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Report

Project 4093

# INTEGRATED ENVIRONMENTAL CONTROL IN MUSHROOM TUNNELS

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Kinsealy Research Centre
Horticulture and Farm Forestry
Series No. 9

# INTEGRATED ENVIRONMENTAL CONTROL IN MUSHROOM TUNNELS

**Project 4093**

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*Teagasc acknowledges with gratitude the support of the European Union Structural Funds (EAGGF) and the support of the Irish Mushroom Growers' Association/North Eastern Producer's Co-operative research committee in the financing of this research project.*

ISBN  1 84170 043 1
March 1999

Teagasc 19 Sandymount Avenue Ballsbridge Dublin 4

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**Acknowledgements**
The substantial contributions of the research students, Mr. Francis Murray and Mr. David Martin, their academic supervisors, Dr. Peter Corcoran (NUI, Galway) and Dr. John Ringwood (DCU), and Mr. Ted Cormican (Kinsealy) are gratefully acknowledged. There was also close contact and fruitful discussion with many people in the mushroom industry.

## SUMMARY

The main objective of this investigation was to achieve improved control of the micro-climate around the mushroom crop. The work was based on two approaches. One, which required the greater part of the work, was gaining an understanding of the characteristics/physics of the climate control system as a whole within mushroom tunnels and the other was the application of modern control strategies to manipulate more effectively the conditions at the cropping surface.

The work showed that the influences of the operation of the air conditioning on the crop micro-climate was far greater than the expected adjustment of, say, temperature and that novel systems and improved measurement of the micro-climate were required in order to optimise the control of air conditions.

The operation of the heating system caused a load dependent, i.e. seasonal, variation in the average drying power of the air at the crop. While heating (on/off control) was in operation, air flow effectively ceased at the cropping surface and the effect persisted for the duration of the heating and a recovery period afterwards. Various simple strategies could be implemented to minimise these effects but a novel design for air distribution provided a means of eliminating the effect.

Because of the complex relationship between the delivery of conditioned air and the consequent flow at the cropping surface, improved feedback from the crop micro-climate was found to be essential for improved control. A new sensor was developed in conjunction with the Department of Electronic Engineering, NUI Galway that provided a low cost measurement of the very low air speeds used in mushroom growing.

The Irish mushroom-growing system (bags and tunnels) offers more potential for accurate control than other, tiered, growing systems. The goal of the second aspect of this project was the provision of an accurate and robust control system for mushroom tunnels. Work focused on the control relationships between inputs and outputs of the system. A Teagasc Walsh Fellowship supported the early work which was carried out in conjunction with the Department of Electronic Engineering at NUI, Galway. Initial work prior to this project, with control specialists in DIT, Kevin Street College of Technology, was extended to provide a mathematical/control model of the main physical processes involved. A second Walsh Fellowship supported a link with the control systems group in the Department of Electronic Engineering, Dublin City University and allowed further control studies in mushroom tunnels.

## INTRODUCTION

With an emphasis on high quality produce, and the attention to detail which this entails, the control of aerial conditions around the developing crop has become very important. Effective control of air movement in a mushroom growing structure (an insulated, polyethylene-covered tunnel) is a requirement for accurate control of the growing conditions of a mushroom crop. The air flow across the cropping surface is necessary to carry heat and moisture into the mushroom microclimate. It is also required for removal of moisture, heat and carbon dioxide.

