MINISTRY OF AGRICULTURE, FISHERIES AND FOOD **CSG 15**

Research and Development

Final Project Report

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Project title	Natural ventilation of commercial greenhouses
MAFF project code	**HH1328SPC**
Contractor organisation and location	Silsoe Research Institute Wrest Park, Silsoe Bedford MK45 4HS
Total MAFF project costs	£ 263,622
Project start date	01/10/98
Project end date	30/09/01

Executive summary (maximum 2 sides A4)

The primary objective of this work was to produce a scientific model capable of predicting reliably the natural wind-driven ventilation of large, commercial glasshouses. Such ventilation is governed principally by the geometry and number of the ventilators, their opening angles, their opening arrangement (i.e. whether leeward ventilators only are open, or combined leeward and windward are open, or windward only are open), and wind conditions. Such a capability does not currently exist and is needed to enable environmental control of commercial-production houses to be optimised with respect to carbon dioxide enrichment, temperature, and relative humidity. The task was challenging since wind-driven ventilation is produced by wind-generated pressure distributions over the building that have a quasi-steady component related to the mean wind speed and a time-varying and spatially-varying component produced by turbulence.

Several different possible methods of obtaining the necessary information were considered. One technique that was tried was abandoned because it proved to be unsuitable. The approach that was ultimately adopted was to develop the model from the results of two programmes of physical testing. The first programme concerned tests on individual ventilators of different aspect (length-to-width) ratios with flaps opened to different angles from the plane of the opening, for flows both into and out of opening, and over a range of air speeds. These tests were conducted using a special test rig designed at Silsoe Research Institute (SRI) in accordance with the British Standard for the testing of fan performance. These tests defined the resistance to flows created by a ventilator in terms of discharge coefficients and effective areas of the opening. The second programme was conducted using a specially constructed large-scale model of a multispan glasshouse in the brand new Atmospheric Flow Laboratory (AFL) at SRI. The model was a 1 : 3.5 scale version of a representative, modern 5-span Venlo glasshouse with discrete, staggered vents of aspect ratio 3. The AFL is a unique wind engineering facility that became available in 2001. It has a large working section measuring 6 m wide by 5 m high by 20 m long, accommodating the testing of large models needed for ventilation studies in order to avoid unrepresentative flow conditions through small ventilator openings. Turbulent, boundary-layer winds are

achieved through the computer control of 56 axial-flow fans arranged in an 8 wide by 7 high matrix. Extensive tests were conducted over a range of mean wind speeds from 1 to 4.5 m/s for a wide range of ventilator opening arrangements. For a given ventilator-opening configuration, ventilation rate varied linearly with mean wind speed. The relationship between ventilation rate and opening arrangement was more complex. Ventilation rate increased with the opening angle of vents, but progressively less so at wider opening angles. For a given opening, windward ventilators ventilated more effectively than did leeward ventilators. When both windward and leeward sets of ventilators were open relatively widely, the ventilation effect was greater than the sum of those when each set was open separately. These effects were built into the model, as were the flow resistances for individual ventilators obtained from the other testing programme.

The model was applied to the test cases used to develop it and it accounted for 97% of the observed variations in ventilation rates. The model was validated against three independent sets of measurements made in three different full-scale Venlo glasshouses, two being commercial houses and one being an experimental house at SRI. The houses had contrasting plan areas of 205, 5178 and 37,800 m_g^2, and ventilator-to-ground area ratios of 0.23, 0.13 and 0.14 respectively. On average for each house, the model provided predictions of ventilation rates that differed from the measured values by +10%, +16%, and –14% respectively. Acquisition of the independent, validating data from the large commercial houses was a significant component of the project. The technique adopted was to use the CO_2 supplied to enrich the internal environment as the tracer gas. This entailed careful measurements of the CO_2 supplied to the houses and of CO_2 concentrations in the houses, correction for CO_2 converted through photosynthesis, temperature measurements to account for thermally-driven ventilation, wind speed measurements, and recordings of the ventilator opening arrangements.

For completeness, natural ventilation produced by thermal effects has also built into the model.

Supplementary studies have been completed of the ventilating and internal flow regimes generated by wind action on glasshouses when ventilators are opened in different arrangements. These were undertaken using the scale model in the AFL. Flows were visualised using smoke and were recorded using a digital video camera. The studies have provided interesting and enlightening information on the physical processes responsible for ventilation. They show, for example, that when leeward ventilators only are open, outflow is greatest at the upwind end because the external roof suctions generated by the wind are greatest there, and as a consequence the internal flow is generally towards the windward wall. They illustrate the strong turbulent-driven component of ventilation that is present especially when only one set of vents (windward or leeward) are open and the associated absence of well-established internal flow regimes. They also show the three-dimensional nature of internal flows when both sets of vents are open and reveal that these are driven by relatively high-speed inflows through windward ventilators.

The work has been, and is being, promulgated through publications and presentations (as listed at the end of the report).

The resulting model is amenable to implementation into horticultural environmental controllers, and discussions have been held with two leading companies and the HDC to this effect.

Scientific report (maximum 20 sides A4)

1. Introduction

The objective of this project was to develop a scientific model of natural ventilation in commercial multi-span glasshouses, and to investigate how the internal airflows are influenced by the ventilation flows. This would provide the information required to determine economically optimal strategies for the control of carbon dioxide enrichment, air humidity and temperature, and to assess ways of improving the summer environment in glasshouses. It would also provide information on the spatial variability of ventilation in large, undivided glasshouse blocks which have multi-zone environmental control. The project addressed wind-driven ventilation because wind is the primary driver of ventilation in UK greenhouses (dominating over buoyancy when the wind speed exceeds approximately 2 m/s, which is approximately 80% of the time), and because the capability to predict it reasonably accurately does not currently exist. However, for completeness and to enhance readiness of application of the model, temperature-driven ventilation has also been built into it. The terms 'glasshouse' and 'greenhouse' are used synonymously in this report.

2. Background to experimental options

The research required experimental studies to measure wind-driven ventilation rates and to visualise the resulting internal airflows. The main parameter sets to be quantified and embraced in the model were:

(a) flow resistance through a ventilator according to its: length/width ratio, angle of opening, and flow direction (i.e. incoming or outgoing flows)

(b) volumetric flow rates according to: opening angle of leeward ventilators, opening angle of windward ventilators, opening angles of leeward and windward ventilators (for both symmetric and asymmetric settings)

(c) wind speed and direction.

The first parameter set could appropriately and efficiently be determined using a Fan Test Rig available at Silsoe Research Institute (SRI) that allows pressure drops and airflow rates through a test device to be monitored accurately and reliably.

The second and third parameter sets required quantification of the ventilation rates in one or more representative glasshouses under appropriate wind conditions. Options considered for tackling this included full-scale measurements in commercial houses, model-scale measurements in a water flume, model-scale measurements in a wind tunnel, and computational fluid dynamics (CFD). CFD is a numerical prediction model rather than a physical monitoring approach. There was a disinclination to base model development on CFD because of the need to validate the adopted modelling approach, and secondly because of its inability to adequately take account of the time-varying, turbulence-driven component of natural ventilation. A pre-requisite, however, to measuring ventilation rates in commercial houses (which may easily be in excess of 10,000 m^2 in plan area or 50,000 m^3 in volume), is the development of a technique that is sufficiently reliable when dealing with such large spaces. An additional objective of the project was therefore the development of such a technique.

The most effective and efficient arrangements for undertaking commercial-scale studies and/or appropriate wind-tunnel studies to obtain the data needed for model development needed to be established. Discussions with the operators of suitable commercial houses containing suitable crops revealed that we would be unable to have the necessary control over the ventilator settings because of the risk to the crop of inappropriate environmental conditions resulting. There would obviously also be no control over the wind conditions. It was decided to use commercial houses to obtain ventilation-rate data only under standard commercial operating conditions, against which the model would be validated. The data to develop the model would be obtained from physical model testing. Model testing was first carried out at the Department of Applied Mathematics and Theoretical Physics (DAMTP) at Cambridge University using their water flume. This is described later, but limitations brought about by blockage effects disrupting flow similitude became apparent. Prospects for undertaking studies in a larger flume in collaboration with researchers at IRTA (Institut de Recerca I Tecnologia Agroalimentaries) in Spain, and of undertaking wind-tunnel tests economically through collaboration with the Japanese NRIAE (National Research Institute for Agricultural Engineering) unfortunately proved not to be feasible. The reserve and preferred option was to use a brand new experimental facility – the Atmospheric Flow Laboratory (AFL) – at SRI. The AFL was designed, planned and funded at the outset of the project, but not built. It was scheduled to become available approximately two years into the project. The AFL offered the unique and substantial attraction of large-scale physical testing under controlled, turbulent wind conditions. Because of the restrictions that existed with the alternatives, this experimental option became the principal data-acquisition source for the model development, and for studying the ventilating flow regimes. Arriving at this position, coupled with delays that arose because of complications with the commissioning of the new facility and its instrumentation, unfortunately meant that completion of the 3-year project was delayed by some 4-5 months.

