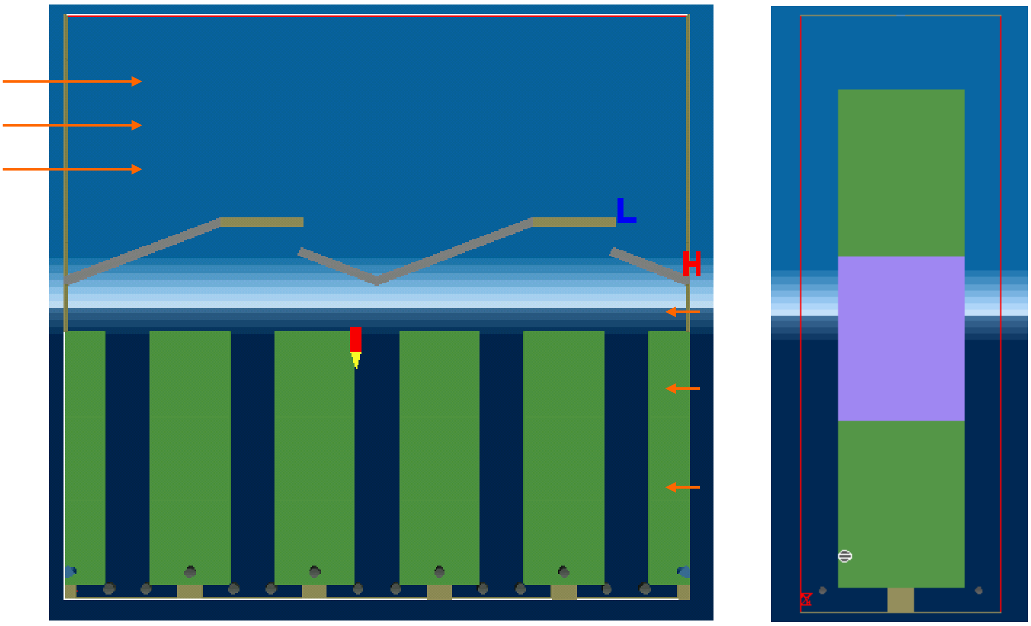
The commercial CFD package PHOENICS V3.1 was used to carry out the modelling and simulate the physical processes of the internal glasshouse environment. PHOENICS stands for: Parabolic Hyperbolic Or Elliptic Numerical Instruction Code Series. CFD is software that solves the conservation equations of heat, mass and energy numerically (i.e. approximately) over a finite volume. These conservation equations describe natural physical processes. The software defines objects in a computational domain that is divided into a number of cells. The smaller these computational cells, the more accurate is the resulting solution but the heavier the demand on computer power (size and speed). The conservation equations are solved in each cell of the domain in an iterative process until values are reached for each solved variable (i.e. temperature, flow speed and direction, pressure, concentration) which satisfy the conservation equations in each cell and for the computational domain as a whole. At this stage the CFD package has achieved a reasonable imitation of the real natural process under study. To reach a solution, initial and boundary conditions (i.e. the concentration of injected CO_2, temperature of the heating pipes, wind speed, direction and profile of wind over the glasshouse) have to be applied to the objects and boundaries of the computational domain; setting such conditions is the most difficult part of the modelling process.

The overall approach to modelling involves a step-by-step evolution with complexity increasing from one step to the next. For this reason and also to reduce computational time, only two dimensional models were considered in this study. Two-dimensional modelling produces simulations in one plane, in two directions only, neglecting the effect in the third direction. To further reduce the computational effort, a representative part of the glasshouse was identified. This representative, repetitive part was a two span section containing five rows of crop. In the two span section a simple model crop was placed which consisted of three different crop canopy layers, following the work of Acock (1) where each layer had a different contribution to the overall CO_2 uptake for photosynthesis (66%, 28% and 8% from top to bottom, respectively). Also the difference in flow resistance of the three layers was taken into account by using different values for porosity, the middle layer being assumed densest, the bottom layer was considered to give a negligible resistance to flow and the top layer was of intermediate porosity (assumed values were 0.5, 0.8 and 1.0 for the middle, top and bottom layer of the crop respectively).

The two span, three layer crop model can be seen in Figure 2

Results

The results from the CFD models will be presented according to objectives 1 to 4. Objective 5, the validation, will be discussed at the end of the results obtained for each objective. In addition to the output in terms of simulations, this project has also produced several publications and papers, an extensive literature list (3) and numerous national and international contacts have been established.



a) b)

Figure 2: *a) Two span section of the glasshouse with leeward ventilation and an internal flow opposite to the external wind direction. Two heating pipes and one CO_2 layflat pipe per crop row, b) Model crop, 3 layers of equal height each with a different CO_2 absorption rate and flow resistance.*

1) A description of the uniformity of CO_2 distribution in the glasshouse as affected by wind, sunlight and temperature and rates of CO_2 supply in order to answer questions relating to the correct positioning/ frequency of sampling points.

The description of the CO_2 distribution was carried out in both a summer condition, with open vents, and a winter condition, with closed vents.

1.1 Summer condition

First, the summer condition, where only leeward ventilation was considered. The outside air temperature was assumed to be 17 degrees Celsius. Pipe temperature and CO_2 injection rate were standard as mentioned in the paragraph 'Materials and methods', 45 degrees Celsius and 49 kg/ $1000m^2$/ h, respectively. Since the CO_2 dispersal is mainly driven by the flow in the glasshouse, either buoyancy or ventilation driven flow, first the flow pattern has to be known before the CO_2 distribution can be described. If the vents are open, an internal flow will occur due to a pressure difference over the glasshouse. To obtain the characteristics of this flow and boundary conditions for internal flow for the two span section, a multi span glasshouse (16-26 spans) with crops inside was modelled and a crosswind normal to the gutters was applied (see Figure 3).

This resulted in a typical flow pattern inside the glasshouse as drawn in Figure 1 or Figure 4. The main flow is in the opposite direction to the external wind direction and a 'dead' zone occurs at 0.6 X the length of the glasshouse from the windward side. This situation is very specific, with pure leeward ventilation with wind normal to the gutter. However, the direction of the main internal airflow is thought to be opposite to the main wind direction under leeward ventilation in general. This is concluded by Wang (2) who did measurements of airflow in an empty fourteen span commercial glasshouse and confirmed by smoke tests by the Exeter team at Cantelo Nurseries Ltd.

A section of two spans in the region where the main internal flow is opposite the external wind direction was taken as a representative part and its boundary conditions were used for the two span model (see Figure 4).