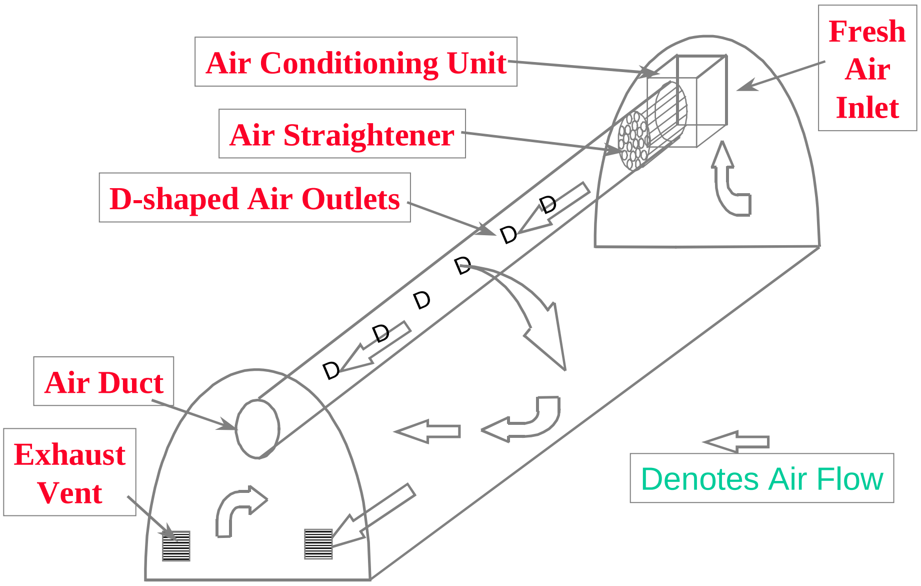

**Figure 1. Schematic diagram of air flow in a mushroom growing tunnel**

Figure 1 shows a typical arrangement ventilation of a mushroom growing tunnel. Air, a mixture of fresh and re-circulated, is conditioned and then distributed from a polyethylene duct. Air movement across the crop on the floor is at very low speeds. The typical range of mean values is 3cms$^{-1}$ to 30cms$^{-1}$. Zero air speed does not occur, as there will always be natural convection, driven by heat flow from metabolic processes in the mushroom compost. The useful range for mushroom growing is from approximately 10cms$^{-1}$ upwards. This can be described as positive air movement. However, even a person walking along the growing tunnel causes disturbances that disrupt this positive air flow for up to 10 minutes.

This project was concerned with identifying those characteristics of the air delivery system that give rise to inconsistency in cropping and seasonality. The most likely effect was from the operations of heating air and then distributing the warmed air at the low speeds required.

Cooling offers potential for improving air conditioning in mushroom tunnels. However, the addition of cooling to the air handling system raises management difficulties that can be difficult to address in manual or semiautomatic control.

It has been the experience of many growers that unexpected difficulties arose from the inclusion of a chilling coil in their air-handling unit. As a grower usually has no means of determining the air speeds at the duct, it is difficult to adjust management of the system to compensate.

## METHODS

Measurements were carried out on a commercial scale tunnel at Kinsealy Research Centre and on commercial growing units. A combination of qualitative techniques such as the use of smoke pellets to trace air streams and quantitative measurements of temperature, humidity, carbon dioxide concentration and air speed were used to study the systems within growing tunnels.

Computer-based modelling and simulation were used for the control studies.

## RESULTS AND DISCUSSION

Causes of inconsistency in micro-climate control were identified and solutions to these problems were developed during the course of the project.

### Heating effects

Air speeds at the cropping surface are subject to two effects of heating. When heating is on, there is a reduction in exit velocity at the duct that leads naturally to a corresponding reduction at the crop. Reductions ranging from 25% to 36% were found.

The total reduction at the cropping surface, however, is far greater than this. This is due to the difficulty of driving lower density, warmed air from the duct through the higher density tunnel air. Because warmer air rises, a situation called stratification arises where there is an upper, circulating zone and a lower, stagnant one where the crop is situated. The net effect of this is that, in most practical situations, air movement at the crop effectively ceases during heating. The mushrooms are left in a stagnant layer for as long as the heating persists.

There then follows an interval, the recovery time, during which air flow is re-established. This time is related to the duct exit velocity. There is no positive air movement for most of the recovery time. At lower speeds the recovery time was considerably longer. Results depend on temperature lift and degree of stratification but, in one extreme situation, a duct air speed of 4ms$^{-1}$ gave a recovery time of approximately 40 minutes while the recovery time for the higher duct speed of 6ms$^{-1}$ was reduced to approximately eight minutes.