3. Format of the report

The ordering of this report is as follows. In Section 4, the assessment of flow resistance through individual ventilators is presented (parameter set 2(a) above). The initial flow studies in the Cambridge University DAMTP water flume are outlined briefly in Section 5. The systematic large-model studies of wind-induced ventilation rates conducted in the SRI AFL (parameter sets 2(b) and 2(c) above) are described in Section 6. Construction of the natural ventilation model to embrace the parameter sets, and validation of the model using independent full-scale data from commercial houses are explained in Section 7, together with the incorporation of temperature-driven natural ventilation to complete the ventilation model. Section 8 presents illustrations of the wind-driven flow visualisation studies undertaken in the AFL to investigate the ventilating flow regimes, and overall conclusions are given in Section 9. Following the acknowledgements and references is a list of publications and presentations emanating from the project work.

4. Flow resistance through individual greenhouse ventilators

4.1 Introduction

The resistance to flow through an opening is commonly characterised by a discharge coefficient, C_d (BS 5925, 1991), given by:

$$Q = C_d A (2\Delta P/\rho)^{1/2} \qquad (1)$$

showing that the volumetric flow rate, Q, through an opening is proportional to the area of the opening, A, and to the square root of the pressure drop across the opening,)P (ρ is the density of air), where the constant of proportionality, C_d, accounts for the flow resistance produced by the complex aerodynamics of the flow through the opening. For a simple, sharp-edged orifice, C_d assumes a value typically of 0.61. For more complex openings such as glasshouse ventilators with different aspect (length/width) ratios, and with a hinged flap at different opening angles, the C_d values need to be determined. Note that the discharge coefficient, C_d, appears as a product term with the area of the opening, A, meaning that different flow resistances for different openings can alternatively be accounted for by an effective area, or by a combination of a discharge coefficient and an effective area. An opening with a hinged flap is a prime example of an opening where the effective area is not apparent.

4.2 Experimental approach and results

The Fan Test Rig at SRI (Moulsley *et al*, 1987) is an ideal experimental facility for determining discharge coefficients for glasshouse ventilators and was employed for this purpose (Fig. 1). It was designed in accordance with the British Standard defining the methods for testing fan performance. It enables the pressure drop across a device such as an opening, and the volumetric airflow rate through it to be measured reliably, allowing the discharge coefficient (or effective area) to be determined. Rectangular openings with aspect ratios from 1 to 36 were tested for the cases where there was no flap and where a flap was present at opening angles of 5^o, 15^o, 25^o, 35^o, and 45^o. The vents were tested for both incoming and outgoing flows. The computed C_d values, based on the simple 2-dimensional area of the rectangular opening are shown in Fig. 2. No statistically significant differences were found between the discharge coefficients for incoming and outgoing flows.

Fig. 1 A 0.7 m square vent and flap mounted on the end of the Fan Test Rig

The results in Fig. 2 show clearly the resistance to flow created by a flap, and the extent to which the resistance increases as the flap opening angle is reduced. The introduction of a 45^o flap reduces the C_d (and hence the volumetric airflow rate for a given pressure drop) by some 30%, whilst a 5^o flap produces approximately an 85% reduction. Ventilator aspect ratio has a lesser effect but, for a given flap case, the C_d value increases for aspect ratios below 5 (compared with the values for aspect ratios of 5-10). This increasing trend below an aspect ratio of 5 is significant for glasshouses which typically have ventilator aspect ratios in the range 2-4. Other greenhouses, particularly continental houses, have ventilators with much larger aspect ratios. The line fits to the experimental data points in Fig. 2 are part of the process of building these results into the ventilation model, which is described in Section 7. The fits shown are obtained from two expressions developed by Bot (1983). The first equation gives the discharge coefficient for openings of different aspect ratios but no flap:

$$C_d = \{1.75 + 0.7 \exp [(-L/H) / 32.5]\}^{-0.5} \qquad (2)$$

where L is the length of the ventilator opening (parallel to the ridge), and H is the width of the opening (perpendicular to the ridge). The area of the opening that would be used with the C_d from Eqn (2) to obtain the flow rate from Eqn (1) is given simply by $A_o = LH$. For openings with flaps, Eqn (2) is modified slightly to become:

$C_d = \{1.75 + 0.7 \exp [(-L/H \sin \alpha) / 32.5]\}^{-0.5}$ (3)

where α is the opening angle of the flap. The effective area through which the flow passes now varies according to the flap angle and is less apparent. To a first approximation, the effective area is the minimum rectangle at the mouth of the opening which is given by $A = (L\,H \sin \alpha)$, or by an area ratio factor, $f\,(= A/A_o)$, of $\sin \alpha$ which is applied to the C_d from Eqn (1) as $f\,C_d$. This gives the straight-line fits shown in Fig. 2. This gives a reasonable prediction of C_d over larger aspect ratios but not over smaller aspect ratios. The reason for this is the contribution from the triangular opening at each side of the flap which becomes more significant for smaller aspect ratios. This requires development of the f factor to include the additional triangular areas but to exclude the proportion of these areas that transmit air that would otherwise pass through the rectangular opening. An equation for the resulting effective area factor of ventilators with flaps has been developed by Bot (1983) where the area ratio A_{lee}/A_o is given by:

$$f_{lee} = \sin \alpha_{lee} \left\{ 1 + a_1 \frac{H}{L} \left[\cos \alpha_{lee} - 2 a_2 \pi \frac{(90 - \alpha_{lee})}{360} \sin \alpha_{lee} \right] \right\} \quad (4)$$

where α_{lee} is the angle of opening of the leeward ventilator and a_1 and a_2 are empirical coefficients. An equivalent expression for f_{wind} is used in the model development described in Section 7. Modelling the flow resistance of ventilators in this form makes the model applicable to greenhouses with different sizes of ventilator.

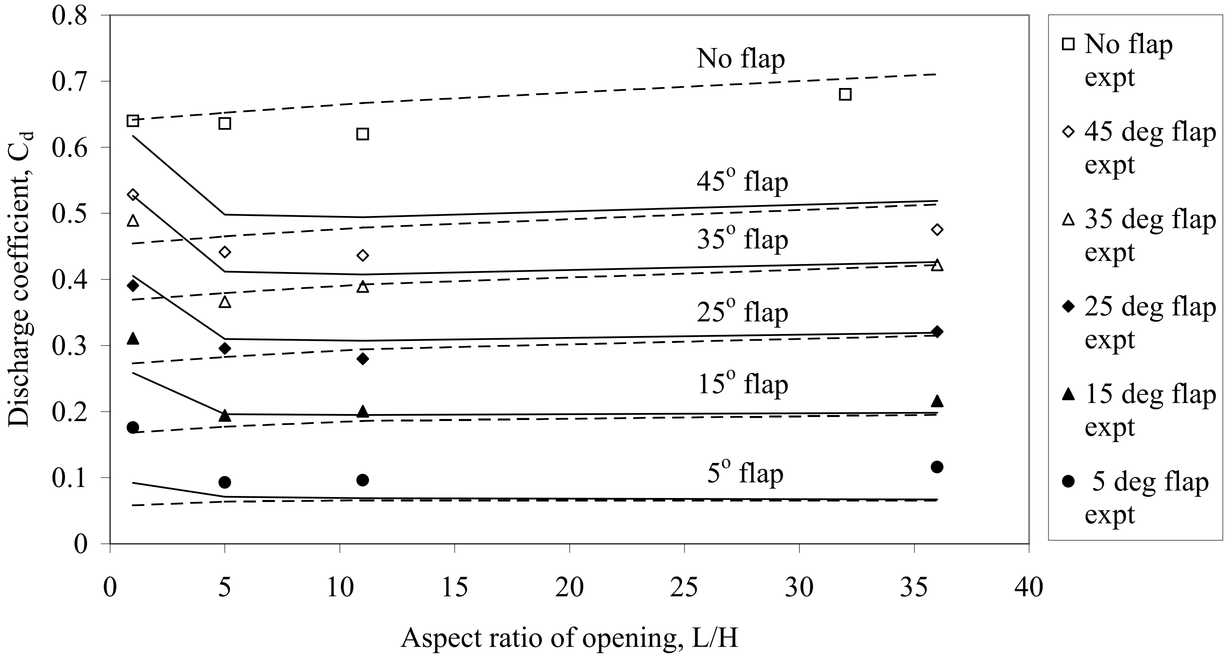

Fig. 2 Experimental discharge coefficients and fits from Eqns (3) (dashed lines) and (4) (solid lines)

Full details and results of this phase of the project are contained in a paper that has been prepared for publication jointly with co-workers who additionally have monitored the effect of introducing insect screens over ventilator openings (‘Air flow resistance of screened and unscreened greenhouse ventilators’, B.J. Bailey, A.P. Robertson *et al*, in preparation).