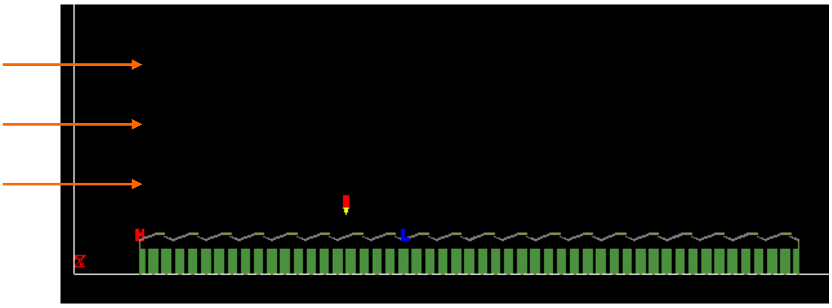


Figure 3: *Multi span glasshouse with leeward ventilation and crops inside placed in a crosswind normal to the gutter.*

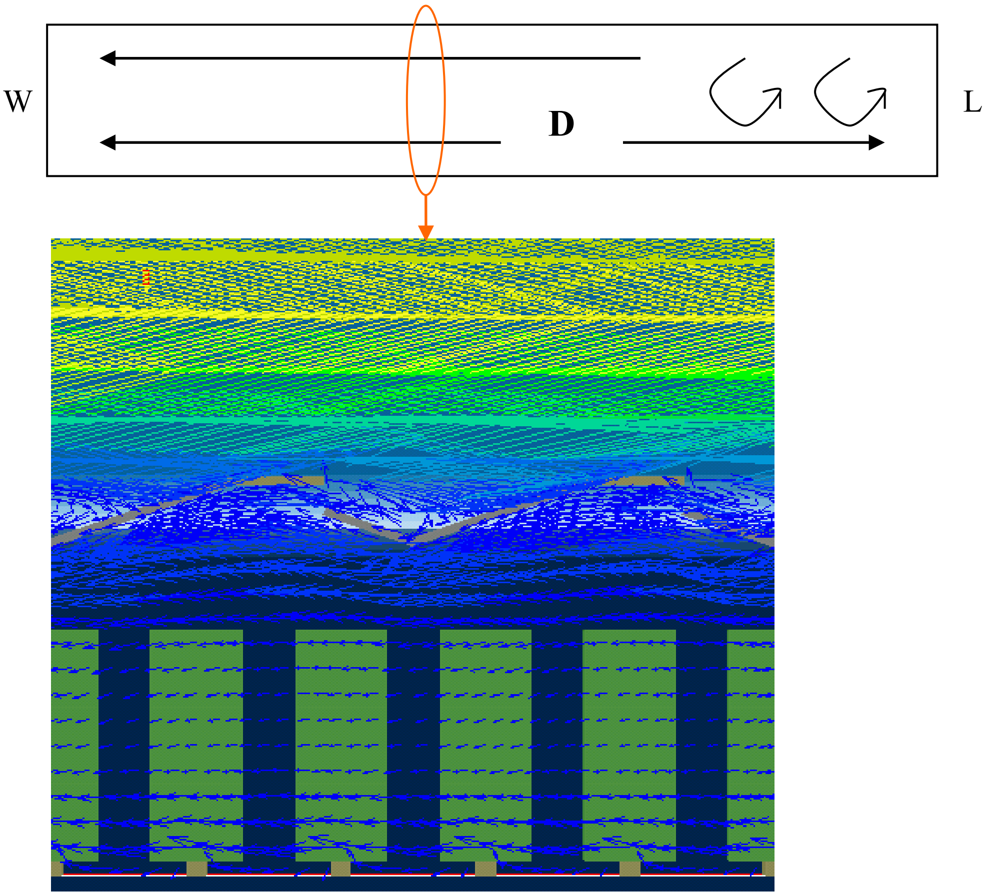


Figure 4: *The two span section taken from the region of the glasshouse where the direction of the internal flow is opposite to the external wind direction. For explanation of the internal glasshouse airflow, see also Figure 1.*

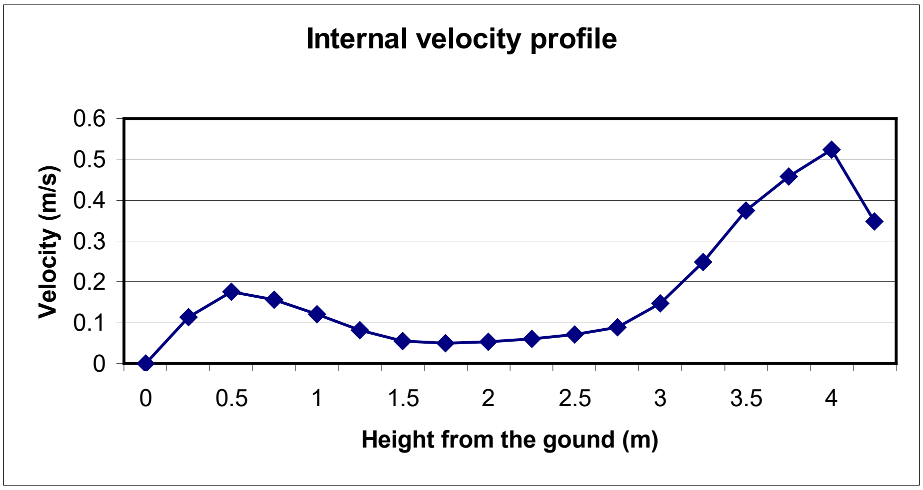
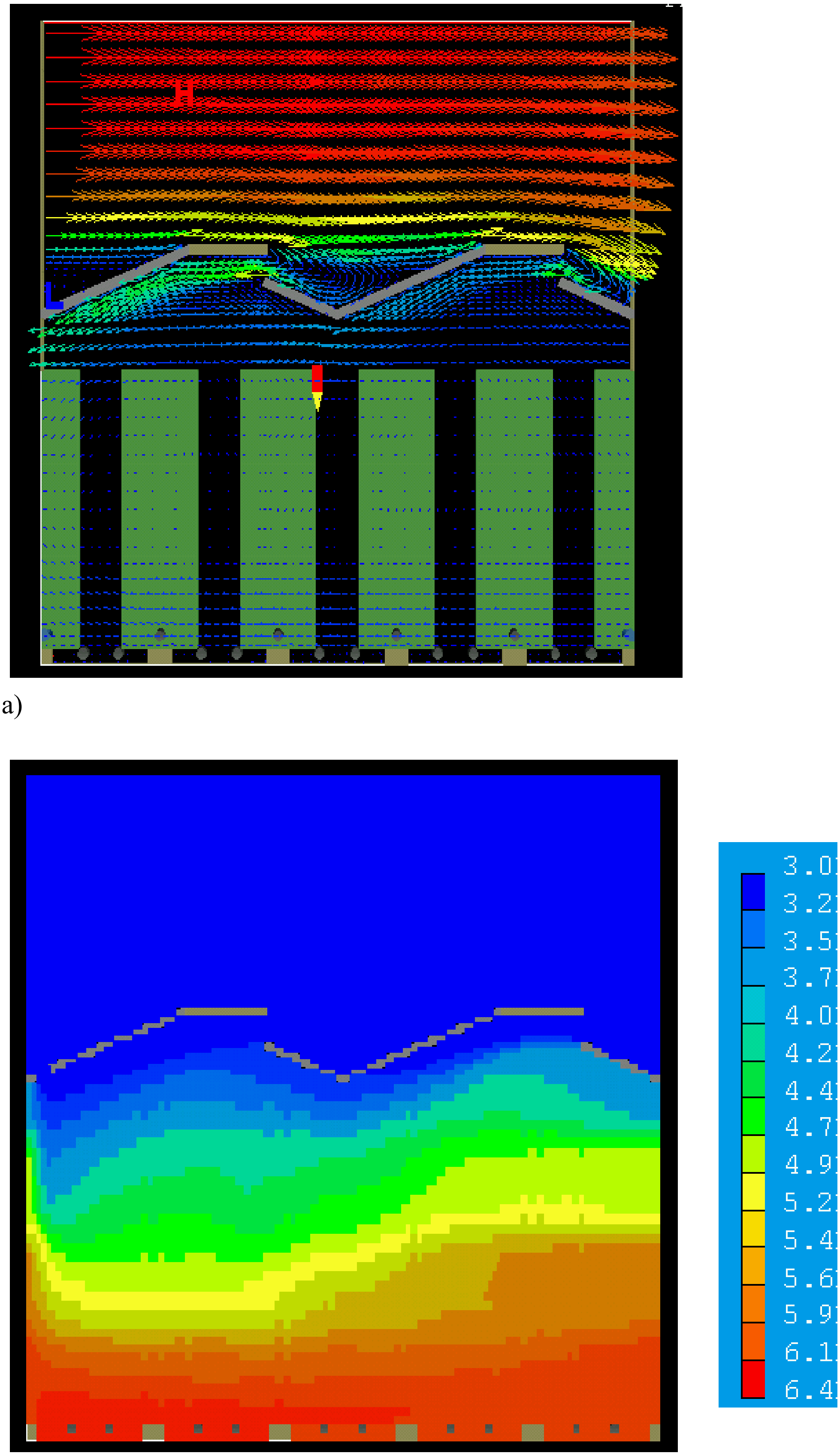


