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Measurement of air exchange time in a mushroom tunnel

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The rate at which fresh air is introduced to a mushroom tunnel has a major impact on the climate in the tunnel. Control of this rate is by adjustment of the ventilation mixing flap setting within the air conditioning unit. The objective of this study was to determine the air exchange time in a standard mushroom tunnel as a function of the flap position. In combination with an understanding of tunnel air exchange efficiency, knowledge of the relation between air exchange time and flap position facilitates control of the tunnel climate, through the use of predictive control strategies. Measurement of the air exchange time was achieved by marking the air in the tunnel with a tracer gas (CO_2) and then recording its rate of decay in the tunnel. A range of mixing flap settings, from 0 to 90°, were used. Results showed that the effect of the flap angle on air exchange time may be characterised by a logarithmic relation. A wide variation in air exchange time exists for any one setting of the flap, especially at high flap angles when the bulk of the air is being re-circulated. This is due to the dependence of air exchange time on both uncontrolled infiltration and fresh air inflow that is controlled by flap angle position. Both of these mechanisms are weather dependent. Back-flow of conditioned air through the mixing box and out through the fresh air inlet was identified as a preventable ventilation short-circuit. The potential increase in air exchange efficiency that results from the increase in understanding of the air conditioning system can be translated into direct energy cost savings to the grower.

Keywords: Air exchange time; climate control; mushroom tunnel

Introduction

The primary objective of this study was to evaluate the air exchange time in a standard mushroom tunnel as a function of the position of the ventilation mixing flap. The air exchange time (k) is used as an indicator of the time constant that characterises the ventilation in a building. It is defined as the ratio of building volume (V) to airflow rate (ϕ) and its nominal value is defined in equation (1).

$$k = V / \phi \tag{1}$$

'The air exchange time of a building cannot be reliably estimated from the building's construction or age, or from a simple visual inspection. Some measurement is necessary,...' (ASHRAE, 1989). This quotation indicates the need to determine air exchange time by direct measurement.

Several different procedures to calculate building air exchange time have been developed. A tunnel's air exchange time is a function of the uncontrolled infiltration of external air through the tunnel (i.e., natural ventilation) and the controlled mechanical ventilation that provides an airflow through the tunnel. Infiltration is dependant on the temperature difference between internal and external air, the stack effect, and the wind effect (Sherman, 1992). The wind effect is variously ascribed to being due either to wind speed alone or both wind direction and wind speed. These effects have been extensively studied for several types of naturally ventilated buildings, including greenhouses (e.g. de Jong, 1990). Regardless of the wind effect relation, both wind effect and stack effect combine to create a local pressure difference between inside and outside air. This pressure difference is a driving force for natural ventilation by infiltration. As there is significant variation in the weather in Ireland, in terms of both temperature and wind, variation in natural ventilation is to be anticipated. Additionally, fan generated pressure differences provide a means of mechanical ventilation.

Measurement of air exchange time is commonly undertaken by marking the air in the tunnel with a tracer gas. Three classes of tracer gas analysis are commonly used, constant injection, constant level, or rate of decay (ASTM, 1995). The rate of decay method consists of a burst release of tracer gas, thorough mixing with the air being monitored, and then continuous monitoring.

Tracer gas analysis can be used to measure residence times (Etheridge and Sandberg, 1996) and hence determine the age of air within a building. This technique is also used to establish a mixing factor, which can be used to characterise the air exchange effectiveness of a building (Drivas, Simmonds and Shair, 1972).

Studies of air exchange time using tracer gas methods have been undertaken in many forms of buildings, e.g. livestock pens (Leonard, Feddes and McQuitty, 1984), and greenhouses (Nederhoff, van de Vooren and Udink ten Cate, 1985). However due to the different forms of construction and ventilation, air exchange times from other building types are not directly comparable to those of a mushroom tunnel.

Mushroom tunnels in Ireland generally conform to a building construction standard (S.151; Farm Development Service, 1987). This ensures that a relatively airtight building envelope exists. This is augmented by good practice, including proper maintenance of the sealing of fire and access doors, etc. on the part of the growers, who are motivated by the cost of lost energy, in the form of conditioned tunnel air.