5. Water flume studies

Flow tests were made using a transparent, 1 : 20 scale, 10-span model of a Venlo glasshouse immersed in the Cambridge University DAMPT flume tank (2.65 m long, 0.3 m wide and 0.57 m deep) through which water was re-circulated. To visualise the flow, a longitudinal vertical cross section of the tank was illuminated using a thin sheet of light. White neutral-density particles seeded in the flow were tracked using a video camera and the images were subsequently analysed digitally to provide velocity profiles. The internal flow observed with leeward ventilators open was in the opposite direction to that observed in a full-scale Venlo glasshouse. Measurement of the pressure distribution along the roof of the model did not agree with those observed on full-scale greenhouses. As a corrective measure, a vertical baffle was placed at roof height upstream of the model which improved the pressure distribution sufficiently to correct the internal flow direction. However, a CFD study (Quinn, Personal communication) to investigate the influence of the baffle indicated that the depth of the flume was insufficient to give an acceptably correct pressure distribution over the model, and as a result this avenue of exploration was abandoned.

6. Ventilation rate measurements in the Atmospheric Flow Laboratory at SRI

6.1 Description of the Atmospheric Flow Laboratory (AFL)

The AFL is a unique wind engineering facility which became operational in 2001. It is shown, together with the model glasshouse used in this project, in Fig. 3.

Fig. 3 View of model glasshouse looking upstream towards fans in AFL

The AFL has a working section measuring 6 m wide by 5 m high by 20 m long. It can be operated in either a recirculating or non-recirculating mode. The internal wall dividing the working section from the return-flow section contains a large glass window measuring 3.5 m high by 12 m long that allows photography and image analysis of flows to be undertaken. A particularly novel feature of the facility is that the airflows are generated by 56 axial-flow fans arranged in an 8 wide by 7 high matrix. The 56 fans are 3-phase, induction motor, axial-flow units, each with a maximum throughput of 3.4 m^3/s at 900 rpm (or 2.8 m^3/s at 50 Pa pressure drop, equating to an air speed of 9 m/s), each with a nominal power rating of 0.7 kW. The rotational speeds of the 0.63 m diameter fans are frequency-controlled as 28 independent pairs which enables them to be accelerated or decelerated between 10% and 90% of their full speed within approximately 1 s. This rapid-response control of the speed of a fan allows it to be programmed to cycle at different frequencies of up to approximately 1 Hz, thereby achieving controlled turbulent airflow throughputs. Since the 28 pairs of the fans can be programmed independently to deliver variable throughputs, phase shifts can be introduced between different pairs of fans, allowing transverse and vertical, as well as longitudinal turbulence to be generated. Representative velocity profiles, turbulence intensities and spectra can thus be generated mechanically for mean wind speeds of up to approximately 5 m/s (Robertson *et al*, 2001).

Four additional fans were mounted transversely within roof ducts above vented ceiling panels at four positions above the window in the dividing wall. These allow air to be extracted from and re-introduced into the test section, and so provide a means of compensating for blockage effects arising with large test specimens.

6.2 The model greenhouse

A dedicated model was built specifically for this project. It was a model of a 5-span, 5-bay Venlo house, constructed at 1 : 3.5 (or 0.28) scale. It is important in ventilation studies that ventilators, and hence models, are not of an unrepresentatively small-scale size otherwise Reynolds number effects are liable to distort flow similarities. Usually, wind-tunnel scale models of low-rise buildings are of the order of 1 : 100 in scale size which is not appropriate for ventilation studies. The model (Fig. 4) had a square plan area of dimension 5.6 m to suit the width of the AFL, an eaves height of 1.2 m, a ridge height of 1.41 m, a span of 1.12 m, a roof slope length of 0.6 m, and a roof pitch of 21^o. The model was constructed of a slender timber frame clad in 6 mm thick twin-walled polycarbonate sheet. The edges of the cladding were sealed along the eaves, verges and corners. The model contained a symmetric arrangement of staggered windward and leeward vents consisting of 10 windward vents (2 on each span) and 15 leeward vents (3 on each span). Each vent measured 0.8 m long by 0.28 m wide (0.255 m clear-opening width). The stagger dimension between adjacent edges of windward and leeward ventilators was 0.27 m.

6.3 Experimental arrangement in the AFL

The model was positioned in the AFL as shown in Fig. 3. A reference ultrasonic anemometer was positioned 4.7 m upstream of the model at the ridge height of the model. This was cross-referenced against a second ultrasonic anemometer mounted at the centre of the model, 1 m above the roof, to correct for wind speed increase produced by blockage. A suite of 6 control algorithms for the fans were prepared to generate turbulent, boundary-layer wind simulations representative of those over rural terrain with a range of mean wind speeds from 1 to 4.5 m/s and a turbulence intensity level of typically 18%.

Nitrous oxide (N_2O) was used as a tracer gas. This was introduced through a line containing a flow control valve and a calibrated mass flow meter (Chell Instruments Ltd, model HFM-200H)) that supplied five perforated plastic pipes distributed over the floor of the house. Five sample tubes were distributed over the plan area of the house that sampled the internal air 1 m above the floor. They were connected to a common sample line connected to an infrared gas analyser (ADC, model 225-Mk3) that was calibrated at regular intervals using 100 ppm N_2O. The tests were conducted with the AFL operating in its non-recirculating mode so that N_2O ventilated from the house was not re-entrained into the oncoming ventilating air.

Vent opening angle was described in percentage terms where 100% equated to an opening angle of 42^o (i.e. twice the roof pitch) when the vent was parallel with the adjacent roof slope. Opening angles of 20% (8.4^o), 40% (16.8°), 60% (25.2°), and 100% (42°) were studied for windward vents alone, for leeward vents alone, and for combined windward-and-leeward vents.

Two methods of measuring ventilating rates were used. A controlled and metered supply of 99% pure N_2O to maintain a predetermined concentration in the house (of approximately 50 ppm in these trials), with mean ventilation rate being calculated according to the supply rate of the tracer was one method. The other was to charge the house with tracer until the concentration exceeded 100 ppm and to monitor the decay in concentration with time and compute the ventilation from an exponential fit to the decay curve. To help to ensure that the tracer gas was fully mixed in the house prior to activating the simulated wind, two simple oscillating desktop fans were introduced towards diagonally opposite corners on the floor of the model. Generally, good agreement was found between the two methods. For certain configurations of ventilators, repeatability between ventilation rate measurements, by whichever method, was somewhat elusive, suggesting that bi-stable or multi-stable ventilating flow regimes of different efficiencies may exist. This is discussed further in Section 8 where visualisation of the ventilating flow fields is discussed. A very substantial number of ventilation rate tests with multiple repeat measurements were made in pursuit of the most reliable measures possible.

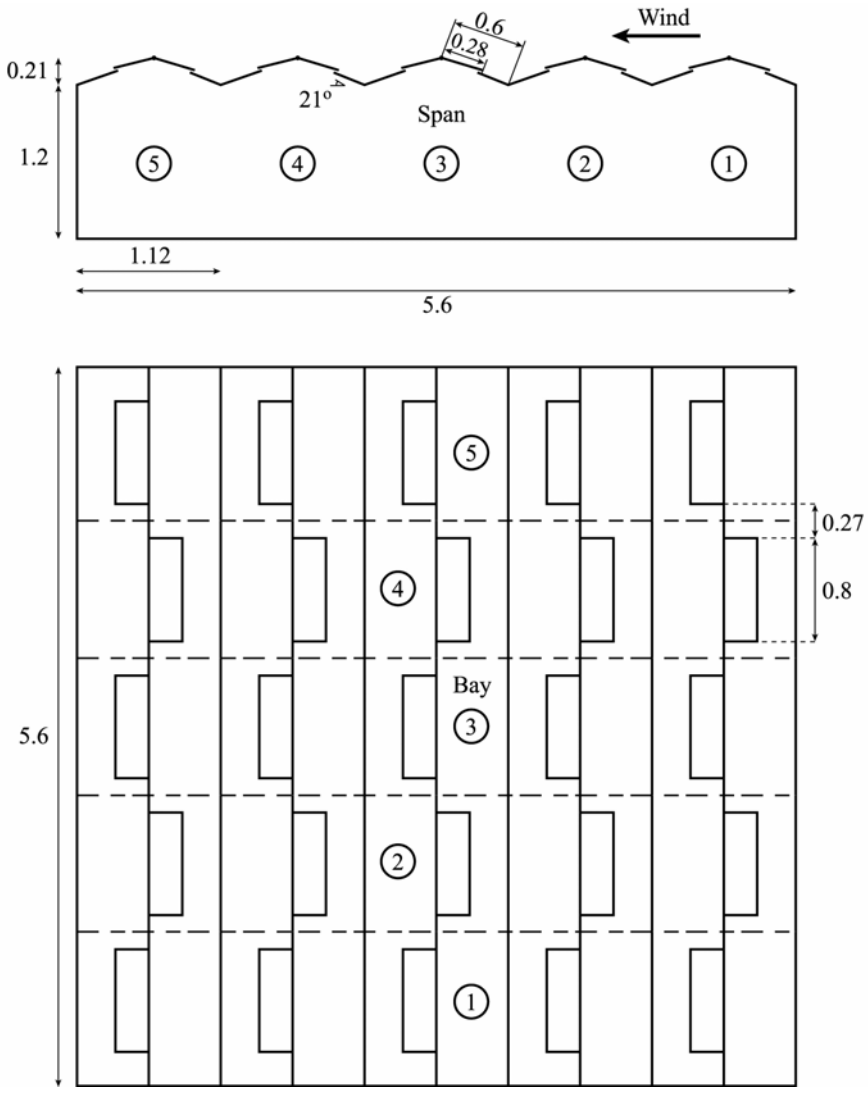

Fig. 4 Side elevation and plan view of 5-span and 5-bay model glasshouse (dimensions in m)

6.4 Ventilation rate measurement results

An illustrative set of ventilation rate measurements is plotted against mean wind speed in Fig. 5. Three plots are shown: leeward ventilators open 100%, windward ventilators open 100%, and windward-and-leeward ventilators open 100%. As expected, the relationship is linear in each case. The results show that the 15 leeward ventilators had a lower ventilation performance than did the 10 windward ventilators. They also show that the ventilation performance for the combined windward-and-leeward opening arrangement was greater than the sum of the performance for the windward vents only open and the leeward vents only open. The reason for this is discussed in Section 8.