Figure 1 shows how quickly air speed across a crop begins to fall. The lower trace in the graph is the air speed at the floor of the tunnel. The turbulent, i.e. widely varying, nature of the flow is evident but it is clear that it is maintaining an average level near 15cms$^{-1}$. The upper trace is the air temperature in the distribution duct. When heat is turned on this immediately begins to rise. The effect on air speed is delayed slightly but in a matter of some three minutes the air speed has decreased to less that 5cms$^{-1}$ and, despite a slight recovery, it stays at this level. This situation persisted as long as the heating was on and for the recovery time afterwards.

It follows from these observations that whenever heat is required there is a reduction in average air speed. The set air speed could be increased to cope with this but, unfortunately, the effect is load dependent, i.e. the higher the heat demand then the greater the reduction in average air speed. On nights with outside air temperatures near zero, and with the tunnel fully open, air speeds are very severely reduced.

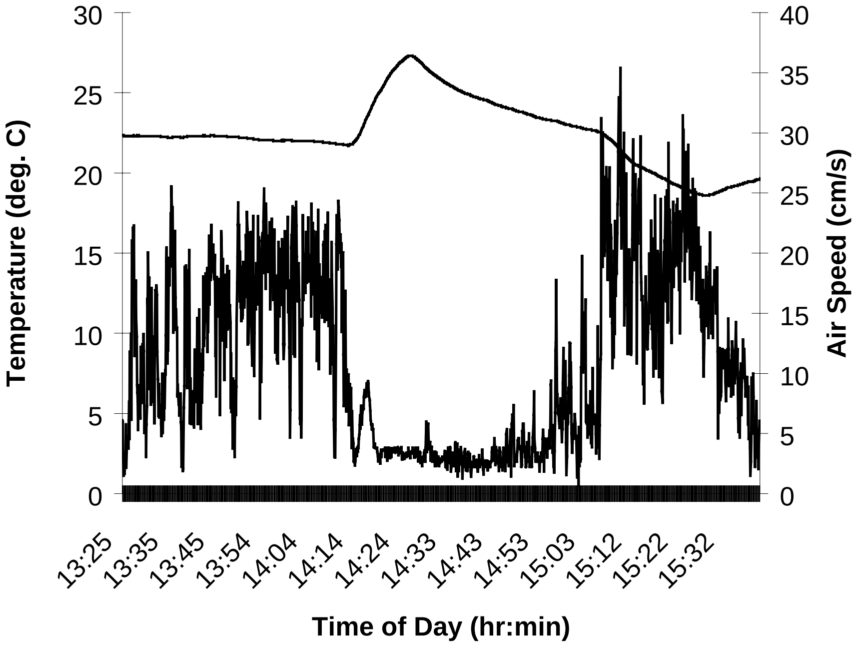

Figure 2: Effect of heating on air flow at the floor of a mushroom tunnel.

A very practical point that arises from this concerns the drying of the surface of the mushrooms which is done after watering and prior to harvest. One of the steps that some growers use to stimulate extra drying is increasing air temperature. This increase causes a drop in air speeds which persists until the heat goes off plus the recovery time for that duct air speed. It can now be seen that this will inhibit rather than aid drying.

## Boiler temperature

One approach to improving the situation was to shorten the time that heating stays on and this can be done by increasing the rate of heat input. The set temperature on the heating boiler plays a part in this. It was found that the higher the boiler temperature then the shorter the on time and the higher the average air speed. However, there are limits on boiler temperature and even at high temperature air speeds are still severely reduced by a high heat demand, i.e. when introducing large amounts of cold, fresh air to control carbon dioxide concentration.

## Position of temperature sensor

Positioning of the temperature control sensor was examined under high heating loads. A sensor position two metres above the floor was preferable to siting it at the cropping surface. This resulted in higher average air speeds.

## Exhaust siting

Another effect of heating is the development of temperature gradients along the length of the tunnel.