Figure 5: *Velocity of the internal air movement under a glasshouse gutter with a crop present.*

The boundary conditions for the internal flow resulting from this study of a multi span glasshouse can be drawn in a graph. In Figure 5, the internal air velocity under a gutter where a crop is present is drawn as a function of height to the gutter. A maximum velocity in the space above the crop and under the roof can be seen as well as a higher velocity in the bottom part of the crop where the flow resistance is negligible compared with the densest middle part and the top part of the crop.

In this specific case of leeward ventilation, a boundary condition for the internal flow and an external crosswind of 2.5 m/s (10 m reference height) normal to the gutter were applied to a two span summer model. In order to assess the effects of the wind speed on CO_2 and temperature distribution, the temperature and CO_2 concentration inside the glasshouse were assumed constant with height throughout the length of the two span section as a boundary condition. In other words, it was assumed that the CO_2 concentration and temperature are cyclical (windward side = leeward side). This ideal situation is used to explore the ability of CFD to model two-dimensional distributions of flow speed and direction, temperature and concentration. The results of the CFD simulations for the two-dimensional two span model are shown in Figure 6.

The predictions show an internal airflow that is opposite to the external wind direction and with flow entering the glasshouse through both vents. The flow is strong at the bottom of the glasshouse and even stronger above the crops and under the roof. Airflow entering the windward span is higher due to an imbalance in massflow over the computational domain. This is the result of modelling only two spans instead of a complete glasshouse and further studies will address this problem. This higher inflow drives the CO_2 concentration down under that span which leads to a maldistribution of CO_2 concentration. The temperature distribution is also similarly affected by this inflow. The maximum temperature in the model is 22 degrees Celsius and the maximum CO_2 concentration is 650 ppm at the bottom of the house, leading to a gradient of 350 ppm to the roof.



a)

b)

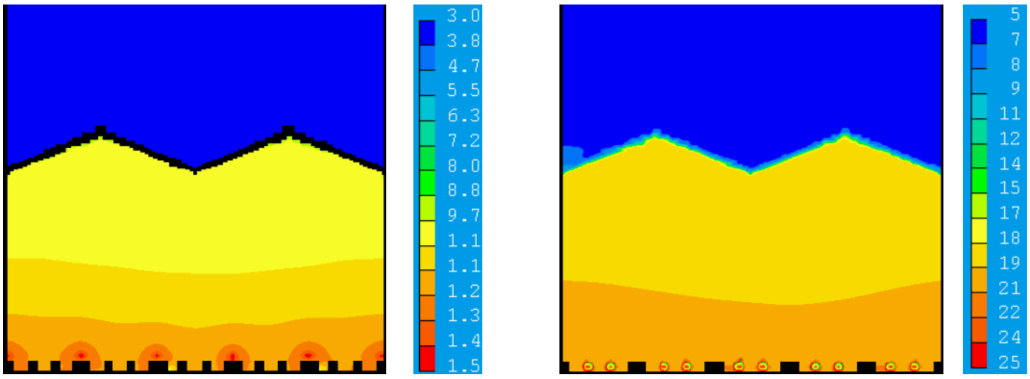
Figure 6: *a) Airflow predictions in the two span summer model, b)* CO_2 *distribution in the two span summer model. (Concentration value X 100 ppm, i.e. 3.0 = 300 ppm).*

1.2 Winter conditions

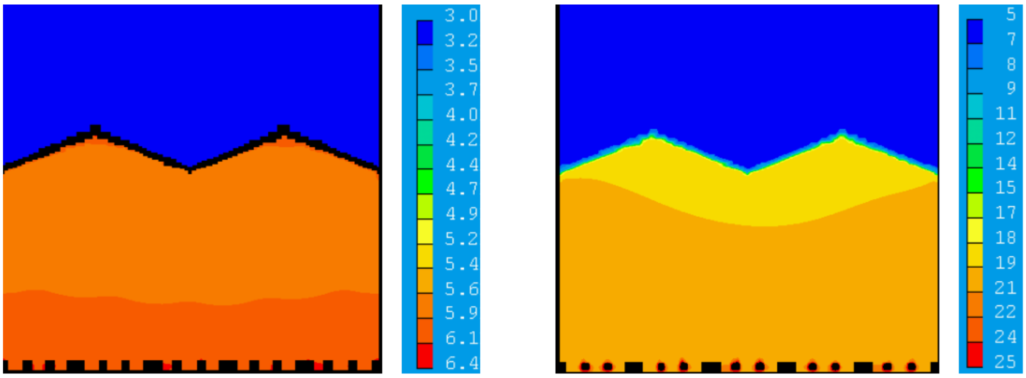
The second condition is the winter condition. The same configuration was used as in the summer condition. The differences were that a sealed glasshouse is assumed which leads to no prescribed internal flow, an outside air temperature of 5 degrees Celsius and a pipe temperature of 60 degrees Celsius. This model was solved under transient conditions, which means solved with respect to time. Four steps were simulated: step 1 with CO_2 injection (for 5 minutes), step 2 without CO_2 injection (for 15 minutes or after 20 minutes), step 3 with CO_2 injection (for 5 minutes or after 25 minutes) and step 4 without CO_2 injection (for 15 minutes or after 40 minutes). The results are shown in Figure 7.

After 5 minutes of CO_2 injection (step 1) an average CO_2 concentration of 1100 ppm was reached with a maximum of 1500 ppm occurring within a few centimetres of the layflat pipes. The temperature was 20 degrees Celsius. After 15 minutes without CO_2 injection (step 2) the CO_2 concentration dropped to 600 ppm average. The temperature remained around 20 degrees Celsius. If the CO_2 injection is switched on again and run for 5 minutes (step 3), the CO_2 concentration again rises to 1100 ppm average with a maximum of 1500 ppm around the layflat pipes. After another 15 minutes without CO_2 injection (step 4), the CO_2 concentration drops down again to an average value of 600 ppm.

