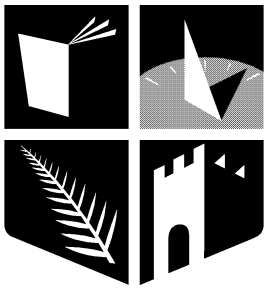

NUI MAYNOOTH

Ollscoil na hÉireann Má Nuad

ENGINEERING OF THE WASTE COMPARTMENT

ESA contract 15689/01/NL/ND

TECHNICAL NOTE TN 71.6.4a

Final Report on Fungi Compartment Studies:
Solid-state Fungi Reactor - Initial Concept

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Executive Summary

The contents of this research report relate to study results from both primary and secondary research activity.

The primary result from this research is a conceptual design for a solid-state fungi reactor in the form of a belt conveyor, which is outlined in page 22 of the report. A second research result is a ventilation model, which is summarised in the report and developed in full detail in the appendix to this report.

The secondary research results are developed summaries of the relevant technologies required to support the conceptual design, *e.g.* a summary of state of the art air filtration technologies is supplied in section 7 to facilitate understanding of the selected air filtration technology option. In addition, auxiliary information that puts the research in context is supplied, *e.g.* the fungal lignin degradation summary provided in sub-section 2.3.

A broad review of state-of-the art material was undertaken to provide the development of the technology summaries and provide a basis for making a particular technology option selection. This is evidenced by the references that justify the technology selections made, from the wide review of source material. Details of the references are provided in the seven pages at the end of the report.

Due to the preliminary nature of this study a number of open questions remain to be resolved. A full list of these open questions is provided in section 13. In particular, the question of reactor scaling remains to be addressed as it is dependent on the performance of the yet-to-be selected fungus. This scaling issue is dealt with in section 12 as a precursor to the less important other open questions. Most importantly, no technology option has been selected that cannot be scaled either up or down. Finally, some initial conclusions are drawn and presented in section 14.

TABLE OF CONTENTS

1. Introduction (WP7.3.18)

This report is one of two delivered in respect of ESA study contract 15689/01/NL/ND. There is an associated contract between EPAS and the National University of Ireland, Maynooth (NUIM). The combination of the two reports fulfils the deliverables obligation on NUIM in respect of this contract. This final report (TN6.4a) is focussed on the growth of fungi and/or mushrooms in a solid-state reactor, whereas the companion initial report (TN6.4b) is focussed on the growth of fungi in a liquid state reactor.

At the start of this project, in January 2002, it was envisaged that the fungi reactor would be based on a solid-state substrate. Consequently, fungi reactor design was approached with this material phase in mind. However, following the release of uncertain results by ATO in early 2003, the solid-state substrate assumption was revised. Quantitative lignin degradation results at a petri-dish scale from ATO in July 2003 led EPAS to propose a shift in work focus as it appeared likely that a liquid, rather than solid state, fungi reactor was required for the Melissa loop. The outcome of the liquid state reactor investigation is described in the companion report (TN6.4b).

This final report details the outcome of the studies on the design of a solid-state fungi compartment bioreactor, up to the end of July 2003. The report is composed of a main body and an appendix. Three study areas of work-package 7 (fibre degradation via fungi compartment) were defined in the associated contract between the National University of Ireland, Maynooth (NUIM) and EPAS, as:

1. Study of different possible fungi compartments including instrumentation and control.
2. Study of material handling, substrate preparation, harvesting and recycling.
3. Study of interactions and interfaces with other compartments.

This report is primarily focussed on the first of these study areas. The study area scope was outlined in more detail in workplan activity 7.4 (Reactor concept) as follows:

> (a) Mushroom, growth is critically dependent on control of microclimate. To-date, climate for mushroom growth has been controlled by single-variable feedback loops. A multi-variable controller is necessary to fully optimise the climate for mushroom growth. In co-operation with ADERSA, NUIM intends to address the development of the measurement and control aspects of providing such a multi-variable controller. *(January 2002 – December 2002)*
>
> (b) Control of the fungi microclimate is critically dependent on the provision of an appropriate air distribution system. Therefore, a key element of the reactor concept is the integration of an appropriate air delivery system. As ventilation efficiency depends on the configuration of the air delivery system, a concept that facilitates a high efficiency is desirable. NUIM intends to identify a configuration that has a higher ventilation efficiency that is currently prevalent, typically circa 50%. *(March 2002 – September 2002)*
>
> (c) It has been established that mushroom growth rate can be controlled or maximised through the control of temperature. Although currently unquantified, other climate variables also determine crop growth characteristics. Several industry observers consider that evaporative climate control is key to controlling the rate of nutrient uptake and consequently the development of mushrooms. For control of evaporation it is necessary to control the air's drying ability, and such control is currently unavailable due to the absence of a multi-variable controller (see study task a). The extension(s) required to a multi-variable controller to incorporate control of the air's drying ability will be examined by NUIM in conjunction with ADERSA. *(March 2002 – September 2003)*

The study area scope outlined in point (b) identified the novelty introduced in this report as a concept for the air distribution system. Associated with this focus is an analysis, from a control and instrumentation perspective, of what implications arise from different potential air distribution systems.