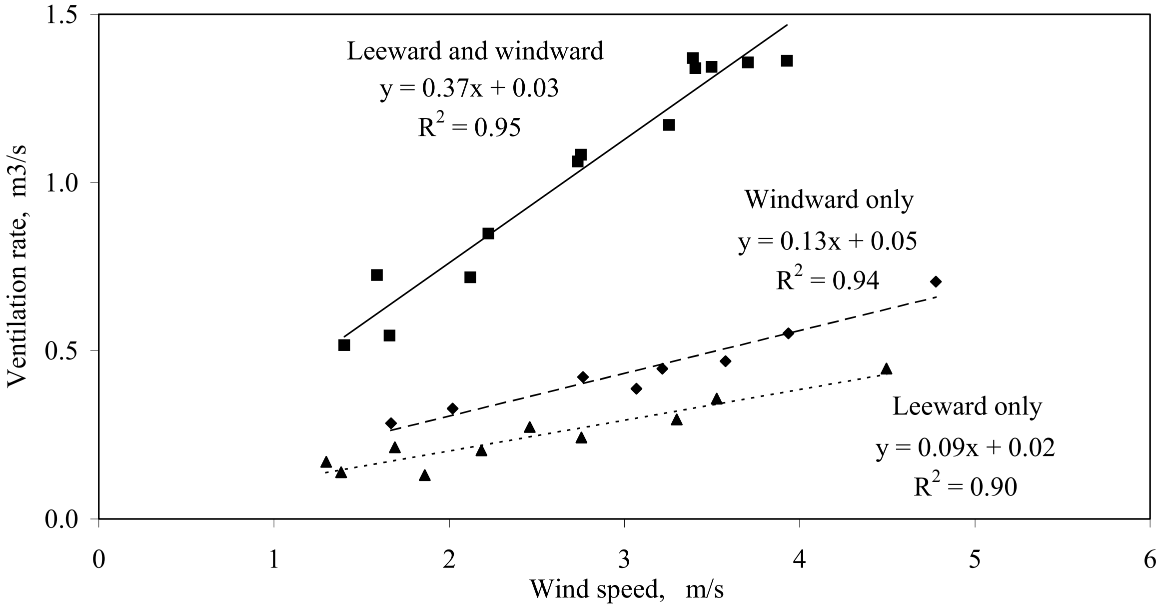

Fig. 5 Results of ventilation rate measurements on the model with: leeward vents open 100%, windward vents open 100%, and both windward-and-leeward vents open 100%

The requirement to operate the AFL in its non-recirculating mode to avoid accumulation of tracer in the ventilating air was achieved by closing the end of the return section, opening large doors in the return leg to exhaust the contaminated air, and opening a large door behind the fans to supply fresh inlet air. This had the unavoidable consequence of exposing the laboratory to the effects of external winds, meaning that testing was confined to occasions when external conditions were relatively calm. External winds effects led to variations in mean speeds about the set of nominal fan-generated speeds, although these variations are of no experimental consequence since they accurately reflect the wind speeds to which the model was subjected during the test, and turbulence levels were not affected significantly. A regression line was fitted to each data set as shown in Fig. 5 to obtain its linear-relationship equation. A range of relatively small positive y-intercept values indicated apparent variations in the ventilation rate at zero wind speed. These may be attributable to external wind-induced air infiltration, to ambient static pressure fluctuations which vary according to wind conditions, or to a small ventilating effect through diffusion being enhanced by the use of the internal oscillating desk-top fans.

The ventilation rates arising from 24 different vent-opening configurations were measured and plotted as illustrated in Fig. 5. The gradients of the fitted regression lines describe the influence of wind on ventilation rate. These gradients were plotted against ventilator opening as shown in Figs 6 and 7. These show that the ventilation rate does not increase linearly with ventilator opening angle. For both leeward and windward ventilators (when opened separately), the effect on ventilation is greatest at small opening angles and decreases as the ventilators are opened more widely.

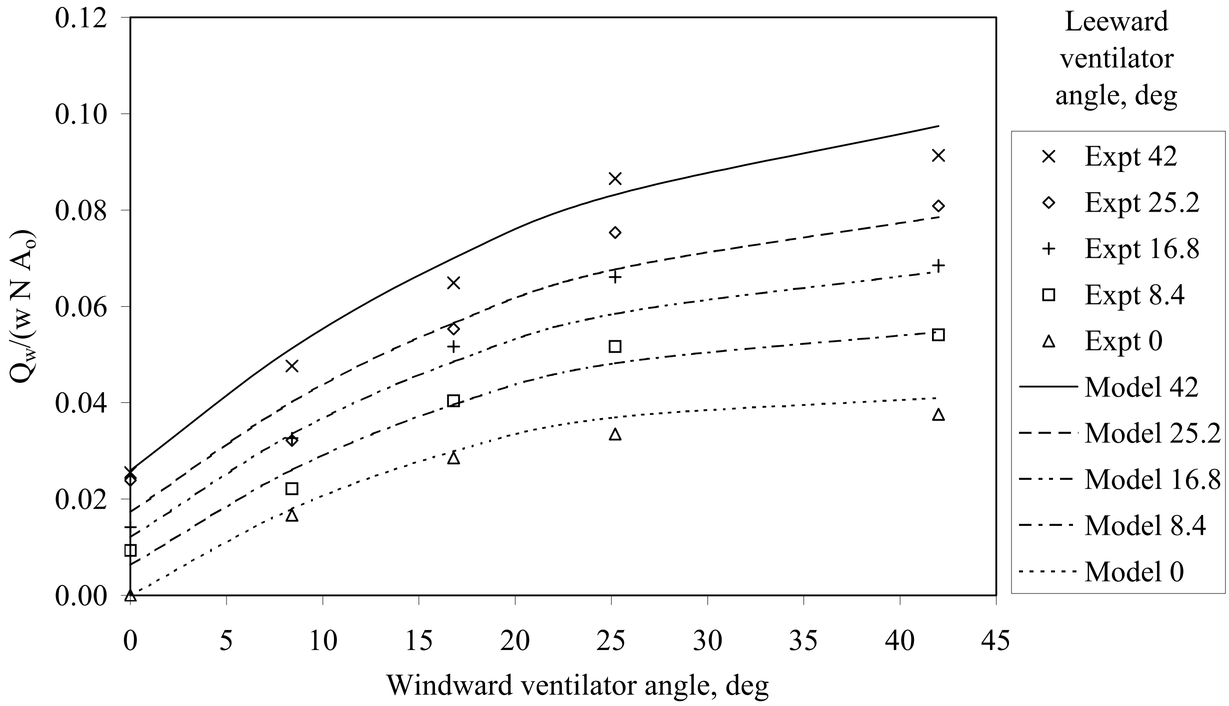

Fig. 6 Multiple linear-regression fits to gradients of ventilation rate vs wind speed results presented as a function of windward ventilator angle

6.5 Pressure measurements

Pressure tappings were made in the model at a number of locations over the roof, ventilators, and walls. Pressure measurements were made using a system comprising sixteen pressure transducers that was developed for full-scale wind pressure monitoring on buildings. The transducers were interconnected using solenoid valves enabling them to be zeroed and calibrated in-situ at regular intervals. Pressure coefficients were formed using the dynamic pressure measured upstream at the ridge height of the model as the denominator. Measurements were made with the ventilators closed and with them open at various angles. Measurements close to the mouths of the vent openings (at positions ⅔ of the way down the roof slopes, see Fig. 4) showed the pressure coefficients to change relatively little (by no more than approximately 0.2) as a result of opening the vents. The internal pressure also changed by a similar amount, depending on wind direction. In terms of ventilation performance, however, windward vents, particularly those on the upwind span, had a more pronounced effect than is indicated by these pressure measurements because of the tendency of the vents at larger opening angles to entrain the dynamic head of the flow into the house. This was achieved without a commensurate change to the static pressure at the tapping locations. This is illustrated further in Section 8. In terms of model development, however, pressure measurements had become unnecessary since the model was to be based on discharge coefficients for openings with flaps, and measurements of ventilation rates on a physical model (see next section).