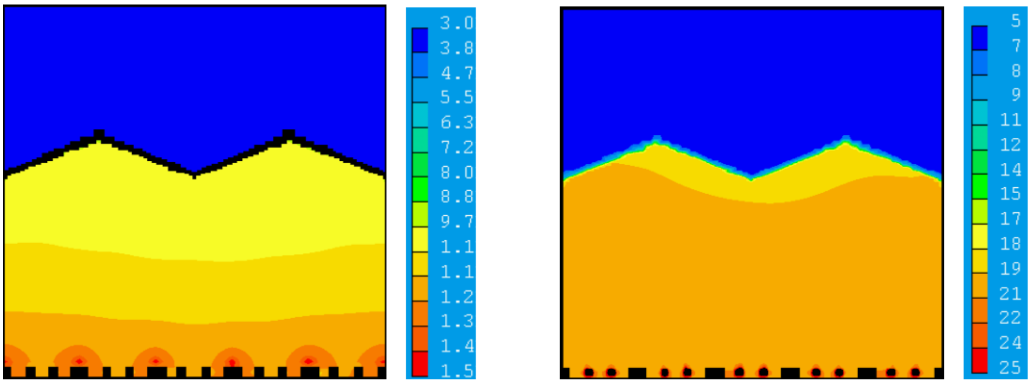
Regarding validation of the results presented above for both the summer and winter conditions, only the predictions of the direction of the internal airflow opposite to the external wind direction can be validated with existing literature (2) and smoke tests by the Exeter team at Cantelo Nurseries. Smoke tests have also been used by the Exeter team to visualise the airflow in the fully grown tomato crop canopy. These showed greatest airflow rates under and over the crop with lower rates in the dense middle and top part of the canopy. The characteristics of the internal glasshouse airflow and values of temperature and CO_2 concentration predicted from the two-dimensional studies were recognised by growers and glasshouse specialists as being similar to those normally recorded or observed.



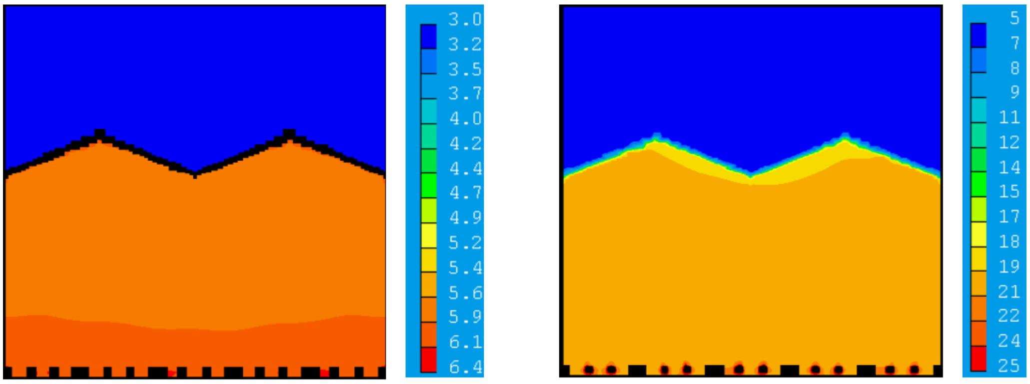
a1) 1000 ppm (max 1500 ppm) b1) 20 degrees Celsius



a2) 600 ppm (max 640 ppm) b2) 20 degrees Celsius



a3) 1000 ppm (max 1500 ppm) b3) 20 degrees Celsius

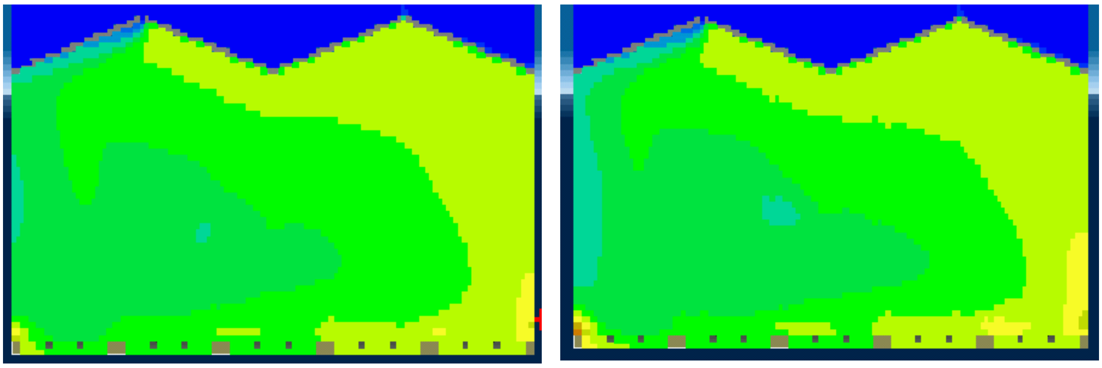


a4) 600 ppm (max 630 ppm) b4) 20 degrees Celsius

Figure 7: *a1-4) CO_2 distribution step 1-4; b1-4) Temperature field step1-4.*

2) **Determination of the relationship between pipe temperature and CO_2 concentration for the same glasshouse air temperature and rate of CO_2 addition in order to indicate when CO_2 increase by means of daytime pipe temperature increase is sensible.**

To evaluate the effect of a change in pipe temperature on the CO_2 distribution, a steady state two span winter model was used with leakage in the top of the roof. Due to the mass balance problems in the summer model and time restrictions to solve this problem, this test was not conducted with the summer model. The standard settings for the winter model as described above were used as a reference and the results of that model were compared with a similar model where only the pipe temperature was changed from 60 degrees to 45 degrees Celsius. The result can be seen in Figure 8.



a) 60 degrees Celsius

b) 45 degrees Celsius

Figure 8: *The effect of pipe temperature on CO_2 distribution. Equal colours represent equal concentrations (yellow = high, blue = low).*

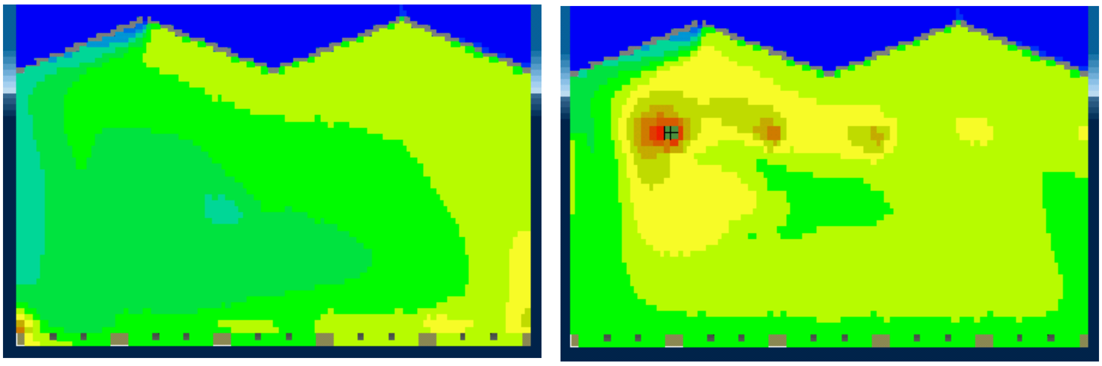
The effect of increasing pipe temperature from 45 to 60 degrees Celsius on the CO_2 distribution was negligible. In practice, an increase in pipe temperature would lead to an increase in CO_2 input into the glasshouse. To maintain a constant air temperature within the glasshouse, ventilation would be necessary. It has not been possible given the time available to calculate the transient effect of this extra ventilation on CO_2 distribution.

For validation purposes, data need to be made available.

3) **Determination of the influence of position of layflats (height and frequency) and arrangement of holes in order to indicate if the current system layouts are optimal and if not how improvements may be accomplished.**

To study the effect of the positioning of the CO_2 layflat tubing, again only the steady state two span winter model with leakage in the ridge was used. The results of the model with standard settings were compared with a model where the layflat pipes were put in the middle of the top layer of the crop. The result is shown in Figure 9.