Regardless of the air distribution system chosen, the air propulsion unit envisaged is a fan. Although, fans can be of many classifications, they fall into two principal types: axial and centrifugal. Both of these types generally use an electric motor as a prime mover. This report assumes that a fan driven by an electric motor is the air propulsion unit. Therefore, although the pressure drop of an air distribution system is a key element in determining the choice of fan, selection of the air distribution system has a limited impact on fan control issues, because the type of prime mover does not vary. Motor speed control (*e.g.*, variable frequency, *etc*.) is a well-studied area of technology, hence, speed control techniques are not examined in detail in this report.

It has been shown (Schultz and Krafthefer, 1993) that instrument error is amplified by the reciprocal of ventilation efficiency. Typical air distribution systems used in growth chambers, Irish mushroom tunnels and Dutch mushroom houses are of a mixing type. Perfect mixing results in a ventilation efficiency of 50% (Etheridge and Sandberg, 1996). Therefore, instrument error is effectively doubled when a mixing type air distribution system is used. Consequently, because of its effect on instrumentation, an air distribution system with a high efficiency is highly desirable. Displacement ventilation systems tend to have high efficiencies, hence they are the prime candidates for the air distribution solution proposed in this report.

Most importantly, the exact climate requirements for the selected fungi have to be established. Then, to achieve the desired climate, a control system has to be defined. Each of the systems involved in achieving the desired control is discussed individually in the following sections. Then some open questions are introduced and where possible, preliminary conclusions regarding the salient fungal reactor design issues are drawn, and the references made are listed. Initially, some essential background material is introduced.

2. Background (WP7.3.18)

"only certain fungi, notably Basidiomycotina and xylariaceous Ascomycotina causing white rot of wood and other plant litter , have been unequivocally shown to have the enzymatic capacity for complete, rapid breakdown of lignin" (Cooke and Rayner, 1984)

The need for a fungi bioreactor in the MELISSA loop arises as a result of the requirement to process a waste substrate with a lignin or lignocellulose element by fungal degradation. The potential for fungi to fulfil this requirement has already been identified by Soler-Rivas *et al*. (2000) and Marin-Vinader *et al*. (2000), in a preceding study.

The lignin waste substrate could be sourced from one or more reactors in the overall loop, but current investigation is focussed on the waste from the first compartment. However, due to the unavailability of this waste for biological experimentation by ATO during the initial study period, qualitative and quantitative analysis for large scale tests has been based on a "bought-in" supply of various materials.

Although mushrooms can be grown on lignocellulosic waste (Pettipher, 1988a; 1988b), the primary purpose of a fungi bioreactor in the MELISSA loop is to degrade the lignin content of the substrate. A secondary objective is the degradation of the cellulose content in the substrate.

Designs for magnetically energized, fluidised bed reactors have been used for the separation of solid waste from an aqueous slurry in a micro-gravity environment (Sornchamni *et al*., 2002). If required, such designs could possibly be adapted for a fungi bio-reactor in a micro-gravity environment, *e.g.* perhaps through oxygen supplementation of the liquid. Fortunately, the fungi bioreactor is planned to be used in a low gravity environment such as that found on the surface of Mars, hence, micro-gravity operation is not an operational requirement of the fungi bioreactor. This facilitates design of the reactor as:

1. the use and effect of gravity is critical in many reactor designs,
2. the use of on-site materials could facilitate an otherwise unacceptably massive design, and
3. the availability of a Martian atmosphere affects ventilation design choices.

Within the MELISSA loop, the production of mushrooms is of relatively low importance due to the high nucleic acid content in the crews' food supply (Lasseur, 2002). Therefore, the choice of fungus to be used for degradation is not limited to those that produce edible fruit-bodies, *e.g. Agaricus Bisporus*.

From an engineering perspective, there are several principal components of a growing system or fungi bioreactor. Cultivation may be natural, *i.e.* harvest only, or constructed around a: bag, tray, rack, petri-dish, *etc*. system, each of which has distinguishing features. Regardless of the cultivation system, the principle (non-substrate) essentials for growth are: a heat, air and water supply. Most closed agricultural systems run as a batch process due to the escalation of disease incidence within the closed system, hence, to minimise the potential for the spread of airborne disease, an air filtration system is required. For metabolism to occur, oxygen has to be readily available and this necessitates the provision of an air distribution system. Even if oxygen is present, the air's condition must at least be such that the fungi is in the survivability zone of climate conditions, and preferably the air's condition should be in the growth zone of climate conditions. An air conditioning system is the normal mechanism to obtain the desired climate conditions in a protected cultivation context.

2.1 Compost/substrate

Compost characterisation/specification and the associated selection of an appropriate fungus, *e.g. Pleurotus* P17 or *Phanerochaete chrysosporium*, has been undertaken by ATO. As compost characteristics significantly affect the design of the bioreactor, characterisation of the compost is a necessary precursor to the final design of the complete bioreactor. For example the design of reactors to handle liquid, slurry, sludge, or solid substrates are fundamentally different.