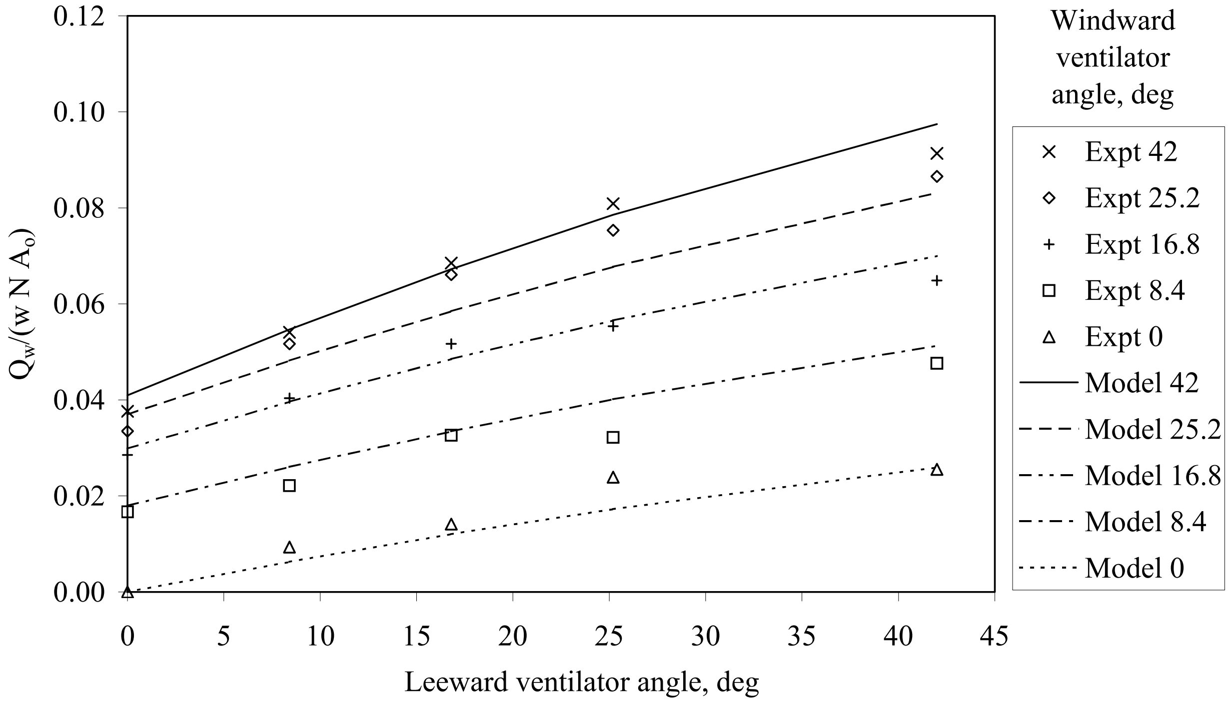

Fig. 7 Multiple linear-regression fits to gradients of ventilation rate vs wind speed results presented as a function of leeward ventilator angle

7. Development of model for wind-driven ventilation rate

7.1 Construction of the model

The two environmental variables that affect greenhouse ventilation are the wind and the temperature difference between the greenhouse and the ambient air. Wind produces ventilation by creating steady and fluctuating pressure differences across individual and groups of ventilators. These pressures can be related to the dynamic pressure of the wind using a wind pressure coefficient C_p defined as

$$\Delta P = C_p\, \rho\, w^2 / 2 \qquad (5)$$

where ρ is the air density and w the wind speed. This has been used as the basis for modelling leeward ventilation in greenhouses (Papadakis *et al*, 1996; Boulard *et al*, 1996). The flow through a ventilator can be described using Eqn (1) described in Section 4.1. Using Eqns (1) and (5), the air exchange created by wind, Q_w, through a single ventilator is given by:

$$Q_w = A\, C_d\, w\, \sqrt{C_p}$$

The area A is the effective area of the ventilator as described in Section 4.1.

The hypothesis was that ventilation rates could be expressed in terms of a discharge coefficient and the effective area of the ventilators. As leeward and windward ventilators can be opened independently, and since when both leeward and windward ventilators were open, an interaction between the effects of each was anticipated, the following equation was proposed:

$$Q_w / (w\, N\, A_o) = a\, (A_{lee} / A_o)\, C_d / 2 + b\, (A_{wind} / A_o)\, C_d / 2 + c\, (A_{lee} A_{wind} / A_o^2)\, C_d^2 \qquad (6)$$

where w is the wind speed, N the total number of ventilators in the greenhouse, A_o the area of the ventilation opening in the plane of the greenhouse roof, A_{lee} and A_{wind} are the effective areas of the leeward and windward ventilators, C_d is the discharge coefficient of the ventilator, and *a, b* and *c* are empirical coefficients. The third term has been included to allow for the interaction influence on the airflow when both leeward and windward ventilators are open. The discharge coefficients and areas were obtained as described in Section 4.1 which provided a reasonably good fit to the values measured in this project (Fig. 2).

The experimental results were corrected, on an equivalent area basis, to obtain the ventilation rates attributable to 10 leeward vents rather than the 15 present on the model. This gave data for ventilator arrangements comprising an equal number of windward and leeward vents (i.e. pairs of vents) representative of large commercial houses. Eqns (3), (4) and (6) were fitted to the experimental data obtained from measurements on the model greenhouse using multiple linear-regression analysis. A reasonable fit was obtained which accounted for 92.9% of the variation in the experimental values. However, because of the non-uniform ventilation response to the windward ventilator, a fourth term was added to Eqn (6) which became:

$$Q_w / (w\, N\, A_o) = a\, f_{lee}\, C_d / 2 + b\, f_{wind}\, C_d / 2 + c\, f_{lee} f_{wind}\, C_d^2 + d\, f_{wind}^2\, C_d^2 / 2 \qquad (7)$$

The regression analysis gave the following values for the coefficients:

a = 0.1156 (standard error 0.0129)
b = 0.3766 (standard error 0.0293)
c = 0.1517 (standard error 0.0293)
d = -0.2161 (standard error 0.0368)

This improved the representation of the experimental values, especially for large ventilator openings. The fit accounted for 97.3% of the observed variation, and the root mean square of the differences between the experimental and calculated values of $Q_w / (w\ N\ A_o)$ was 0.004. The representation by the model of the experimental data used for its development is shown in Fig. 8.

The air exchange that results from a difference in temperature across a ventilation opening can be represented by the following equation developed by Bot (1983):

$$Q_t / A_o = \frac{C_d}{3} \left[\frac{g\,(T_i - T_o)\,H}{\bar{T} + 273} \right]^{0.5} \left[\sin\beta - \sin(\beta - \alpha)\right]^{1.5} \qquad (8)$$

where Q_t is the temperature-driven air exchange through a single ventilator, g the acceleration due to gravity, T_i and T_o the internal and external temperatures respectively, H the width of the ventilator, β the angle of the greenhouse roof and α the angle of the ventilator. The value of $[\sin\beta - \sin(\beta - \alpha)]$ has a maximum value of $\sin\beta$ which occurs when the roof ventilator is horizontal. This equation has been applied to leeward and windward ventilators, but since an interaction between the respective airflows is less likely than it is with wind-driven ventilation, no interaction term has been included.

As with the wind-driven ventilation, a correction term equivalent to Eqn (4) can be applied to allow for flows through the triangular openings at the ends of the vent flaps. This is given by:

$$f_{temp} \quad = \quad 1 + 0.6198\,\frac{H}{L}\left[\frac{\sin(\beta-\alpha)}{\sin\beta\,\sin(\beta-\alpha)}\right]^{1.5}\left(\frac{\sin\alpha}{\sin\beta}\right) \qquad (9)$$

which is applied as a multiplication factor to Eqn (8).