When the layflat pipes were put higher in the canopy, the CO_2 concentration increased and the uniformity of the CO_2 distribution improved. In other words, with the same CO_2 injection rate, a higher CO_2 concentration is reached with a smaller CO_2 gradient in the glasshouse. However, in practice, the CO_2 injection will only occur for 25% of the time during the winter period and the average distribution will therefore be different. Some indication of the effects of non-continuous CO_2 injection on the CO_2 distribution pattern can be seen in Figure 7.



a) Low position

b) High position

Figure 9: *The effect of CO_2 layflat position on CO_2 distribution. Equal colours represent equal concentrations (red = high, blue = low).*

Under winter conditions if CO_2 is delivered at a high level in the crop, ventilation will be required to control humidity. Therefore, there will be need for future assessment in other conditions.

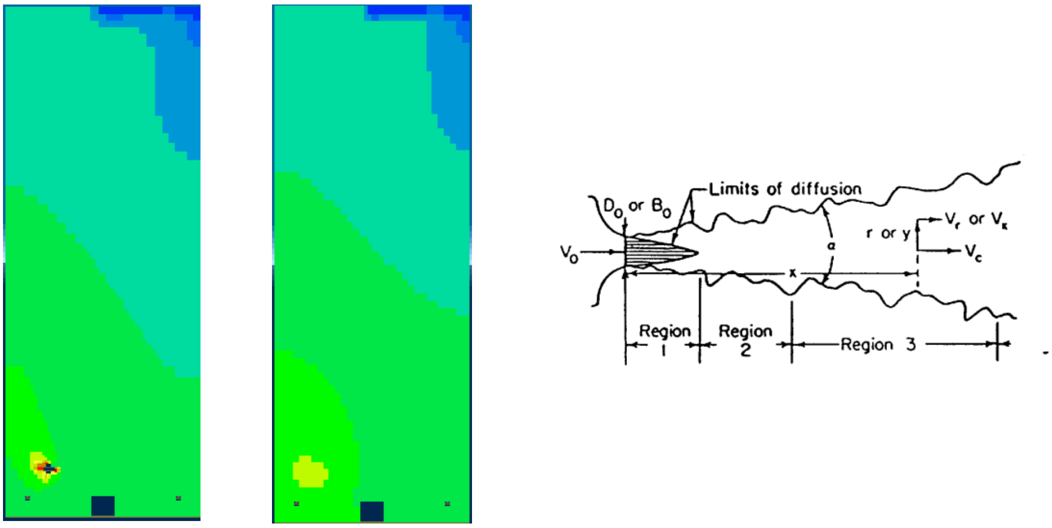
Detailed sampling from commercial sites is needed to provide confirmation of this two-dimensional simulation. Some confirmation was given by growers and glasshouse specialists who recognised the results from the two-dimensional studies (G Taylor, personal communication).

4) The analysis of the movement of CO_2 from the layflat holes as a function of hole size, orientation, spacing, supply pressure (i.e. exit gas velocity) and supply gas concentration.

Regarding the CO_2 diffusion from the jet, two aspects were investigated. First the mixing of the jet was studied and secondly the effect of the CO_2 injection temperature. Mixing of the jet from a layflat hole was investigated. Mixing from a layflat with 4 holes was modelled and also diffusion from a layflat that is considered as a single source were compared. This comparison can be seen in Figure 10a and 10b.

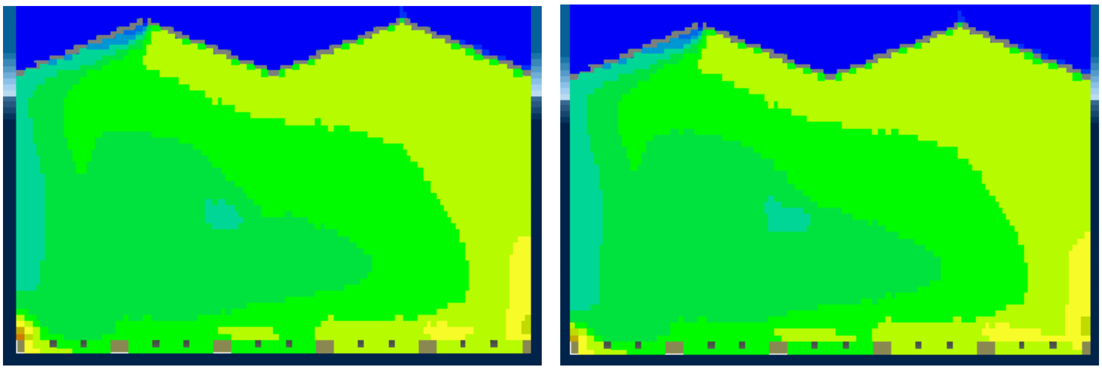
As can be seen in Figure 10a,b, the difference in overall CO_2 distribution between modelling 4 jets or modelling a single source of CO_2 is negligible. In Figure 10c, the flow from a single jet is represented. The influence from a turbulent free jet disappears at the end of region 3 in Figure 10c, which is maximum 100 X nozzle diameter. With a nozzle diameter of less than 1 mm for a layflat hole, the jet influence on overall CO_2 distribution can be neglected. This small jet influence also demonstrates that the rate of flow of CO_2 through a nozzle is of no influence.

The effect of CO_2 injection temperature on the distribution of CO_2 can be seen in Figure 11 where again two steady state winter simulations are compared, the standard two span winter model and a model where the CO_2 temperature has been lowered from 30 to 3 degrees Celsius.



a) b) c)

Figure 10: *Dispersal from layflat with a) 4 jets, and b) a single source. c) Turbulent free jet flow. Equal colours represent equal concentrations (red = high, blue = low).*



a) 30 degrees Celsius b) 3 degrees Celsius

Figure 11: *The effect of CO_2 injection temperature on CO_2 distribution. Equal colours represent equal concentrations (yellow = high, blue = low).*

The influence of the change in CO_2 temperature is negligible as the dispersal is mainly driven by airflow that is a result of either ventilation or buoyancy as in this case.

The effect of the distribution pattern of the injection holes along the layflat tubes could not be determined using a two-dimensional simulation. Further work using a three dimensional model will be required to address this objective.

Validation for the mixing effect of jets is taken from the Chemical Engineers Handbook (Perry, 1963). Experimental data on the effect of temperature of injected CO_2 are not available.

Discussion and conclusions

In this section the conclusions of the work and the current position of deliverables against set objectives are discussed. Only two dimensional models were considered in this work. A short summary of the results per objective are listed below:

1. In both a summer and winter two span glasshouse model with simple tomato model crops, heating pipes and CO_2 layflat pipes inside, a description of the CO_2 distribution is given. In the winter model, also the transient effect is studied. A multi span glasshouse model under summer conditions revealed a typical flow pattern that includes a main airflow that is opposite to the main wind direction and the existence of a 'dead' zone.
2. No relationship between pipe temperature and CO_2 concentration for the same glasshouse air temperature and rate of CO_2 addition was found in a steady state winter model. Different pipe temperatures resulted in a negligible difference in CO_2 distribution.
3. The effect of the height of the layflat tubes on the CO_2 distribution was found to be significant using a steady state winter model. Increasing layflat height increased the CO_2 concentration and decreased the CO_2 gradient in the glasshouse.
4. The influence of the flow generated by the layflat holes on the dispersal of CO_2 was proven negligible. Therefore, the rate of flow of CO_2 through a nozzle is of no influence. In addition, the effect of CO_2 injection temperature on CO_2 dispersal was found negligible.
5. Smoke tests at Cantelo Nurseries Ltd and existing literature could verify the internal airflow predictions and airflow around crops (objective 1). The influence of flow and flow rate from layflat holes was verified with existing theory. Other verifications resulted from personal communications with growers and glasshouse specialists. However, more experimental data are needed.