It needs to be emphasised that the characteristics and availability of nutrients in the compost/substrate, determine to a large extent whether, and to what extent a mycelium colonises a substrate. In particular, the filamentous nature of fungal growth requires a structure upon which the filaments can grow. Normally, the first stage of solid waste processing is chopping and/or grinding (to a powder). Chopped straw waste from wheat production is an excellent structure for fungi to grow upon. Indeed, this is one of the principal ingredients of the traditional horse manure used for commercial compost.

The compost must be sufficiently porous to allow sufficient gas exchange for metabolism to occur. For this reason, the water content of the compost should not be so great that fungal growth is limited by oxygen diffusion through liquid water, which is a slow process. It is envisaged that the compost is a blend of liquid, sludge and solid material wastes from different parts of the MELISSA loop. It has been estimated that the agglomeration of the residual wastes to be processed by the fungi reactor, would result in a compost with a minimum water content of approximately 70% (Demey, 2002). At this high water content level it is possible that respiration may become anerobic with potential reduction in lignolysis (Rayner and Boddy, 1988).

The effect of chopping and/or grinding the solid wastes is to increase the ratio of surface area to volume. This is normally the first step involved in producing compost for use in mushroom production. A high surface to volume ratio facilitates access by the fungal mycelium, through the filamentous nature of the hyphae, of the nutrients in the compost substrate.

In the Melissa fluid loop, an ultra-fine membrane filter separates the solid component of the fluids fed to the first (*Rhodospirillum*) reactor into a sludge form of material waste. Originally, it was envisaged that the compost supplied to the fungal bioreactor would be sourced solely from the fluid loop, as shown in Figure 2.1.

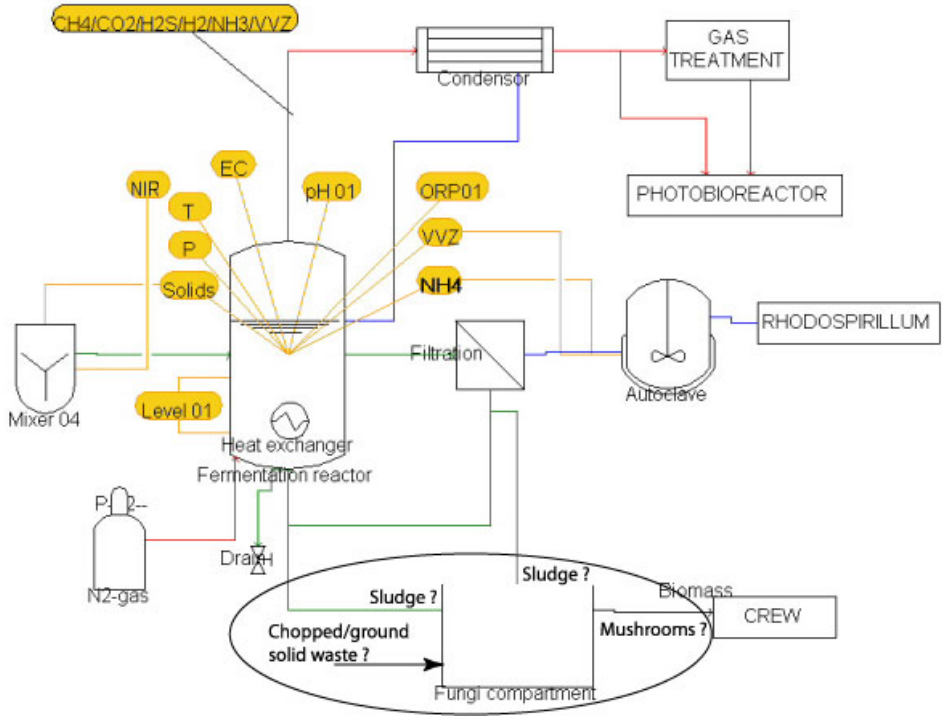

Figure 2.1: Layout of the secondary fluid waste processing loop (after Hermans, 2002)

However, this configuration does not readily match the traditional cultivation systems used for fungal growth. Traditionally, the growth substrate, which is known as compost, is a mixture of floral and faunal wastes, *e.g.*, horse manure. The texture of what would be supplied to the reactor as shown in Figure 2.1 is unlikely to have sufficient porosity to allow gas exchange in the compost and thus inhibit mycelial growth. Porosity can be increased through the addition of solid material, *e.g.*, the output of one, or more, of the solid waste processors, as shown at the bottom of Figure 2.1.

2.2 Metabolism

> "It appears that only the so-called white-rot fungi can completely decompose lignin to carbon dioxide and water." (Hudson, 1986)

In terms of metabolism, Loeffen and Martin's (2001) calculations of mushroom heat production were based on the assumption that the heat liberated can be approximated by the exothermic oxidation of glucose ($C_6H_{12}O_6$) as described by Equation (2.1).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Heat.} \qquad (2.1)$$

This mushroom metabolism approximation is similar to that proposed by Gerrits (van Griensven, 1988) who suggested that for every input of dextrose (180 g) and oxygen (192 g), an output of carbon dioxide (264 g), water vapour (108 g) and heat (2824 kJ), occurred. Note that Equation (2.1) is an approximation of metabolism to facilitate understanding. In practice, there is a wide variation in metabolism as indicated by the measurements of Loeffen, shown in Figure 2.2.