A study undertaken by Meath (1993) measured the mixing factor (Constance, 1970) in an experimental mushroom tunnel using the method proposed by Albright (1990). The mixing factor is a term used to characterise ventilation in a building and is expressed in a slightly different form of equation (2). Equation (2) is the standard ventilation equation (Liddament, 1996) used to describe a contaminant concentration (C) as a function of time (t), knowing the initial concentration (C_0) and the air exchange time (k). In the mixing factor form of expression, t/k is replaced by m.N where N is the number of air changes and m is described as the mixing factor.

$$C_t = C_0 e^{-t/k} \qquad (2)$$

In a previous study (Staunton, 1985) a relation was established between the fresh air flow rate and flap position in an experimental tunnel. This work established a nominal air change rate but it excluded natural ventilation and air exchange time was not measured directly. Furthermore air exchange efficiency was not determined. Hence the results cannot be used in the formation of predictive control strategies. Both Bishop (1979) and Burrage *et al.* (1988) have proposed a relationship between flap angle and the ratio between fresh and re-circulated air. We have not located any study relating flap position to air exchange time for both natural and mechanical ventilation.

The three main objectives of tunnel climate control, in order of priority, were given by Martin, Ringwood and Grant (1997). The first objective is to maintain the temperature of the crop growing medium at the set point for each phase of crop growth. The second objective is to maintain an appropriate air drying power for the mushroom crop, to ensure that the mushroom surface becomes neither too dry nor too wet. As a significant part of the first objective is achieved via evaporative cooling, (Gielen, 1995) control of the drying power also has a prime role in maintaining temperature regulation. The

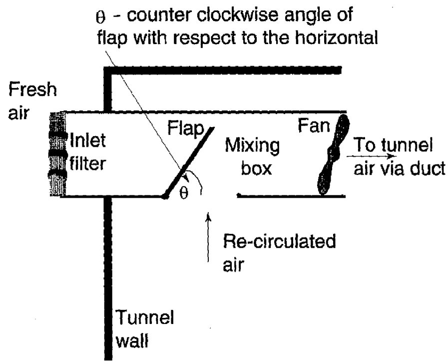

Figure 1: Layout of the mixing box in the air conditioning unit.

third objective is to maintain an appropriate CO_2 concentration for crop growth. A level that is too high discourages cap formation.

When it is desired to induce pinhead formation, the CO_2 concentration is reduced. As the mushroom crop is a source of carbon dioxide, the reduction is achieved by flushing the tunnel with fresh air, thus diluting the tunnel carbon dioxide. Mushroom tunnels have a concrete floor and polythene walls and ceiling, hence there is no sink or source of carbon dioxide in the building fabric. Control of the rate of dilution is achieved by the setting of a mixing flap in the air conditioner or via a separate fresh air fan. A simplified diagram of the mixing box within an air conditioner is shown in Figure 1.

The introduction of fresh air into the tunnel affects all the climate parameters of interest. To understand the impact of the disturbance that the control of carbon dioxide has on temperature and humidity control, and to facilitate control of the climate in the tunnel, an understanding of the relation between air exchange time and flap position is necessary.

Materials and Methods

The tunnel used for the measurements was one of standard construction located at the Kinsealy Research Centre. The tunnel was empty for the duration of the measurements so no source of carbon dioxide was in the tunnel during this period.

From the range of gases commonly used, carbon dioxide was chosen as the tracer due to its ready availability, re-cycability through the carbon cycle, cost, ease of measurement using infra red gas analysis (IRGA) and low toxicity. The HORIBA (1989) IRGA meter used had a range of 0 to 3,000 μmol mol^{-1} and was calibrated according to the manufacturer's procedure before the series of measurements, and checked for drift afterwards. No drift was detected.

The zero point of the scale was set using a gas injection can of pure nitrogen, i.e. a CO_2 concentration of 0 μmol mol^{-1}. The high point of the scale was set using a gas injection can of 2,475 μmol mol^{-1} CO_2 concentration. The meter was then checked using outside air that is approximately 340 μmol mol^{-1}.

As tracer gas analysis is critically dependent on complete mixing of the tracer with the air an evaluation of the mixing method is required. The desired airflow pattern in a mushroom tunnel is illustrated in Figure 2. An inspection of this pattern leads to the conclusion that good mixing of the air in the tunnel is to be expected.

The general airflow sequence is as follows. Each number below refers to one of the numbered airflows in Figure 2.

1. Air exits the air conditioning unit and flows through the duct.
2. Air exits the D-shaped flaps from the duct.
3. The air jets becomes entrained to the curved wall of the tunnel by the Coanda effect (Tritton, 1977).
4. Air flows laterally over the horizontal crop surface.
5. The airflow meets the opposing airflow from the other side of the tunnel, and, either
6. flows towards the re-circulation vent, and/or,
7. flows towards the exit vent.