The net airflow created by wind and temperature effects was obtained by summing the squares of the individual flows (Walker and Wilson, 1993):

$$Q = [\,Q_w^{\,2} + Q_t^{\,2}\,]^{\,0.5} \qquad (10)$$

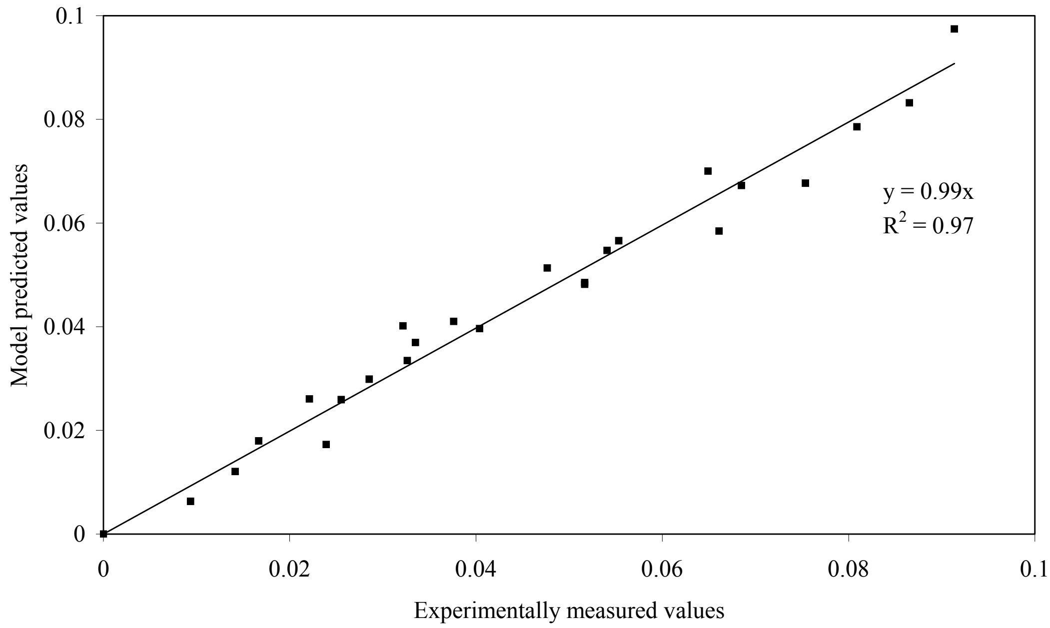

Fig. 8 Model representation of data used to create model: values are ventilation rate / (wind speed x total ventilator area)

7.2 Acquisition of ventilation rate data from large commercial glasshouses to validate the model

7.2.1 Method of measuring ventilation rates in large commercial glasshouses

Measuring ventilation rates in large commercial glasshouses using a tracer gas is difficult and expensive because large quantities of tracer gas are required and it must be uniformly distributed throughout the glasshouse. These problems were avoided by using as the tracer gas the CO_2 added to the greenhouse by the grower to increase photosynthesis. This was contained in the exhaust gases of a natural gas-fired boiler which were cooled by mixing with air and were distributed uniformly through the greenhouse by an array of perforated film plastic tubes. The air exchange rate was obtained from the following:

$$\overline{v_a} \quad = \quad \overline{\left[\frac{v_t - v_p}{C_i - C_o}\right]} \quad - \quad \frac{V}{t_2 - t_1}\ln\left[\frac{C_{2i}}{C_{1i}}\right] \qquad (11)$$

where the overbars signify time averaged values, v_a is the volumetric ventilation rate, v_t the volumetric supply rate of CO_2, v_p is the volumetric rate of CO_2 assimilated by the plants, C_i and C_o the fractional volume CO_2

concentrations inside and outside the greenhouse, V the greenhouse volume, $(t_2 - t_1)$ is the measurement period, and C_1 and C_2 are the CO_2 concentrations at the start and end of the measurement period.

The CO_2 assimilated by plants was determined by estimating the rate of net canopy photosynthesis using an expression developed by Nederhoff, 1984:

$$\rho\, v_p = 3600\, \xi\, J_o\, \tau\, C' / (\xi\, J_o + \tau\, C') - R \qquad (12)$$

where ρ is the density of air, ξ is the canopy light use efficiency, J_o the photosynthetically active radiation at the top of the canopy, τ the light extinction coefficient of the canopy, C' the CO_2 concentration in units of g/m^3, and R the canopy respiration rate. The implementation of this method requires measurements of the CO_2 supply, internal and external CO_2 concentrations, greenhouse volume and solar radiation.

7.2.2 Data acquisition from three full-scale glasshouses and validation of model

Glasshouse No. 1

This house, at Cantelo Nursery, near Ilminster, comprised a 37,800 m^2 Venlo glasshouse with sixty, 4 m wide spans, 157.5 m long, an eaves height of 4.5 m, a roof angle of 22^o, and was aligned with gutters north-south. The ventilator panels, arranged on alternate sides along each ridge, were 2.25 m long by 1.20 m wide and could be opened to a maximum angle of 44^o. The total area of the ventilators was 5292 m^2, equal to 14.0% of the greenhouse floor area. The house was divided into two by a central east-west, 4.5 m wide concrete path, with an external access door at the east end and transparent plastic curtain at the west end separating the house from a short corridor linking to another greenhouse. The house was exposed on the north, south and east sides. The soil was covered with sheets of white polyethylene film, which reduced the influx of CO_2 generated by soil micro-organisms. The rows of tomato plants, grown in rockwool using the high wire training system, were aligned north-south. During the measurement period the plants had reached the crop wires and were being layered and de-leafed in the customary way, this meant that the leaf area of the crop could be assumed to be constant.

The CO_2 rich boiler exhaust gases carbon dioxide was supplied to the inlet of a fan which pumped the gas mixture to the greenhouse through a 600 mm diameter metal duct and then into two metal ducts along the north and south walls. The gas was distributed across each half of the house by 75 m long, 60 mm diameter film-plastic tubes with pairs of 1 mm diameter holes at 0.3 m intervals placed at ground level between each double row of plants. The supply rate of the exhaust gas was measured using a pitot probe placed on the axis of the primary supply duct to measure the gas dynamic pressure. A correction was applied for the difference between the dynamic pressure measured at the duct axis and the average value determined by the log-linear method using six sampling points. The CO_2 concentration of the enrichment gas was measured with an infrared gas analyser and the gas temperature measured with a platinum resistance thermometer which enabled the gas volume to be corrected for changes in moisture content. Measurements of these variables were made at five-minute intervals and recorded by a data logger.

The house was divided into six zones for environmental control and sensors for measuring temperature and humidity, and the sampling points for CO_2 measurement, were contained in aspirated and reflective plastic enclosures at a height of 1.5 m within the crop canopy. The sampled air was pumped to a multiplexer and then in turn to an infrared gas analyser. The measurement cycle included an air sample drawn from outside the greenhouse. Values of the internal air temperatures, CO_2 concentrations, ventilator opening angles, and external temperature, CO_2 concentration, wind speed and solar radiation were measured by the greenhouse environment controller during its normal operation. Data records at five-minute intervals were obtained weekly from the controller.

Measurements were made continuously during July and August when the ventilation and CO_2 enrichment strategies were adjusted as considered necessary by the greenhouse manager based on the state of the tomato plants and the weather.

The records of CO_2 supply were combined with the environmental data to provide a dataset with records at five-minute intervals. The records of CO_2 supply were used to identify periods when the supply was constant, ventilation rates were calculated for these periods using Eqn (11) with a correction for the CO_2 used in photosynthesis obtained from Eqn (12). The maximum correction for photosynthesis was 15 % of the CO_2 supply. The magnitude of the term in Eqn (11) which corrects for changes in the tracer gas contained in the greenhouse atmosphere was generally less than 15%. The uncertainty in the air exchange rate values was calculated to be ±10%; this was based on maximum errors of 10 vpm in gas concentration, 0.1 m^3/s in carbon dioxide supply rate, and 2000 m^3 in the volume of the greenhouse (equivalent to a 5 cm error in measuring greenhouse height), and a recording interval of five minutes.

The data were sorted into classes of 10^o increments of ventilator openings and data excluded when wind speeds were less than 0.5 m/s because of unreliability in wind speed measurements using the growers' cup anemometers. The ventilation model (Eqns (3), (4), (7), (8), (9) and (10)) was then used with the dimensions of the ventilators (L = 2.25 m, H = 1.2 m, N = 1980) to calculate the ventilation rates from the wind speeds, temperatures and ventilator opening angles. The agreement between the measured and calculated values is shown in Fig. 9. The coefficient of proportionality between the calculated and measured values was 1.10 and had a standard error of 0.05. Thus the model overestimated the ventilation rate by 10%; the root mean square of the differences between the experimental and calculated values was 0.004 $m^3/s\ m_g^2$ (where the unit m_g^2 denotes the ground area of the greenhouse).

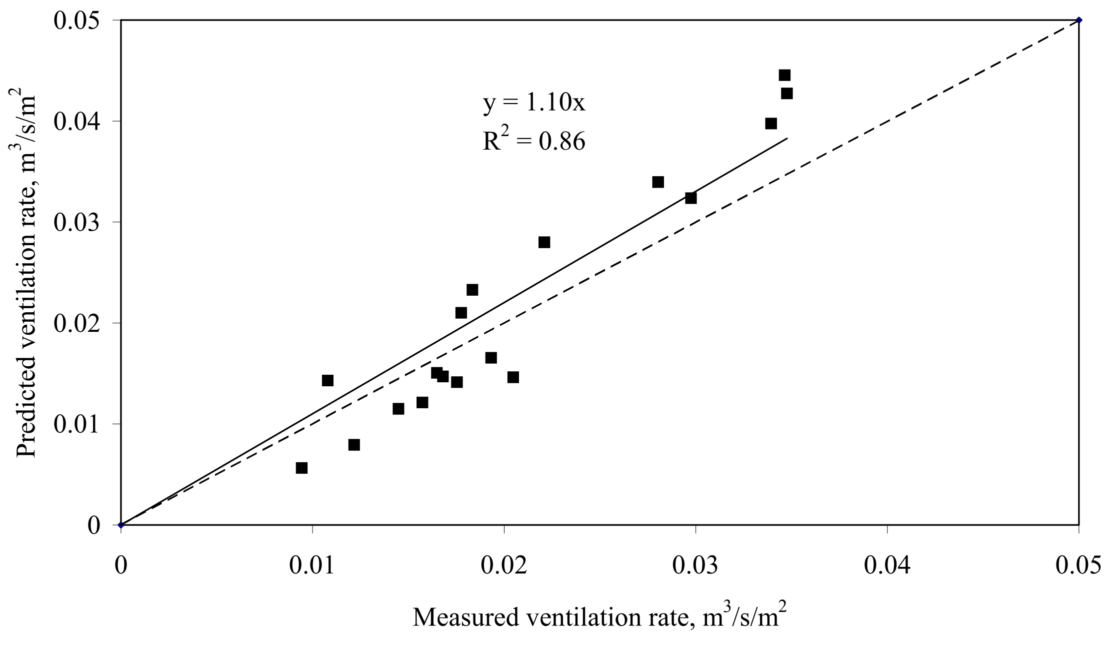

Fig. 9 Modelled and measured ventilation rates in a 37,800 m^2 Venlo glasshouse at Cantelo Nursery near Ilminster