As Treschow (1944) has shown with hyphal tip growth rate, *i.e.*, affected by energy flow control, it is suggested that in an analogous fashion, growth rate could also be affected by mass/nutrient flow control, during the phase of growth where fruit bodies are produced. It is widely accepted that water acts as the nutrient transport mechanism within the mycelium (Flegg, 1999). For the mushroom growth phase, indirectly, by controlling the evaporative pressure between the mycelium/compost and the air above it, it may be possible to control water flow rates within the crop/mycelium. However, a necessary pre-cursor to any detailed study is the identification of a suitable growing system, which is discussed in more detail in section 3.

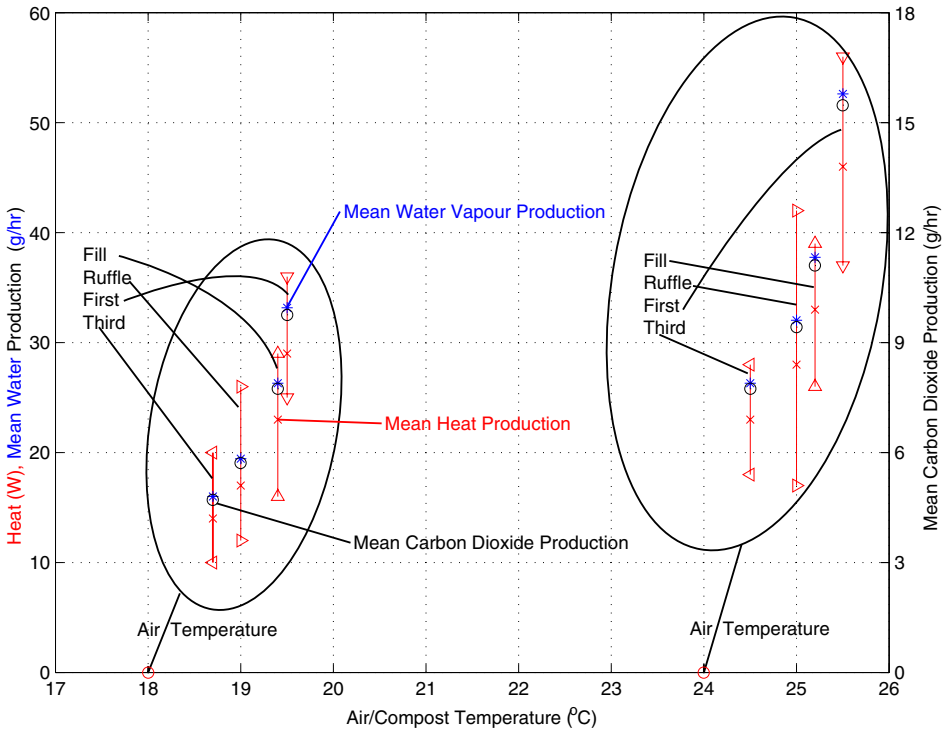

Figure 2.2: Measured (estimated error ±5%) and calculated crop metabolic outputs per square metre of crop/compost surface, for two air temperatures, 18°C and 24°C, in a Dutch house at 80 kg/m^2 compost fill

2.3 Lignin degradation by fungi

"In only one organism *Phanerochaete chrysosporium* has a defined lignin degrading enzyme, lignin peroxidase, been isolated and characterised." (Wood *et al*., 1988).

It has been recognised since at least 1981 (Kirk and Chang) that fungi can be used to advantage for lignin degradation in "Improved waste treatment processes …". By using fungi for lingo(-cellulose) degradation, the overall efficiency of the first reactor in the full MELISSA loop may be improved and this part of the loop may be maintained as a complete bio-regenerative process.

The study of lignolytic activity by fungi is one metabolic degradation niche of a wider range of fungal decomposition metabolisms. Consequently, a fungal lignolytic study requires the examination of a relatively wide range of mycological texts, *e.g.* that provided by Frankland *et al*. (1982). From the perspective of how the enzymes produced by a fungus contribute to lignin degradation, one has to extend beyond a mycological study. This enzymatic extension is not undertaken here, other than to note that a relatively recent review focussing on peroxidase action was undertaken by Martinez (2002), and that lignolytic enzyme action appears to have been studied from before the start of some dedicated enzyme journals (Kirk *et al*., 1968; Kirk, 1979). As an enzymatic study would naturally encompass a broader scope, *e.g*. bacterial degradation of lignin (Vicuna, 1988), this section summarises the salient points found from a fungal focussed study only.

Cultivation systems vary significantly from one fungus to another, as does the lignin degradation capability of different fungi, and even variants within one species, *e.g*., lignin degradation for different variants of *Phanerochaete chrysosporium* ranged from 5.9% to 21.4% after two weeks (Johnsrud, 1988). Consequently, until a target lignin degradation fungus has been finally selected by ATO, the level of detail to describe the supporting cultivation system is necessarily limited. Note that a list of system requirements and research areas is provided in Zadrazil's (2000) review of lignin-degradation reactor research summary.