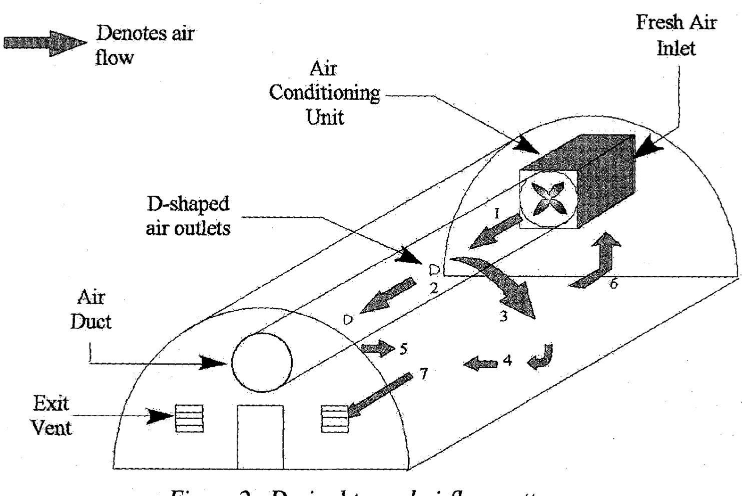

Figure 2: Desired tunnel airflow pattern.

As over 30 series of measurements were planned to be taken in a large space, the cost of the tracer gas was of concern. Hence the rate of decay method was selected over constant injection or constant concentration. Measurement of the airflow leaving the air conditioner was 3,150 m^3/h on full fresh air (Grant, 1998. Personal communication). A calculation of air volume in the test tunnel yielded a result of 512 m^3. A nominal air exchange time of 9.75 min was thus established.

The time it takes for air to flow from the re-circulation inlet through the air conditioner, down the duct, and back to the re-circulation inlet, i.e. the 're-circulation time', (2 to 3 min) was established by the pulsed release of tracer in the tunnel during preliminary investigation. A knowledge of the re-circulation time facilitates the planning of a mixing strategy for conducting a tracer gas experiment.

A measure of the effectiveness of the airflow pattern within a building is the air exchange efficiency (Sutcliffe, 1990). When the air exchange time is equal to the nominal value given in equation (1), conditions of ideal piston-flow exist, and air exchange efficiency is at a maximum of 100% (Etheridge and Sandberg, 1996). This occurs when the air moves from the inlet to the exit vent, displacing the air in the building and not mixing with it. If there is some mixing along with displacement, efficiency will be in the range of 50 to 100%. Complete and instantaneous mixing gives an efficiency of 50%. A short-circuiting flow pattern will result in efficiencies lower than 50%.

Analysis of airflow in full fresh air mode, i.e. flap angle (θ) $= 0°$, suggests that air exchange time is due to both infiltration and inflow through the air conditioner. The shortest airflow path is one where there is a flow of air from the duct at the exit vent end direct to the exit vent. The corresponding longest airflow path is a flow from the duct outlet at the air conditioner, through the length of the tunnel to exhaust through the exit vent. In between these two flow paths, there are flow paths of progressively shorter length as one moves from the inlet towards the exit vent from each duct outlet to the exit vent. Taken on an individual basis, each one of these paths constitutes a displacement flow. Except for the path length from the first duct outlet, i.e. the one nearest the inlet, to the second duct outlet, which is solely a displacement flow, each duct outlet flow also mixes with all its' predecessors as they move through steps 1 to 5, and 7 of Figure 2, collectively towards the exit vent. This would imply that the flow pattern is best approximated by a complete and instantaneous mixing airflow (Etheridge and Sandberg, 1996).

Air exchange time in full re-circulation mode, i.e. flap angle $= 90°$, is by infiltration only. Duct outlet flow paths follow steps 1 to 6 of Figure 2, except the direction is not towards the exit vent but reversed towards the re-circulation inlet of the mixing box.

In between these two modes, i.e. θ between 0° and 90°, a combination of the above two flow types exists. The flap position determines the relative contribution of the two flow types to the overall flow in the tunnel.

The flap angle was varied from 0° to 90°, in 9° increments. Three experiments were made for each flap angle setting, in an attempt to encompass a range of weather conditions. Previous studies (Malik, 1978) have established that there is a variation in infiltration due to weather conditions. It was not the objective of this study to include weather conditions in the relation between flap angle and air exchange time. Rather to facilitate the control of tunnel climate, the objective was to establish a range of variation in air exchange times resulting from different weather conditions.