In re-circulation mode air flow is towards the fan and when a tunnel is completely open it is towards the exhausts. If the exhausts are situated at the same end as the fan then air flow is always in the same direction and areas nearer the fan are subject to a higher rate of air exchange than others. Due to temperature gradients in the distribution duct, a situation can arise where temperature in the tunnel is lower at the end furthest from the fan. If the exhausts are installed at the end of the tunnel distant from the fan then gradients are eliminated whenever there is an intake of fresh air.

Siting an exhaust at a high level will result in energy wastage. If stratification occurs during a period when there is a fresh air intake then air leaving the tunnel will be at a high temperature. If the control sensor was at low level then there would be considerable heat loss while the temperature rises in its vicinity. Low level exhaust siting therefore offers at least the expectation of increased energy efficiency.

Figure 3. Using smoke pellets to examine air circulation

## The application of cooling in mushroom tunnels.

Cooling is used for the removal of excess heat from the system. There are two sources of this heat. The first is the production of heat by the metabolism of the fungus itself and this has been reported as reaching rates of 900 Watts per tonne of compost. Heat transfer into the tunnel through the insulated walls is also important during warmer times of the year.

It was found that cooling affects air speeds less than the heating system. It can increase air speed at the cropping surface but the effect is difficult to detect outside carefully controlled conditions and it was of a much lower magnitude that the effects due to the heating system. There was a quick recovery when cooling was turned off.

Cooling coils reduce air speeds and air volume compared to the standard, heating only installation. The extent of reductions depends on the operating characteristic of the fan in use but, typically, reductions in air speed at the duct after adding a cooling coil were approximately 25%, e.g., a reduction from 6.5 metres/second to 4.8 metres/second. Air volume can fall by the same percentage. With a recommended range of 4 to 6 $ms^{-1}$, this reduction is speed presents difficulties in growing. It is possible to adjust air speed by means of the duct design. The number of holes in air ducts can be reduced to increase air speed but it is necessary to monitor the resultant volume delivered. If difficulty is experienced with, say, flushing of excess carbon dioxide then it may indicate that the fan is inadequate and needs to be upgraded.

## Cool/reheat dehumidification

Dehumidification would normally be defined as the removal of moisture from air without a change in temperature. A chilling unit is used to provide a cold surface which is below the dew point of the air stream so that condensation occurs and moisture is removed from the air. Chilling of the air stream is a consequence of this process and, since we normally want to maintain the tunnel temperature a heat input is required. This counteracts the resultant drop in average tunnel temperature.

It was found that, when the heating was turned on, the result was very similar to the normal heating situation, despite the production of chilled air. The temperature in the duct rose and this caused a rapid drop in air speed.

The recovery time of the air speed, after heating was turned off, was minimised because the chilled air accelerated the rate of temperature decline in the duct. Despite this the average air speed over the crop was greatly reduced. The consequence of this was that the maintenance of drying power of the air, the object of the dehumidification, was inhibited.

## Siting of humidity sensors

It was observed that the humidity recorded by growers’ instruments did not correspond to the humidity changes measured at the crop as the growers’ sensors were generally located at some distance above this. This indicates that the air stream causes these effects at the cropping surface some time before the main volume of air is affected. This would be expected from the well-known pattern of movement where the air stream from the duct adheres to the wall and then moves across the crop in a relatively thin layer. There is, thus, a case to be made for siting the humidity sensor at a low level in the primary air stream.

## Cropping-surface air speed sensor

Much of the difficulty in controlling air speeds at the mushroom cropping surface could be removed by providing on-line information on the low speed air flows involved.

Following initial work as part of a Teagasc Walsh Fellowship, an air speed sensor for use at the mushroom cropping surface was developed in conjunction with the Department of Electronic Engineering in NUI, Galway. The hot-wire principle was implemented with a heated thermistor and sensitivity was optimised for the low speeds of interest (5 to 40 $cms^{-1}$). The sensor was compared with a low flow velocity analyser and it was found that there was a high correlation between one minute averages from the sensor and the analyser.