It has been shown by Gerrits (1969) that the rate of lignin degradation by *Agaricus* is highest during the spawn run phase. Results showed that between 63-92% of the lignin degradation that occurred was in this phase. This result is supported by other researchers results, *e.g*., Singer and Harris (1987). It is widely believed (Kavanagh, 2002) that, via the action of enzymes, the degradation occurs at the growing hyphal tips of the mycelium. Note that the spawn run phase has a very high mycelial growth rate because this is the phase where colonisation of the compost/substrate by the fungal mycelium occurs.

Lignin is brown in colour, and hence its removal has historically been observed by what remains after material, *e.g*. wood, degradation has occurred, leaving a degraded material that is white in colour. Hence the term "white-rot fungus". Two different types of white-rot degradation can occur, the selective degradation of lignin, and the degradation of both lignin and the (hemi)cellulose that it encases. Despite the fact that there are two types of degradation, lignin oxidation requires the corresponding use of some cellulose or other carbohydrate, thus indicating that a range of metabolic activities may be required for lignin degradation by fungi. This has been called "lignin cometabolism" (Griffen, 1993). So, it would appear that a pure lignin substrate could not be degraded by fungi, *i.e*., degradation by fungi requires a cometabolisable substrate.

The term lignin does not describe a homogenous family of compounds. Lignin may be thought of as a three-dimensional polymer based on a carbon skeleton to which various alcohols are joined at random, using various links, to form an asymmetric molecular network. Various authors attempt to model some version of a lignin molecule, either specifically (*e.g*. Griffen, 1993) or generally (*e.g*. Carlile and Watkinson, 1994). When using the term lignin it is important to recall that it relates to a specific form of the molecule existing in a specific substrate, and that it may not be prudent to extrapolate results based on one specific lignin substrate to any other context (Downes, 2003).

Due to the diversity of lignin forms, it is thought unlikely that the ecological strategy used for lignin degradation by a fungus is the production of a specific enzyme that targets a particular form of lignin. Instead, for energy conservation reasons, it is thought (Evans and Hedger, 2001) that the enzymes produced by fungi are likely to have a non-specific form of lignin degradation. Furthermore, degradation may require one or more agents/catalysts (Evans *et al*., 1994) in addition to the enzymes.

Three broad spectrum enzymes have been identified as being important for fungal degradation of lignin. The first enzyme to be identified (Evans and Hedger, 2001) was lignin peroxidase in 1984, which is thought to be produced by most, but not all, white rot fungi. The second enzyme is manganese peroxidase, which has been found to be produced by all white rot fungi studied, and the third enzyme is laccase. All three enzymes require some availability of one or more minerals, principally: iron, manganese, or copper, respectively. Different fungal species produce various combinations of all three enzymes. The presence of oxygen for oxidation activity by laccase is particularly noted by Evans and Hedger (2001). One study (Tuor *et al*., 1995) attempted to classify a variety of white-rot fungi on the basis of their enzyme system, however allocation to specific hosts proved to be ambiguous.

It has been asserted that, although fungal metabolism of lignin is a carbon process, this metabolic activity is regulated by nitrogen nutrition, through the establishment and maintenance of a secondary metabolic state (Kirk and Fenn, 1982). However, it has also been noted that the regulation dependence on nitrogen may be limited to specific fungi, *e.g*. *Phanerochaete chrysosporium*, or *Trametes (Coriolus) versicolor* (Evans and Hedger, 2001), because "Two other lignolytic Basidiomycetes, *Lentinus edodes* and *Pleurotus ostreatus*, showed no repressive effect of nitrogen, …" (Griffen, 1993). Furthermore, it may be the case that the regulation dependence only occurs for particular enzymes and not just particular fungi, as Fu *et al*. (1997) showed for *Pleurotus sajor-caju* that although manganese peroxidase activity was at a maximum under nitrogen-limited conditions, conversely "laccase production was not influenced by nutrient nitrogen levels". The scene is further complicated by the observation (Tuor *et al*., 1995) that "Environmental conditions may be crucial in governing the selectivity of fungal biodegradation …".

The question of how dependent the lignolytic activity is on nitrogen, or other factors, may depend on the perspective taken on what exactly the active lignolytic agent is. For *Phanerochaete chrysosporium*, Feng *et al*. (1996) showed that lignin peroxidase activity was at a maximum under nitrogen-sufficient conditions,

compared to nitrogen-limited and nitrogen-excess, whereas manganese peroxidase activity was at a maximum under nitrogen-limited conditions. Furthermore, the question of whether any lignolytic activity occurs at all, may be dependent on: the age, the variant, or mutation, of the fungus under study. In this regard, Ouyang (2002) distinguishes between non-lignolytic *Phanerochaete chrysosporium* and lignolytic *Phanerochaete chrysosporium,* and Fiechter (1993) notes that "no true stability in enzyme synthesis of fungal systems has been attained … ; even repetitive batch cultures are generally fading out in their activity of ligninase or protein excretion on the whole."

In summary, it appears that lignin degradation by fungi is a strongly oxidative process and may require the release of a whole range of enzymes and catalysts. Hyphal contact with the substrate though fungal filaments ensures that the release of agents such as lignin peroxidase and hydrogen peroxidase come in direct contact with the substrate (Dix and Webster, 1995). Griffen (1993) makes three major points regarding lignin degradation by fungi.