All the objectives have been addressed and most of the deliverables have been met albeit for a limited range of conditions. Although limited useful data for modelling purposes were available, a model canopy with CO_2 absorption and flow resistance was developed and put in a model glasshouse. Both summer and winter conditions were considered. In the glasshouse, heating and CO_2 injection were present and the CO_2 injection system has been looked at in more detail. Due to mass balance problems in the summer model, no parametric study was carried out using this model. The mass balance problems exist because only a two span section was modelled instead of a complete glasshouse. Both summer and winter models have shown that CFD is capable of predicting airflow, temperature distributions and CO_2 gradients within a commercial glasshouse. Validation was carried out where possible but is the weakest point of this work since hardly any useful experimental validation data were available.

Due to the fact that only simple models could be build in this one year study (and therefore the modelling has been kept two dimensional), clear recommendations and advice to growers can not be given at this stage. However, this first attempt at CFD modelling of the internal environment of glasshouses has led to some useful observations and has indicated priorities for future research and highlighted gaps in experimental data that are currently available.

One conclusion that can be drawn directly from the results is that growers should use more than one sampling point for the control of glasshouse environmental parameters. This is because of the possible existence of a 'dead' zone at 0.6 X the length of the glasshouse from the windward side where very low airflow speeds were shown from our simulations. The studies also suggest that the height of the layflat pipes in a tomato crop have a significant influence on CO_2 dispersal and prove the negligible influence of the flow from the layflat holes.

Recommendations for further studies

After modelling two span sections of commercial glasshouses in two-dimensions, as a continuation of this study, a recommendation can be made to develop detailed two dimensional models of multi span glasshouses to study the internal airflow. These models can be used as a first step towards more complex models and can indicate areas of special attention for future research. If satisfactory models are achieved, expansion to the third dimension should be made to be able to study the three dimensional effects of the internal flow (i.e. position of vents). In addition, simple model crops can be placed in the glasshouse in both two-dimensional and three-dimensional models and heating and CO_2 injection can be introduced. After sufficient validation of the models, a parametric study can be conducted where different weather situations, strategies of glasshouse control, management, and design can be studied. This can lead to optimising efficiency and effectiveness of glasshouse production and a reduction of costs for the industry.

Not only can recommendations be made for continuation of this work, also recommendations for other research that can eventually support this work can be made. Most importantly, experiments that can validate flow patterns in a commercial glasshouse, preferably with crops inside, would be very valuable. Other valuable experiments would be smoke tests where smoke is injected through the layflat pipes, a good way to visualise the way CO_2 travels through the internal glasshouse space. Valuable information can also be gained from wind tunnel tests of crops where flow resistance characteristics can be studied and translated into useful modelling information (flow resistance values, porosity, permeability, turbulence characteristics).

Acknowledgements

For their continuous support, we would like to thank the HDC, Andy Marchant of Hennock Industries Ltd., Gary Taylor of Cantelo Nurseries, Gerry Hayman of GHHC, Nigel Dungey of Hazlewood VHB and Philip Pearson of A. Pearson & Sons. Special thanks are expressed towards Cantelo Nurseries for welcoming the Exeter team during visits and allowing smoke tests at their site. Work by Alberto Pantanelli and Francesco Ferioli is acknowledged as a valuable contribution to this project.

References

[1] Acock, B., Charles-Edwards, D.A., Fitter, D.J., Hand, D.W., Ludwig, L.J., Wilson, J. Warren and Withers, A.C., The Contribution of Leaves from Different Levels within a Tomato Crop to Canopy Net Photosynthesis: An Experimental Examination of Two Canopy Models, Journal of Experimental Botany, Vol. 29, No. 248, August 1978, page 815-827

[2] Wang, S., Measurement and Modelling of Natural Ventilation in a Large Venlo-type Greenhouse, PhD thesis, Gembloux, 1998

[3] List of literature:

Acock, B., Charles-Edwards, D.A. and Hand, D.W., An Analysis of Some Effects of Humidity on Photosynthesis by a Tomato Canopy under Winter Light Conditions and a Range of Carbon Dioxide Concentrations, Journal of Experimental Botany, Vol. 27, No. 248, August 1978, page 933-941

Aikman, D.P., Turning a Tomato Crop Simulation Model into a Procedure for Computing a CO_2 Set-Point, Horticulture Research International, Wellesbourne, Warwick CV35 9EF, UK

Aikman, D.P., Chalabi, Z.S., Fenlon, J.S., Bailey, B.J. and Cockshull, K.E., Optimal Control of Carbon Dioxide Enrichment for a Glasshouse Tomato Crop, Horticulture Research International, Wellesbourne, Warwick CV35 9EF, Littlehampton, Sussex

Babtsita, F.J., Bailey, B.J., Randall, J.M. and Meneses, Greenhouse Ventilation Rate: Theory and Measurement with Tracer Gas Techniques, Journal of Agricultural Engineering Research 72, 1999, page 363-374

Bache, D.H., Momentum Transfer to Plant Canopies: Influence of Structure and Variable Drag, Atmospheric Environment, Vol. 20, Great Britain, 1986, page 1369-1378

Bailey, B.J. and Chalabi, Z.S., Improving the Cost Effectiveness of Greenhouse Climate Control, Computers and Electronics in Agriculture 10, 1994, page 203-214

Bailey, B.J., Harral, B.B. and Fernandez, J.E., Air Recirculation in Greenhouses, Research report PC 47, Contact Report No. CR/628/95/8934, Silsoe Research Institute, December 1994

Bailey, B.J., Natural Ventilation of Greenhouses – Achievements, Constraints and Limitations, Presented at the International ISHS Symposium Greenhouse Techniques towards the 3rd Millennium, Haifa, Israel, 5-8 September, 1999

Bailey, B.J., Wind Driven Ventilation in a Large Greenhouse, Presented at the International ISHS Symposium Greenhouse Techniques towards the 3rd Millennium, Haifa, Israel, 5-8 September, 1999

Bird, R.B., Stewart, W.E. and Lightfoot, E.N., Transport Phenomena, John Wiley & Sons, Inc., Fourth printing, New York – London, July 1964

Boomen, van den, A.J.W.M., Luchtverdeling via Kunststof Kanalen (in Dutch), De Chapignoncultuur 32(2), 1988, page 59-69

Bot, G.P.A., Physical Modelling of Greenhouse Climate, The Computerised Greenhouse, Academic Press, 1993, page 51-75

Boulard, T., Papadakis, G., Kittas, C. and Mermier, M., Air Flow and Associated Sensible Heat Exchanges in a Naturally Ventilated Greenhouse, Agricultural and Forest Meteorology 88, 1997, page 111-119

Boulard, T., Roy, J.C., Lamrani, M.A., and Haxaire, R., Characterising and Modelling the Air-Flow and Temperature Profiles in a Closed Greenhouse in Diurnal Conditions, IFAC Mathematical and Control Applications in Agriculture and Horticulture, Hanover, Germany, 1997, page 37-42

Boulard, T., Kittas, C., Papadakis, G., and Mermier, M., Pressure Field and Airflow at the Opening of a Naturally Ventilated Greenhouse, Journal of Agricultural Engineering Research 71, 1998, page 93-102