Throughout the experiments the decay rate sampling point was maintained constant in the middle of the tunnel laterally, one third along the tunnel from the exit vent, 1 m above the floor. Fan speed was also kept constant at 95% of maximum. The experimental procedure used for each series of measurements was as follows:

(i) The mixing flap angle was set to 90°.

(ii) The tracer gas was released beneath the re-circulation inlet until the IRGA meter indicated over-range (3,000 μmol mol^{-1}) at the sampling point. A minimum mixing time of double the time from initial release to over-range indication, plus double the re-circulation time was used to allow complete mixing of tracer with the tunnel air.

(iii) It was assumed that once the meter reading was over-range throughout the tunnel, then there would be even mixing in the tunnel before the readings fell within the meter's range. A check for even distribution of tracer gas in the tunnel using the IRGA meter was made by extending the meter sampling tube for the period of the check, so that samples could be taken at any point in the tunnel. The check consisted of ensuring that at representative spatially distributed sampling points the IRGA meter reading was over-range. The over-range check was employed to ensure full use of the available range of the meter. The sampling points were spaced in three lateral rows, one row in the middle of the tunnel and the other set 1 m from either end of the tunnel. Each row was of two layers. The lower layer was approximately 1 m above the tunnel floor and had three sampling points. One sampling point was in the middle of the tunnel, and the other two were 1 m from either edge. The upper layer was approximately 2 m above the tunnel floor and had two sampling points. The sampling points were approximately 2.2 m in from either edge of the tunnel.

(iv) The mixing flap angle was set.

(v) Samples of the IRGA meter reading were logged until the reading approached background level.

(vi) The air exchange time was calculated from the decay rate data using a log fit (ASHRAE, 1989).

This procedure leads to the release of a greater amount of carbon dioxide into the tunnel than the minimum required for the experiment, but it was adopted to ensure reliable mixing of tracer with tunnel air.

Due to the limited range available on the IRGA meter, over 10% was covered by the background level of carbon dioxide in air. Measurements of the background level of carbon dioxide at Kinsealy indicated that there is a significant diurnal variation in the level, as illustrated in Figure 3. Hence, all values less than 500 μmol mol^{-1}, were omitted from the analysis.

It would have been preferred to have the tracer gas at a significantly higher concentration level to reduce this component of measurement error. Tracer gas cost considerations and availability of meters with a high range prevented this approach.

Data from the meter was recorded using a data logger (Grant, 1988) at a 15 s sample interval, which is the response

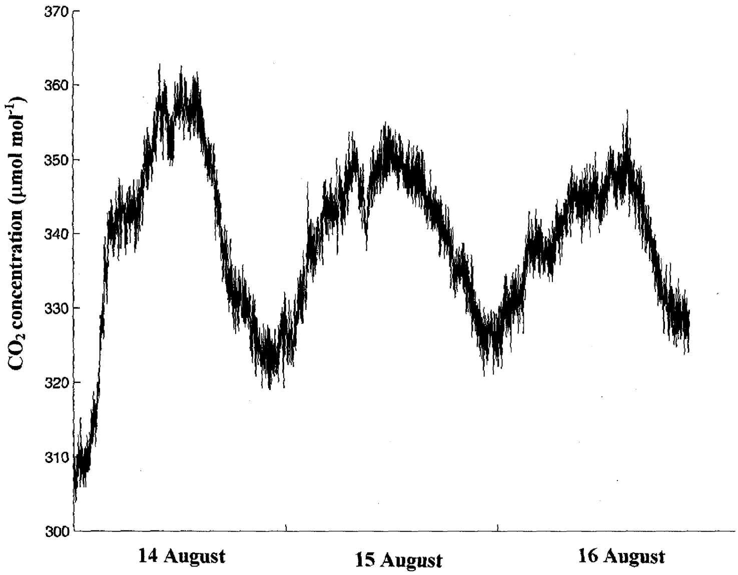

Figure 3: Diurnal variation in ambient level of CO_2 on 14 to 16 August 1998.

time of the IRGA meter used. This data was then averaged on a 1 min basis to filter any variation due to turbulence from the continual fan mixing, prior to analysis. For the highest ventilation rate, i.e. full fresh air, this gives a sample interval which is approximately 5.5% of the mean air exchange time and approximately 11% of the nominal air exchange time.

Results

A plot of the results for a flap angle $\theta = 72°$ is shown in Figure 4. Note the variation in results due to different weather patterns. The curves of steeper descent correspond to weather conditions of greater wind and/or stack effect.