1. "First, fungi are the only organisms that have been clearly demonstrated to extensively degrade lignin to CO_2."
2. "Second, lignin degradation occurs by a predominantly oxidative, rather than hydrolytic attack, without releasing monomeric units into solution,".
3. "Third, lignin degradation does not provide a primary source of carbon and energy for fungal growth,".

Regardless of the absolute veracity of the first two points, *e.g*. Vicuna (1988) discusses bacterial degradation of lignin; the first two points highlight the importance of gas exchange, *i.e*. the supply of oxygen and removal of carbon dioxide, to fungal degradation of a lignaceous substrate. Further support for the assertion that gas exchange is of primary importance is derived from the use of the title "Enzymatic "combustion": the microbial degradation of lignin" by one of the leading researchers in the field (Kirk and Farrell, 1987).

The third point indicates the basis for the claim that "Lignin is the most recalcitrant natural product." (Griffen, 1993), whose claim is supported in the title of Feng *et al*.'s study (1996), and Fiechter's (1993) note on fading activity in successive batch cultures. Of course this recalcitrant nature leads to a corresponding difficulty in maintaining reproducibility of results, particularly with non-homogenous substrates.

It is important to note that many open questions remain to be answered regarding fungal degradation of lignin. For example: even the basic question of what is the natural ecological niche of the most studied lignin degrading fungus, *Phanerochaete chrysosporium*, remains unanswered (Evans and Hedger, 2001); or whether the known lignin degrading mechanisms represent the full spectrum of fungal degradation modes as a whole. This may be unlikely, as most laboratory cultures studied to date have originated from northern temperate or taiga forest ecosystems, whereas it is probable that fungal biodiversity (and variety in lignin degrading activity) is higher in tropical forest ecosystems.

On a final cautionary recalcitrant note, that highlights the crucial importance of appropriate temperature control, Lonergan *et al*. (1993) observed for the well established lignin degrader, *Phanerochaete chrysosporium,* that some qualitative lignin degrading screening tests, *e.g*. a particular dye, "will give reactions that would suggest that … are not lignin degraders". This would imply that some quantative lignin degrading measure should be used even at the preliminary evaluation/selection stages for fungal degradation of lignin.

2.4 Supplementary containment of hazards to crew

By developing improved techniques to identify micro-climate conditions suitable for determining optimal growth, it is likely that these techniques can also be used to identify conditions that are counter-conducive to growth. In the context of the work by Novikova (2001, 2002) and Deshevaya *et al*. (2002), where inorganic materials such as glass, plastic insulation, aluminium and titanium that were used in the Mir space-station were degraded as a result of fungal growth, this may be of particular importance.

It is unlikely that the material degradation occurred through use of the inorganic substrate as a nutrient source, because filamentous fungi can grow using nutrients (dirt) and water in the air. This emphasises the

requirement for the use of clean air through air filtration. In this context note that Eggins and Allsopp (1975) include the following materials as subjects of biodeterioration/biodegradation by fungi: cellulosic materials (*e.g.*, cotton, paper, *etc*.), plastics, glass, hydrocarbon fuels, paints and paint films, leather, glue, drugs, cosmetics, and stored foodstuffs. It is probable that material degradation occurs as a result of the more minor (in terms of mass) secondary metabolites released during fungal activity.

For *Agaricus*, Lockard (1962) established that five volatile gases were released during mushroom growth in addition to the water vapour and carbon dioxide from metabolic respiration. The volatile gases identified by Lockard were: ethyl alcohol, acetaldehyde, acetone, ethyl acetate, and, ethylene. Kavanagh (2002) noted production of other metabolites including acetic acid. Rayner and Boddy (1988) noted that "At low oxygen tensions anaerobic respiration may … build-up … ethanol, methanol, formate, acetate, lactate and propionate".

All of these substances can be regarded as secondary fungal metabolites. Indeed, the samples discussed here are only a small selection, as a figure of over 1,000 metabolites has been quoted by Bu'lock (1975). A new handbook of secondary fungal metabolites was launched in August 2003 (Cole *et al*., 2003) and claims to "contain data on approximately 1,200 fungal metabolites", thus increasing the range further. Regardless of the particular metabolite(s) that may have caused the degradation, it is suggested that one mechanism to prevent material degradation is to provide a micro-climate that is counter-conducive to fungal growth.

3. Cultivation (WP7.3.19)

"..., more things can go wrong in more ways at more times with a mushroom crop than with any other crop on earth." (Pinkerton, 1954)

As a final selection has not yet been made regarding the strain and species of fungus, or fungi, to be cultivated, what follows is necessarily general in nature. All the components of a cultivation system are dealt with on an individual basis in the following sections to some level of detail, subject to the constraint of a contractual focus on solid-state cultivation. Nonetheless, it is noted that cultivation of fungi in liquids has been undertaken, as evidenced by the inclusion of a fungal liquid culture sub-section in Onions *et al*.'s book (1981) or the discussion of (micro) fungal (liquid) fermenter design issues by Solomons (1980). Furthermore it is noted that fungi have been cultivated in fluidised bed reactors (Atkinson and Lewis, 1980), which is a hybrid liquid-solid reactor form, and recall that fluidised bed reactors have been demonstrated in micro-gravity environments (Sornchamni *et al*., 2002).