Boulard, T., Lamrani, R.M., Roy, J.C., Jaffrin, A. and Bouirden, Natural Ventilation by Thermal Effect in a One-Half-Scale Model Mono-Span Greenhouse, Transactions of the ASAE, Vol. 41(3), 1998, page 773-781

Boulard, T. and Wang, S., Greenhouse Crop Transpiration Simulation from External Climate Conditions, Agricultural and Forest Meteorology 2683, 1999, page 1-10

Boulard, T., Haxaire, R., Lamrani, M.A., Roy, J.C. and Jaffrin, A., Characterization and Modelling of the Air Fluxes Induced by Natural Ventilation in a Greenhouse, Journal of Agricultural Engineering Research 74, 1999, page 135-144

Bradley, M.R., Bailey, B.J. and Robertson, A., Review of Greenhouse Design and Technology for Tomato and Cucumber Production, A Report to the Horticultural Development Council 18 Lavant Street, Petersfield, Hants, GU32 3EW, Project Number PC68, March 1994

Breuer and Braak, Een Statisch en een Dynamisch Simulatie Model voor Klimaatprocessen en Energiestromen in Kassen (in Dutch), (Partly copied)

Campen, J.B. and Bot, G.P.A., New Dehumidifying System for Greenhouses, Presented at the International ISHS Symposium Greenhouse Techniques towards the 3rd Millennium, Haifa, Israel, 5-8 September, 1999

Cant, R.J., Castro, I.P. and Walklate P.J., Plane Jets Impinging on Porous Screens, (February, 1998, not published yet)

Chalabi, Z.S., A Generalized Optimization Strategy for Dynamic CO_2 Enrichment in a Greenhouse, European Journal of Operational Research 59, North-Holland, page 308-312

Chalabi, Z.S., Bailey, B.J. and Wilkinson, D.J., Optimal Control of Greenhouse Climate, Contract Report CR/613/95/8994, Silsoe Research Institute, December 1994

Chalabi, Z.S. and Fernandez, J.E., Estimation of Net Photosynthesis of a Greenhouse Canopy Using a Mass Balance Method and Mechanistic Models, Agricultural and Forest Meteorology 71, 1994, page 165-182

Challinor, Paul, Close to the Edge, Greenhouse Grower, (after 1996), page 15-17

Cooke, Alison, High on CO_2?, Grower, April 9, 1998, page 33-37

Dayan, E., Keulen, van, H., Jones, J.W., Zipori, I., Shmuel, D.and Challa H., Development, Calibration and Validation of a Greenhouse Tomtato Model 1: Discription of the model, Agricultural Systems 43,1993, page 145-163

Dayan, E., Keulen, van, H., Jones, J.W., Zipori, I., Shmuel, D.and Challa H., Development, Calibration and Validation of a Greenhouse Tomtato Model 2: Field Calibration and Validation, Agricultural Systems 43, 1993, page 165-183

Elwell, D.L. and Bauerle, W.L., TOMMOD, a New Model of Greenhouse Tomato Development, ASAE, St.Joseph, June 1990

Evans, L.T., Environmental Control of Plant Growth, Chapter 5,7,8 and 9, Proceedings of a Symposium Held at Canberra, Australia, August 1962, Academic Press, 1963, London

Ferioli, F., M Eng Eur thesis, Exeter, 1999

Fernandez, J.E. and Bailey, B.J., The Influence of Fans on Environmental Conditions in Greenhouses, Journal of Agricultural Engineering Res. 58, 1994, page 201-210

Grant, R.H., The Scaling of Flow in Vegetative Structures, Boundary-Layer Meteorology 27, 1983, page 171-184

Groot Koerkamp P.W.G., Speelman, L. and Metz, J.H.M., Litter Composition and Ammonia Emission in Aviary Houses for Laying Hens: Part II, Modelling the Evaporation of Water, Journal of Agricultural Engineering Research 73, 1999, page 353-362

Ham, Ph. J., Mollier-h/x Diagrammen voor Vochtige Lucht, Geconstrueerd door middel van de Computer (in Dutch), Klimaatbeheersing 13. Nr. 8, August 1984, page 269-273

Hand, D.W., A Null Balance Method for Measuring Crop Photosynthesis in an Airtight Daylit Controlled-Environment Cabinet, Agricultural Meteorology, 12, 1973, page 259-270

Hand, D.W., CO_2 Enrichment, the Benefits and Problems, Scientific Horticulture, Vol. 33, 1982, page 14-43

Hand, David and Slack, Gerry, What price summer CO_2 enrichment?, Grower, Feb. 11, 1988, page 27-32

Hand, D.W., Clark, G., Hannah, M.A., Thornley, J.H.M. and Wilson, J. Warren, Measuring the Canopy Net Photosynthesis of Glasshouse Crops, Journal of Experimental Botany, Vol. 43, No. 248, March 1992, page 375-381

Hand, David and Thornley, John, Making Light Work of Cues, Grower, March 12, 1992, page 7-11

Harten, van, J., The Distribution of Carbon Dioxide in Glasshouses, Groenten en Fruit, 1 June 1984, page 33-35

Haxaire, R., Roy, J.C., Boulard, T., Lamrani, M.A. and Jaffrin, A., Etude Numerique et Experimentale de la Ventilation par Convection Naturelle dans une Serre, Actes du Congres Annuel de la SFT, Marseille, 5-7 May, 1998, Elsevier, Paris, 1998, page 64-69

Haxaire, R., Roy, J.C., Boulard, T., Lamrani, M.A. and Jaffrin, A., Greenhouse Natural Ventilation by Buoyancy Forces, EPIC’98/11 Proceedings of the 2nd European Conference on Energy Performance and Indoor Climate in Buildings and 3rd International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Ecole Nationale des Traveaux Publics de l’Etat, Lyon, France, November 1998, page 522-527

Haxaire, R., Boulard, T. and Mermier, M., Greenhouse Natural Ventilation by Wind Frces, Presented at the International ISHS Symposium Greenhouse Techniques towards the 3rd Millennium, Haifa, Israel, 5-8 September, 1999

Heijna, B.J., Warmtehuishouding van kassen (in Dutch)

Heuvelink E., Tomato Growth and Yield: Quantative Analysis and Synthesis, PhD Thesis, Wageningen, 1996

Ho, Lim and Cockshull, Ken, Tomatoes to the Limit, Grower, February 1, 1996, page 11-15

Hoxey, R.P. and Moran, P., Full Scale and Wind Pressure and Load Experiments – Multispan 167* 111 m Glasshouse (Venlo), Div. Note DN. 1594, AFRC Engineering Research, Sisoe, January 1991

Hufton, C. and Dungey, N., Tomatoes CO_2 Survey, Project Report, Project Number PC110, Horticultural Research International, July 1996

Jones, J.W., Dayan, E., Jones, P., Hwang, Y. and Jacobson, B., Modelling Tomato Growth for Greenhouse Environment Conrol, ASAE, St. Joseph, December 1988

Jones, J.W., Dayan, E., Allen, L.H., Keulen, van, H. and Challa, H., A Dynamic Tomato Growth and Yield Model (TOMGRO), Transaction ASAE 34(2), March-April 1991

Jong, de, T., Natural Ventilation of Large Milti-Span Greenhouses, PhD Thesis, Wageningen, 1990

Keulen, van, H. and Dayan, E., TOMGRO: A Greenhouse-Tomato Simulation Model, (Partly copied), CABO-DLO, Wageningen, 1993

Koppe, R., temperatuur- en Circulatiepatroon in Kassen (in Dutch)