Glasshouse No. 2

This Venlo glasshouse at Silsoe Research Institute was a 205 m^2, 4-span house, measuring 16 m long, 12.8 m wide, with an eaves height of 4.1 m, a 22^o roof slope and aligned with gutters east-west. The ventilators, arranged on alternate sides along each ridge, were 3.0 m long by 1.0 m and could be opened to a maximum angle of 42^o. The total ventilator area was 48 m^2, which was equal to 23.4% of the greenhouse floor area. The house had a concrete floor with a door at the south end of a path adjacent to the west gable wall. During the ventilation measurements the house did not contain plants.

Nitrous oxide (N_2O) was used as the tracer gas in this house. The gas was supplied at a constant rate to give a concentration in the greenhouse of approximately 50 ppm and the flow rate measured by a calibrated mass flow meter. The gas was distributed through a 25 mm diameter perforated plastic pipe at low level along each span. The greenhouse air was sampled at a height of 1.2 m at the centre of each quarter and at the centre of the house. The samples were mixed and pumped to an infrared gas analyser calibrated at regular intervals. Measurements of gas supply rate, mean gas concentration, inside and outside temperatures, wind speed and direction and solar radiation were made at one-minute intervals and recorded by a dedicated data acquisition system (Magus, Measurements Systems Ltd). Measurements were made for periods of thirty minutes for a range of ventilator openings.

Average values of ventilation rate and wind speed were calculated for each set of experimental data and the ventilation model (Eqns (3), (4), (7), (8), (9) and (10)) was used with the ventilator dimensions to calculate ventilation rates. The agreement between the measured and calculated values is shown in Fig. 10. The coefficient of proportionality between the calculated and measured values was 1.16 and had a standard error of 0.05. Thus the model overestimated the ventilation rate by 16%; the root mean square of the differences between the experimental and calculated values was 0.007 $m^3/s\ m_g^2$ (where the unit m_g^2 denotes the ground area of the greenhouse).

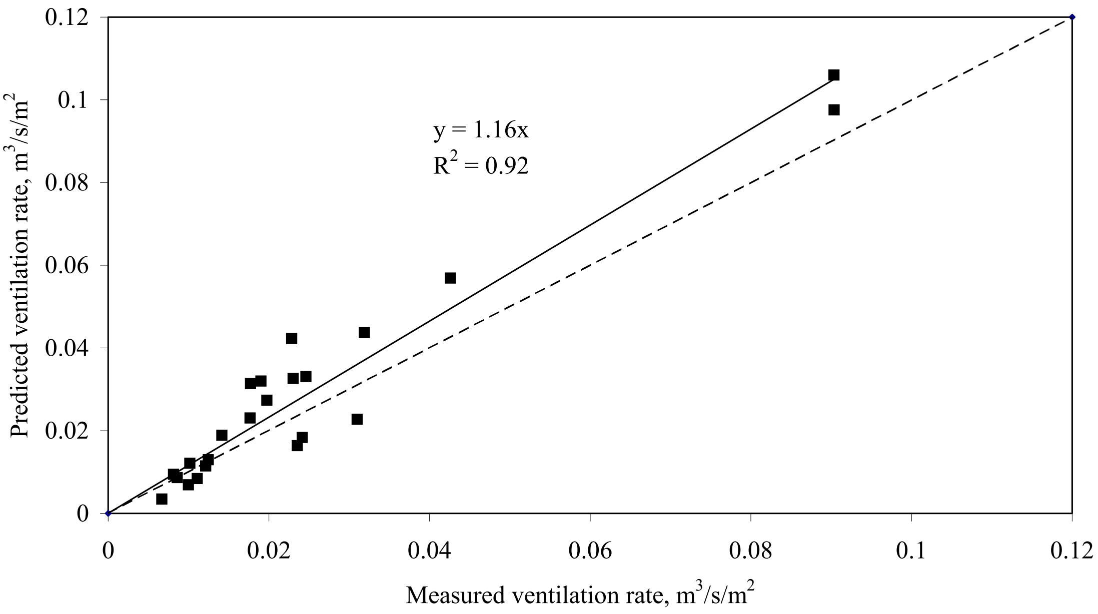

Fig. 10 Modelled and measured ventilation rates in a 205 m^2 Venlo glasshouse at SRI

Glasshouse No. 3

This glasshouse was at Lansdale Nursery, near Ormskirk. It was a 5178 m^2 Venlo house with twenty-two, 3.2 m wide spans, 75 m in length, an eaves height of 3.0 m, a roof angle of 25^o, and was aligned with gutters east-west. The ventilators, arranged on alternate sides along each ridge, were 2.0 m long by 0.825 m wide and could be opened to a maximum angle of 44^o. The total ventilator area was 558 m^2, which was equal to 12.9% of the greenhouse floor area. The house was divided into two by a central north-south, 3 m wide concrete path with a door at the north end. The house was exposed on the south and west sides, sheltered on the north by a greenhouse and boiler house, and was separated from another glasshouse on the east side by a glass partition wall. The soil was covered with sheets of white polyethylene film. The rows of tomato plants, grown in rockwool blocks using the high wire training system, were aligned east-west. During the time of the measurements the plants had reached the crop wires and were being layered.

The CO_2 supply from the boiler house was via a 315 mm diameter duct, which supplied ducts along the east and west gable walls. The gas was distributed across each half of the house by 35 m long, 60 mm diameter film-plastic tubes with pairs of 1 mm diameter holes at 0.3 m intervals placed at ground level between each double row of plants. The method used to measure the CO_2 supply rate was as that described for Greenhouse No. 1.

The house had a single aspirated screen with sensors for measuring temperature and humidity, and a sampling point for CO_2 at a height of 1.5 m in the crop canopy. The sampled air was pumped to an infrared gas analyser. The measurement cycle of the gas analyser included an air sample drawn from outside the greenhouse. The data logger used to record the CO_2 supply also recorded the greenhouse CO_2 concentration. Values of internal air temperature, ventilator opening angles, and external temperature, wind speed and solar radiation were measured by the greenhouse environment controller during its normal operation, and data records at five-minute intervals were obtained from the controller. The measurements were made from April until September during which time, the ventilation and CO_2 enrichment strategies were adjusted as considered necessary by the greenhouse manager based on the state of the crop and the weather.

The data were averaged over 30 minute periods and values with wind speeds greater than 0.5 m s^{-1} were sorted into 10 % classes of ventilator openings. The model (Eqns (3), (4), (7), (8), (9) and (10)) was used with the relevant dimensions of the greenhouse and ventilators, and average values of ventilator openings, wind speed and temperatures to estimate ventilation rates. The comparison between measured and calculated values is shown in Fig. 11. The coefficient of proportionality between the calculated and measured values was 0.86 and had a standard error of 0.05. Thus the model underestimated the ventilation rate by 14%; the root mean square of the differences between the experimental and calculated values was 0.005 $m^3/s\ m_g^2$ (where the unit m_g^2 denotes the ground area of the greenhouse).

7.2.3 Conclusions on validation of the model

A ventilation model has been developed for glasshouses with opening roof ventilators. It has been tested using independent data from three glasshouses with plan areas of 205, 5178 and 37,800 m_g^2 having ventilator-to-ground area ratios of 0.23, 0.13 and 0.14 respectively, and was shown to predict ventilation rates with an accuracy of 0.004-0.007 $m^3/s\ m_g^2$.