The physical structure within which the bioreactor is to be contained is not yet defined. This compounds the difficulties inherent in the general nature of the discussion that follows and raises several non-trivial questions, *e.g.*, does the reactor need on-site radiation shielding to protect against genetic damage which may reduce or destroy fungal nutrient (lignin) uptake potential (Hooley and Clipson, 1995) ?

Until the physical structure surrounding the bioreactor is better defined, it is assumed that the bioreactor is housed in some form of mushroom tunnel, which is in common use in the mushroom industry. This assumption facilitates design because "This type of batch reactor offers excellent process control" (Miller, 1991) and is "adaptable to solid waste processing" (Miller, 1991).

Although Miller's (1991) introductory chapter in Martin's book (1991) provides an excellent introduction to composting as a means to biodegrade waste, his systems review omits the use of a conveyor belt reactor configuration for continuous processes. Perhaps this omission arises because his review is of "common systems". As the system proposed in this report is a belt configuration, his introduction should be read with this in mind.

There are many books, *e.g.*, van Griensven, (1988), symposia contributions, *e.g.*, Hayes, (1980), articles, *e.g.*, Middlebrook, (1991) and papers, *e.g.*, Wood and Smith (1988) devoted to the cultivation of edible

species of fungi, but, there are not so many publications that focus on inedible species. In this context, a workshop (Zadrazil and Reiniger, 1988) that had a lignoceullolosic focus is particularly relevant for the design of a lignin degrading bioreactor. Note, however, that this workshop had a white rot fungi, *e.g.*, *Phanerochaete chrysosporium*, focus.

For commercial production of edible fungi, two principal types of cultivation system have emerged, Dutch and Irish. Both of these systems are quite well documented, *e.g.*, van Griensven, (1988), and Grant *et al.* (2001a; 2001b). Regardless of the fungal species, the bioreactor is anticipated as being a solid-state bioreactor of some form, such as that shown in Figure 3.1.

The bioreactor shown in Figure 3.1 is similar to the principal aerobic reactor type introduced by Weiland (1988). Weiland (1988) provided a solid introduction to solid-state bioreactor layout and distinguished between aerobic bioreactors and solid-state fermenters. Note that Figure 3.1 shows a commercial scale bioreactor, which would have to be scaled down for lower throughputs. A minor design difference is that this layout uses a longitudinal major airflow axis, whereas the principal aerobic ones described by Weiland use a vertical major airflow axis. In this design the compost or substrate is stationary, whereas slowly mixed substrates are used in other contexts. This obviates the need for any mixing equipment, but may limit application to batch operation processes. Note that mixing of the substrate may be beneficial to growth (akin to cutting back a plant), but if mixing is excessive, then damage to the mycelium is likely.

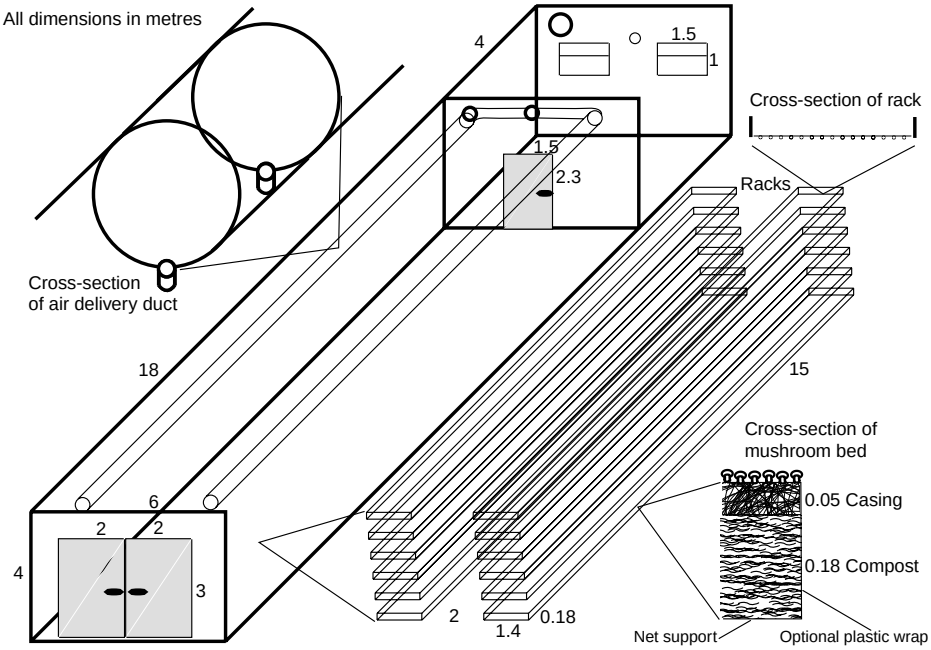

Figure 3.1: Layout of a typical Dutch commercial solid-state fungi bioreactor

To facilitate worker access and inspection the compost should be placed on a rack. To avoid stretching injury rack width should be less than 1.2 m, rather than the 1.4 m shown in Figure 3.1. Racks should be at a height such that access is easy, whether: sitting on an appropriate stool, standing, or standing on an appropriate step-ladder. Given the space context the material used for rack construction should be as light as possible, or else the material should be available on site. If weight restrictions rule out a rack system, then the bag system may be used.