A calculation check was made on each set of experimental data. Each data set was divided into decay ranges of 2,000 to 1,170 μmol mol^{-1} and 1,000 to 670 μmol mol^{-1}. Two calculations of air exchange time were made using the upper and lower range of data. This was done in an attempt to determine whether the error contribution from the IRGA meter was as large as would be implied by a simple error analysis because the accuracy is 10% of full scale and not of reading. Except where there was a clear change of air exchange time due to a noted variation in weather conditions, no major difference in result was detected by this error check. Also, a simple calibration check, i.e. the measurement of outside air background CO_2 concentration, was undertaken at the end of each experiment. The calculation check combined with the fact that the IRGA meter consistently read an outside air background CO_2 concentration within approximately 30 μmol mol^{-1} of 340 μmol mol^{-1} implies that the accuracy of the meter was considerably better than that quoted by the manufacturer.

From these measurements, the mean and range were calculated for each flap angle setting. A third order polynomial fit to the mean data is shown in Figure 5.

The large vertical spread in data points

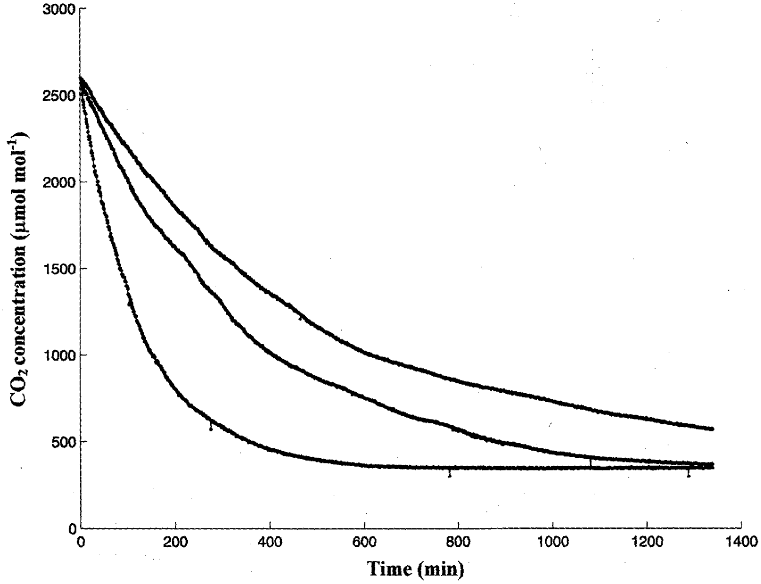

Figure 4: The decay of CO_2 concentration in a mushroom tunnel with a flap angle of 72° under three sets of external conditions.

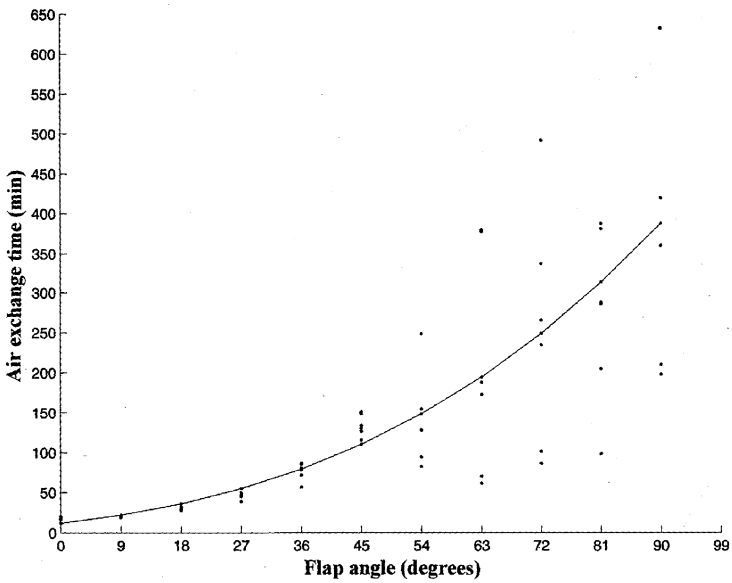

Figure 5: The relationship between flap angle and the air exchange time measured from October 1997 to February 1998.

at high flap angles in Figure 5 is, to a significant degree, due to the spectrum of weather conditions encountered. Larger mixing flap angles had an experimental duration of greater length than smaller angles and hence were more likely to experience weather variation. In some cases, significant weather variation occurred during a single experiment.