An analogue display provided the instantaneous air speed and the sensor was designed to provide a quick check of average air speeds by means of a LED display. The full scale was divided into five intervals with each of these represented by a high-brightness LED. An indication sequence provided a rapid indication of instantaneous air speed as well as 15-minute and 24-hour averages. An output voltage was provided for data logging and to allow connection to a control system.

## Twin-duct air distribution system

A twin-duct distribution system, implemented by a grower as a solution for the difficulties posed by thermal buoyancy, was examined and a new method of implementation was developed.

In forming the twin-duct system, a second air distribution duct was introduced. The function of this duct was purely re-circulation of tunnel air. The two ducts contribute to air circulation with the resultant cropping surface air speed approximately equal to that expected from the sum of the exit air speeds of the two ducts. It was found that air speed could be boosted to normal levels while heat is on by increasing air speed from the re-circulation duct.

It was shown in this project that benefits can be obtained by retaining the existing, conventional duct without alterations and adding a second one positioned just below the original. This is then a retrofit operation that can be done at any time without interfering with normal operation of air conditioning. With a suitable sensor it is now possible to maintain a constant air flow across the mushroom crop.

Apart from overcoming the thermal buoyancy problem there are a number of other advantages that the twin duct system offers.

1. The system overcomes the problem of reduced air speeds due to the installation of heat exchangers for cooling. Provided that sufficient volume of conditioned air is available then the speed at the cropping

surface can be maintained because the two ducts drive the air stream together.

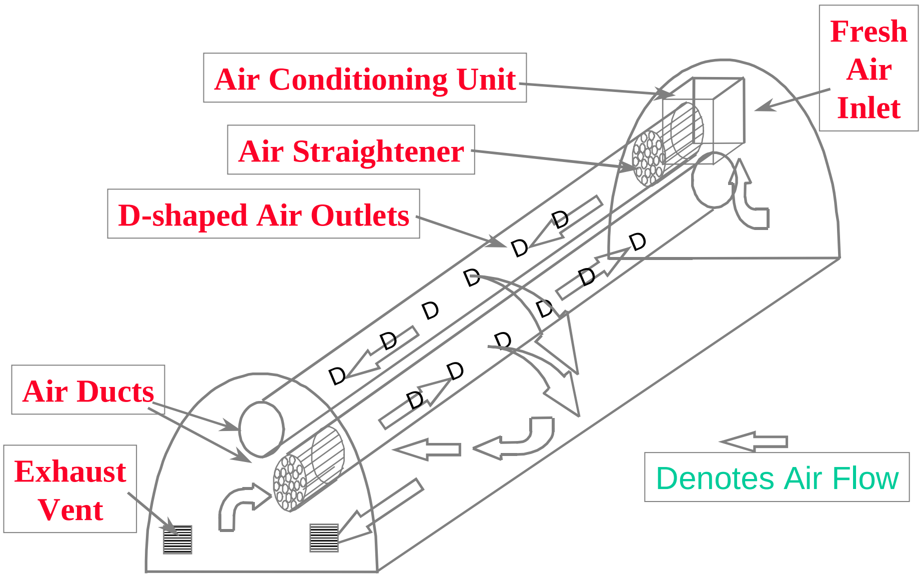

**Figure 4. Schematic diagram of the twin duct air distribution system**

2. Conflicts between speed and volume delivery could be resolved because it is possible to separate the functions of air conditioning (heating, cooling, fresh air control) and of ventilation of the cropping surface. It is possible to set the conditioned air duct to low speeds and, hence, high volume while the circulation duct could be used to provide a range of speeds. The combination could maintain cropping surface air speeds while maximising the volume through chilling coils.

3. The direction of the air flow in the second duct can be run in the opposite direction to the first, to counteract temperature and humidity gradients that can arise along a tunnel .

4. A second duct positioned above or below the first can be extended over or under the existing air-handling unit, thereby providing positive air flow in a normally unventilated area.