MAFF reports:
HH1306SPC, HH1311SPC, HH1326SPC, HH1317SPC

Marler, Thomas E., Discekici and Haluk M., Plants and CO_2: A Quick and Easy Laboratory Exercise, HortTechnology, Oct/Dec. 1995, page 346-349

Martin, P.H., Exchanges between Structured Canopies and their Physical Environment: A Simple Analytical Solution for a Generic Configuration, Ecological Modelling 122, 1999, page 1-24

Miguel, A.A.F., Transport Phenomena through Porous Screens and Openings, PhD Thesis, Wageningen, 1998

Mistrionis, A., Arcidiacono, C., Picuno, P., Bot, G.P.A. and Scarascia-Mugnozza, G., Computational Analysis of the Natural Ventilation in Greenhouses at Zero-and Low-Wind-Speeds, Agricultural and Forest Meteorology, 88(1-4), 1997, page 121-135

Mistrionis, A., Bot, G.P.A., Picuno, P. and Scaracia-Mugnozza, G., Analysis of the Efficiency of Greenhouse Ventilation using Computational Fluid Dynamics, Agricultural and Forest Meteorology, 85, 1997, page 217-228

Mistriotis, A., Jong, de, T, Wagenmans, M.J.M. and Bot, G.P.A., Computational Fluid Dynamics (CFD) as a Tool for the Analysis of Ventilation and Indoor Microclimate in Agricultural Buildings, Netherlands Journal of Agricultural Science 45 (1), 1997, page 81-96

Mistrionis, A., Picuno, P., Bot, G.P.A. and Scarcia-Mugnozza, G., Computational Study of the Natural Ventilation driven by Buyoncy Forces, Proc. of the 3rd Interational Workshop on Mathematical and Control Applications in Agriculture and Horiculture, Pergamon Press, 1997, page 67-72

Nederhoff, E.M., Effects of CO2 Concentration on Photosynthesis, Transpiration and Production of Greenhouse Fruit Vegetable Crops, PhD Thesis, Wageningen/ Naaldwijk, 1994

Nijs, L. and and Berg, van den, G.A., Ontwikkelen en Introduceren van een Methodiek ter Oplossing van Klimaatverschillen in Kassen (in Dutch), Rapport 147, Naaldwijk, August 1998

Pantanelli, A., M Eng Eur thesis, Exeter, 1999

Papadakis, G., Frangoudakis, A. and Kyritsis, Experimental Investigation and Modelling of Heat and Mass Transfer between a Tomato Crop and the Greenhouse Environment, Journal of Agricultural Engineering Research 57, 1994, page 217-227

Patankar, S.V., Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, 1980

Raupach, M.R., Coppin, P.A. and Legg, B.J., Experiments on Scalar Dispersion Within a Model Plant Canopy, Part 1: The Turbulence Structure, Boundary-Layer Meteorology 35, 1986, page 21-52

Rees, A.R., Cockshull, K.E., Hand, D.W. and Hurd, R.G., Crop Process in Controlled Environments, Proceedings of an International Symposium held at the Glasshouse Crops Research Institute, Littlehampton, Sussex, England, July 1971, Academic Press, London, 1972

Reichrath, S., Ferioli, F. and Davies, T.W., A Simple Computational Fluid Dynamics (CFD) Model of a Tomato Glasshouse, Presented at the International ISHS Symposium Greenhouse Techniques towards the 3rd Millennium, Haifa, Israel, 5-8 September, 1999

Rijsdijk, T. and Sluis, van der, B., Too Little Attention Paid to the Technique of CO_2-Dosage, Groenten + Fruit / Glasgroenten, No. 25, 24 June 1994

Rijdijk, Ton, Position Ducts High for Better Use of CO_2, Groenten + Fruit/ Glasgroenten, No. 40, 7 October 1994, page 16-18

Salisbury, Frank B. and Ross, Cleon W., Plant Physiology, Third Edition, Wadsworth Publishing Company, Belmont, California, USA, page 216-228

Sase, S., The Effects of Plant Arrangement on Airflow Characteristics in a Naturally Ventilated Glasshouse, Acta Horticulturae 245, 1998, Energy Saving in Protected Cultivation, page 429-435

Scott, G. and Richardson, P., The Application of CFD in the Food Industry, Trends in Food Science and Technology, Vol. 8, Elsevier, April 1997

Seginer, I. and Sher, A., Optimal Greenhouse Temperature Trajectories for a Multi-State-Variable Tomato Model, The Computerised Greenhouse, Academic Press, 1993, page 153-172

Short, Ted H., Aerodynamic Design Improves Ventilation, Ohio State University, USA

Smith, Ben, Summer CO_2: a Natural Choice, Grower, March 21, 1996, page 28-32

Stanghellini, C., Transpiration of Greenhouse Crops an Aid to Climate Management, PhD Thesis, Wageningen, 1987

Stanghellini, C. and Jong, de, T., A Model of Humidity and its Applications in a Greenhouse, Journal of Agricultural Forest Meteorlogy 76, 1995, page 129-148

Svensson, U and Haggkvist, K, A Two-Equation Turbulence Model for Canopy Flows, Journal of Wind Engineering and Industrial Aerodynamics 35, Elsevier, The Netherlands, 1990, page 201-211

Thornley, H.M., Hand, D.W. and Wilson, J. Warren, Modelling Light Absorption and Canopy Net Photosynthesis of Glasshouse Row Crops and Application to Cucumber, Journal of Experimental Botany, Vol. 43, No. 248, March 1992, page 383-391

Vermeulen, Peter, CO_2 Installation Last in the List for Consideration, Groenten en Fruit, No. 46, 18 November, page 12-13

Walklate, P.J., Weiner, K.-L. and Parkin, C.S., Analysis of and Experimental Measurements Made on a Moving Air-Assisted Sprayer with Two Dimensional Air-Jets Penetrating a Uniform Crop Canopy, Journal of Agricultural Engineering Res. 63, 1996, page 365-378

Walklate, P.J. and Weiner, K.-L., Penetration of a Uniform Row Canopy Structure by a Moving Air-jet, Flow and Dispersion through Groups of Obstacles, Clarendon Press, Oxford, 1997, page 33-46

Wang, S., and Deltour, J., Lee-side Ventilation-induced Air Movement in a Large-scale Multi-span Greenhouse, Journal of Agricultural Engineering Research 74, 1999, page 103-110

Wang, S., Boulard, T. and Haxaire, R., Air Speed Profiles in a Naturally Ventilated Greenhouse with a Tomato Crop, Agricultural and Forest Meteorology 96, 1999, page 181-188

Wang, S., and Boulard, T., Predicting the Microclimate in a Naturally Ventilated Plastic House in a Mediterranean Climate, Journal of Agricultural Engineering Research 00, 1999, page 000-000

Wills, Peter, Pumping Up the CO_2, Grower, June 16, 1994, page 31-33

Wilson, J.D., A Second-Order Closure Model for Flow through Vegetation, Boundary-Layer Meteorology 42, 1988, page 371-392

Wilson, J. Warren, Hand, D.W. and Hannah, M.A., Light Interception and Photosynthetic Efficiency in Some Glasshouse Crops, Journal of Experimental Botany, Vol. 43, No. 248, March 1992, page 363-373

Zekki, H., Gary, C., Gosselin, A., and Gauthier, L., Validation of a Photosynthesis Model through the Use of the CO_2 Balance of a Greenhouse Tomato Canopy, Annals of Botany 84, 1999, page 591-598