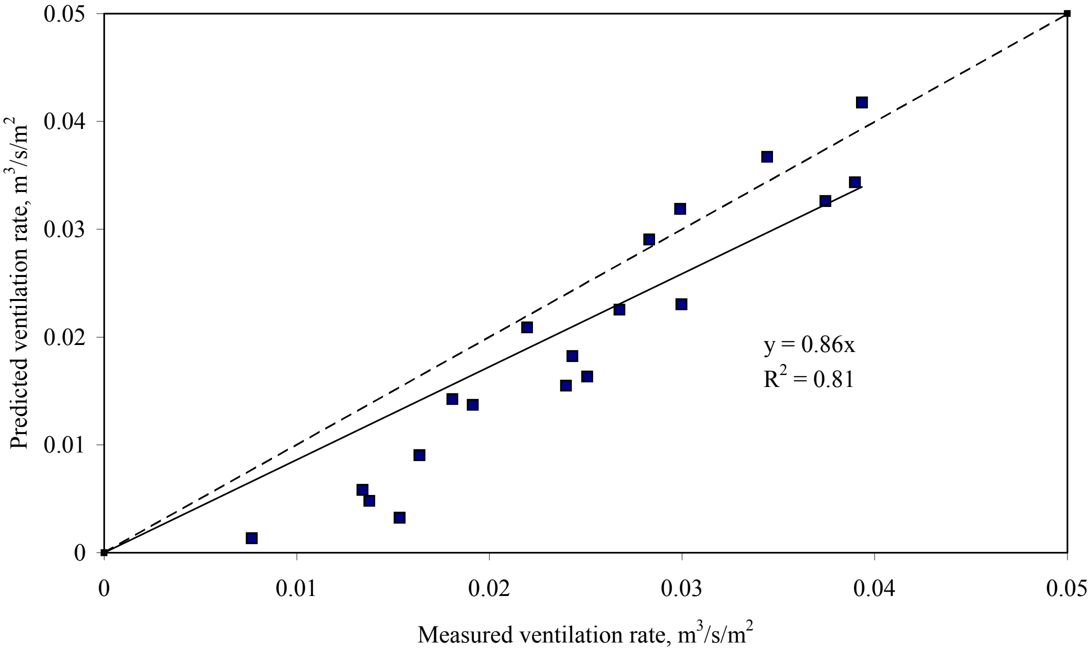

Fig. 11 Modelled and measured ventilation rates in a 5,178 m^2 Venlo glasshouse at Lansdale Nurseries near Ormskirk

8. Visualisation of ventilating flow regimes

7.3 Experimental approach

Tests were also conducted in the AFL to study the ventilating flow regimes. The flows were visualised using a mineral-oil smoke generator and recorded using a digital video camera from behind the large glass window in the dividing wall of the AFL (see Fig. 3). Two different visualisation techniques were used. Controlled smoke injection was made using a hand-held nozzle at specific locations throughout the internal volume and at individual vents. This gave information on the directions and relative speeds of internal flows, and on whether a particular vent was acting as an inlet or an outlet, or both. The house was also filled completely with smoke (with the fans switched off) and the ventilation of the smoke recorded with the fans running. This also gave information on which vents were acting as inlets and which as outlets, and on which areas of the house were preferentially cleared of smoke (i.e. were most effectively ventilated). In both cases, recordings were made for a range of ventilator opening arrangements, and a number of hours of monitoring were undertaken.

7.4 Results

Several interesting and enlightening findings resulted from these qualitative studies of the ventilating airflows. Since the monitoring comprised video records, it is difficult to present these findings in an illustrative way in a written report. The main findings may be summarised as follows.

1. Ventilation has a significant turbulent-driven component. This was evidenced by the airflow through a large proportion of ventilators fluctuating between inflow and outflow. This was particularly the case

when either windward vents only, or leeward vents only were open. Figure 12 gives an illustration where the two pictures, taken only a few seconds apart, show different ventilators to be acting as outlets (all windward ventilators were open at 60% and leeward ventilators were closed).

2. There is a general tendency for air to be extracted from upwind ventilators and for air to infiltrate through downwind ventilators because wind suctions generated over the roof are highest at the upwind end. However, the flow through the ventilators in the downwind-most span (Span ⎛, Fig. 4) was often significantly outwards, though fluctuating.

3. Windward ventilators on the upwind-most span (Span ®, Fig. 4) tend to act less as an outlet and more as an inlet as the opening angle is increased because the vent increasingly captures more of the dynamic head of the external flow that separates from the windward eaves. If only windward ventilators are open, the ventilators on the next span downwind (Span ©, Fig. 4) then act increasingly as outlets.

4. When windward ventilators on the upwind span act as outlets, the outflowing air becomes trapped in the separated flow bubble of the external flow regime and either spills over and around the vent whilst the vent continues to act as an outlet, or re-infiltrates into the house when the vent fluctuates to acting as an inlet.

5. When windward and leeward ventilators are open, a more discernible mean ventilating flow regime is established, although fluctuations still arise at several ventilators. When both sets of vents are open, windward ventilators are able to act more generally in their inclined sense as inlets, and leeward ventilators in their inclined sense as outlets. Figure 13 provides an illustration of this for the case where leeward ventilators were open 100% and windward ventilators were open 60%. Again, the two pictures were taken only a few seconds apart. Flow through the leeward ventilators is highly predominantly outwards. Flow through the windward ventilators is predominantly inwards, though those on the upwind span (right-hand side) fluctuate between inflow (top picture) and outflow (bottom picture), providing an illustration of the point described immediately above.

6. When both windward and leeward ventilators are open to a reasonably significant extent, there is evidence of preferential ventilation of local regions in the house. This arises when outflow, generally greatest at the upwind end, combines with inflow at the adjacent or at an intermediate span (rather than principally from the downwind span) to create a local circulation of flow that preferentially ventilates the upwind spans.

7. Internal flows are often not well established because of the turbulent nature of the driving mechanism.

8. Internal flows, when established, are very much three-dimensional. When windward ventilators act as inlets, the inflows are relatively high-speed jets that move down the underside of the adjacent roof slope and are projected downwind and towards the floor. This generates internal flows in the along-wind direction in bays with windward ventilators (Bays © and ∑, Fig. 4), but the internal flows in bays with leeward ventilators (Bays ®, ™, and ⎛, Fig. 4) are in the opposite, into-wind, direction.

9. Internal flow speeds are generally low, particularly near the ground. The highest internal air speeds are generated by inflows at windward ventilators.

Fig. 12 Illustration of turbulent fluctuations producing outflow through downwind ventilators (top picture, left-hand end) and, a few seconds later, through upwind ventilators (bottom picture, right-hand end) for case when windward ventilators were 60% open

Fig. 13 Illustration of when both windward and leeward ventilators are open (leeward 100% and windward 60% in this case), leeward ventilators tend to act as outlets and windward ventilators as inlets, though windward ventilators on upwind span fluctuate between acting as inlets (top picture, right-hand side) and outlets (bottom picture, right-hand side)

9. Conclusions

The objective of the work has been completed successfully. A model of the natural wind-driven ventilation of large, commercial Venlo glasshouses has been developed, and for completeness, buoyancy-driven natural ventilation has also been built into the model. The wind-driven model has been developed from the results of physical tests on ventilators of different aspect ratios with flaps at different opening angles, and from an extensive series of measurements on a 1 : 3.5 scale model of a 5-span Venlo glasshouse in the new Atmospheric Flow Laboratory (AFL) at Silsoe Research Institute (SRI). Wide ranges of ventilator opening arrangements and wind speeds were tested. The model, when applied to the test cases used to develop it, accounted for 97.3% of the observed variations in ventilation rates. The model was validated against three independent sets of measurements made in three different full-scale Venlo glasshouses, two being commercial houses and one being an experimental house at SRI. The houses had contrasting plan areas of 205, 5178 and 37,800 m_g^2 and ventilator-to-ground area ratios of 0.23, 0.13 and 0.14 respectively. The model predicted ventilation rates with an overall accuracy of 0.004-0.007 $m^3/s\ m_g^2$, and on average for each of the three houses gave predicted rates that were 110%, 116%, and 86% of the measured values. Acquisition of the independent, validating data from the large commercial houses was a significant component of the project. The technique adopted was to use the CO_2 supplied to enrich the internal environment as the tracer gas. This entailed careful measurements of the CO_2 supplied to the houses and of CO_2 concentrations in the houses, correction for CO_2 converted through photosynthesis, temperature measurements to account for thermally-driven ventilation, wind speed measurements, and recordings of the ventilator opening arrangements.

Supplementary studies have been completed of the ventilating and internal flow regimes generated by wind action on glasshouses when ventilators are opened in different arrangements. These were undertaken using the scale model in the AFL. Flows were visualised using smoke and were recorded using a digital video camera. The studies have provided interesting and enlightening information on the physical processes responsible for ventilation. They show, for example, that when leeward ventilators only are open, outflow is greatest at the upwind end because the external roof suctions generated by the wind are greatest there, and as a consequence the internal flow is generally towards the windward wall. They illustrate the strong turbulent-driven component of ventilation that is present especially when only one set of vents (windward or leeward) are open and the associated absence of well-established internal flow regimes. They also show the three-dimensional nature of internal flows when both sets of vents are open and reveal that these are driven by relatively high-speed inflows through windward ventilators.

The resulting model is amenable to implementation into horticultural environmental controllers, and discussions have been held with two leading companies and the HDC to this effect.

Acknowledgements

Thanks are extended to the staff of Cantelo Nurseries Ltd and Lansdale Nursery for allowing the measurements to be undertaken at their respective sites. Thanks are also extended to Tony Lockwood of SRI for persevering with the testing programme through the difficult commissioning stages of the AFL.

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