Discussion

Air exchange efficiency, which is discussed here solely in the context of full fresh air operation, was 54%. This result is in agreement with that expected, i.e. somewhere slightly better than the 50% (Etheridge and Sandberg, 1996) for complete and instantaneous mixing.

A variation in results was expected due to the prevailing weather conditions. Furthermore, there is also a local spatial and temporal variation in background CO_2 levels. Figures from other air exchange time studies reported ranges from 3 (Sherman and Wilson, 1986) to 5 (Malik, 1978). The maximum range of air exchange times for any one flap angle (63°) was 6.13:1.

Examination of the form of the curve in Figure 5 suggests an exponential of some form. A plot of the natural logarithm of the mean data is shown in Figure 6 together with a corresponding best linear fit to the mean logarithm data and the corresponding 95% confidence limits of the fit. Note that 83% of the measured data lies within these limits.

As the flap angle is increased the ingress of fresh air becomes more dependant on natural ventilation and less dependant on mechanical ventilation. Consequently variation in air exchange time increases as flap angle increases and this is illustrated in Figure 5.

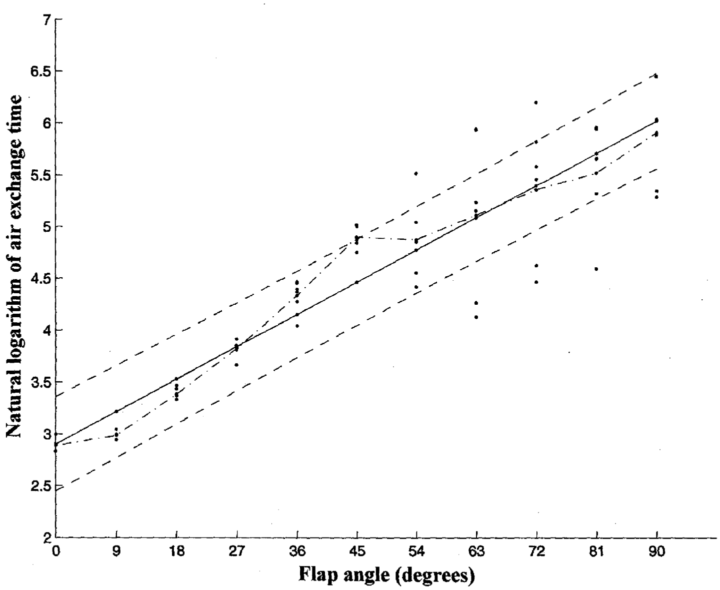

Figure 6: The relationship between flap angle and the natural logarithm of the air exchange time.

Whilst it would have been desirable to incorporate different fan speeds in the relationship study, this would lead to significant errors as mixing quality would deteriorate in the experimental procedure adopted. Hence this factor was excluded from the study.

Other studies (Leonard *et al.*, 1984) achieved results which agreed with each other within 5 to 20% using three different tracer measurement methods. This option was not available in the present study.

The manufacturer's quoted meter accuracy was 10% of full scale (3,000 μmol mol^{-1}). Hence this error contribution could vary from 60% to 10%, corresponding to data of 500 and 3,000 μmol mol^{-1}. A means of calibrating the IRGA meter against a higher accuracy standard was not available. Hence it was not possible to determine its experimental accuracy. However given its significantly better practical performance, it was decided than an error analysis using the quoted accuracy would not make a significant contribution to the study. Consequently an evaluation of what contribution such an error analysis would have on the variation in results was not undertaken. Given the scope for error contributions, the objective of this study was limited to establishing time-scales for air-exchange at different flap angle settings. Furthermore, the lack of an objective measure of determining mixing quality eliminates the potentially largest error contributor from any calculations.

No study that measured or described air exchange times in the context of a mushroom tunnel has been located by the authors. Hence no comparison of these results with any other work is currently possible. Further work to establish the theoretical basis between flap position and air exchange time is needed.

An increased understanding of the relation between mixing flap angle and air exchange time has been obtained and this will facilitate the development of predictive control strategies. As there is a relatively large tunnel population of similar design, the results from this study have wide applicability.

If air exchange efficiency in a mushroom tunnel can be improved through the removal of ventilation short circuits this will benefit growers. In the course of this study it was discovered that there are conditions under which there is a back-flow of conditioned air through the fresh air inlet. Hence the appropriate recommendation is to ensure the flap operation point is outside the region where back-flow occurs. Further research is necessary to establish these conditions. This will enable growers to lower energy costs by removing the back-flow of conditioned air.

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