With a twin duct system, it is possible to produce very high air speeds and to cause scaling of the mushroom surface (excessive drying). To derive maximum benefit from the twin duct system, controllers have to be upgraded to make use of the facility that it provides. A dynamic control is required that keeps a balance between contributions from the two ducts and feedback from the cropping surface air speed sensor would be a key component of such a control system.

## Modelling and control of tunnel environment

In order to maximise the use of information on the growing system a mathematical model was constructed. This was an extension of previous work and took account of effects not previously considered in detail. The model was found to be non-linear and was linearised around an operating point and rewritten in state space format. The model was expressed in the state space formulation because of the ease of accommodation of Multi-Input Multi-Output models. The states were tunnel temperature, tunnel humidity and carbon dioxide concentration.

Figure 5. Low flow velocity analyser for measurement of low air speeds

The linear model was verified in simulation against the non-linear model and the effects of step changes and disturbances were examined. Perturbations around the operating point showed that time constants of the state variables were relatively long and that the system was slowly varying and could be regarded as continuous.

The control inputs were fresh air flow rate, heating/cooling and humidification. Disturbances were outside air conditions, products of crop metabolism (heat and carbon dioxide) and heat due to solar radiation. The simulation was further verified against measurements made in growing tunnels.

The control characteristics of the system were investigated and optimal control was used to derive control laws. Pulse Width Modulation was used to provide an approximation for the theoretical control function and control action was evaluated.

The second Walsh Fellowship, with DCU, began by examining the difficulties posed by the assumption, in previous studies, that the internal environment could be modelled as a well-mixed control volume. The stratification of air flow produced by thermal buoyancy is the main source of difficulty with the assumption. Initial work was done to allow the use of system identification as a means of highlighting effects due to incomplete mixing.

Control software in the experimental unit at Kinsealy was rewritten to allow more extensive experimentation and testing of the systems was undertaken using Pseudo Random Binary Sequences. Neural network models were constructed and compared as a means of modelling the results. A number of tunnel climate control processes were characterised. For example, condensate re-vaporisation was seen to have a significant effect on humidity levels after switching off chilling coils in the air handling unit.

Sensor error, and its implications for the use of control based on evaporation, was examined. It was proposed to calculate an evaporation potential for the mushroom tunnel air mass and to take this as the most important control variable. This evaporative condition has to be maintained within a band between too moist and too dry. The overall error in the calculation of evaporation potential due to the combination of sensor errors can be of the same order as the width of this band under some conditions. Known errors associated with humidity sensors were used to place limits on the allowed error in air speed measurement and to determine desired operating points to avoid control difficulties.

A series of ventilation measurements were carried out to characterise mixing factors, i.e. divergence between nominal and actual air change, and the effect of external wind conditions. The objective of this study was to determine the air exchange time in a standard mushroom tunnel which would facilitate control of the tunnel climate by the use of the mixing flap. The effects on the total air volume were determined by tracer gas methods using carbon dioxide supplementation of an empty tunnel. A large number of measurements were conducted with varying flow rates and under varying external conditions. The potential increase in ventilation efficiency (resulting from the increase in understanding of the air conditioning system) can be translated into direct energy cost savings to the grower.

A complete conceptual model of the physical processes that affect the mushroom tunnel micro-climate was constructed as a precursor to the construction of a more complete mathematical model incorporating the results of these studies.

## CONCLUSION

It is known from previous work that the control of micro-climate is a source of difficulty for even the best growers and that this results in unnecessary loss of premium quality produce. The detailed examination of the operating characteristics of the air control and conditioning systems in mushroom growing tunnels that was made in this project has resulted in an improved understanding of the processes involved. As well as allowing the development of the solutions presented in this report it will be used as the basis for future work on engineering problems in mushroom production. A durable, commercially-produced instrument based on the experimental work on the air speed sensor is in development and its production will allow significant improvement in optimising future production. When combined with new systems like the twin duct it can make the production of high quality mushrooms more consistent.

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