This type of bioreactor generally operates on a batch principal, hence it may not be suitable for a continuous process application. A gravimetric, agitator, or screw-in-a-tube reactor is more commonly used where continuous process operation is required. A negative aspect of the screw-in-a-tube reactor is the compaction effect the screw has on the compost or substrate. Compaction reduces the porosity of the substrate thus increasing the resistance to growth for filamentous fungi and reducing the void spaces that facilitate gas exchange. A fluidized bed reactor is of course the other extreme of reactor design and presumably has not

been widely used previously due to throughput and/or energy use limitations. However, note that a fluidised bed reactor was used in a microgravity environment (Sornchamni *et al*., 2002). A commonly used reactor design, *e.g*., for demonstration or trial yeast fermentation processes, is the of the jacketed agitation type shown in Figure 3.2.

Figure 3.2: Photo showing small-scale jacket fermenter with central agitator.

Note the three mixing paddles that are mounted on the rotating central spindle. Thermal control is maintained via regulation of the heat exchange fluid that flows through the jacket that surrounds the central reactor. The fluid enters and leaves the jacket through piped connections to the thermal regulator. Similarly, the fluid in the central reactor can be pumped through the reactor and/or agitated within the reactor for continuous processes. Alternatively, the fluid in the central reactor can be continuously or intermittently agitated, using the paddles on the central spindle, for batch processes.

Unfortunately, the type of agitator shown in this fermenting type of reactor can create compaction and liquefaction in the substrate, which may be undesirable. Furthermore, structural irregularities within a non-homogenous substrate can cause premature wear and/or failure of the agitator.

4. Watering (WP7.3.19)

As part of most mushroom cultivation texts, *e.g.*, Wuest (1982), the importance of a proper watering regime is specially highlighted. The role of water in mushroom production has been the focus of dedicated works, *e.g.*, Batista (1991), as has its role as an element of soil (substrate) in general, *e.g.*, Foth (1990). Other than to note that it should meet EU drinking water standards (Teagasc, 2000), this section does not discuss the quality, or the role of water or watering regimes *per se*, rather it focuses on the mechanism of water delivery.

Note that the typical cylindrical or tubular nature of a gravimetric, agitator, or screw-in-a-tube bioreactor does not facilitate the watering process because the outside tube is itself an access barrier. Using a tube within a tube arrangement where the inner tube is used to supply water can circumvent this. Unfortunately, this arrangement has severe maintenance penalties.

Conversely, watering for the rack system is relatively simple. Water can be applied:

1. directly overhead via spraying - as used in commercial practice,
2. through capillary reservoirs – as tried by Flegg (1962) and shown at left in Figure 4.1,
3. alternatively, capillary supply could be supplied from underneath through a semi-sided permeable membrane, or,
4. through porous tubing – as tried by Lomax (1986) and shown at right in Figure 4.1. Note that Lomax (2002) has: "… not continued with irrigation studies because the tubing that we were using

was not uniform enough. There was too much variation along the length of that tubing, so some spots would have excess water and some spots would have no water".

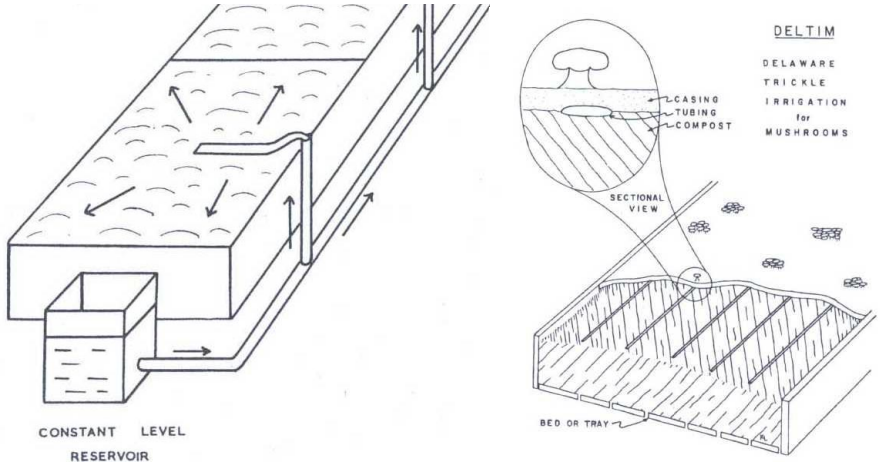

Figure 4.1: Layout of, **Left**: Capillary system (Flegg, 1962), **Right**: Porous tubing system (Lomax, 1986)

When water is applied from above in commercial growing systems, gravity is used as a means of water delivery, such that there is generally no significant water gradient through the compost and/or casing. The presence of dry areas, *i.e.*, a water gradient, will act as a local inhibitor to growth. Hence, a simple specification for a watering system to meet is, to provide compost conditions where no significant water gradient exists.

5. Fungal climate requirements (WP7.3.18)

Until a final selection has been made regarding the specific fungus, no specific climate requirements can be determined. However, to illustrate the range of climate requirements that need to be considered, some examples of the climate requirements to be met for fungi in general are shown in Figures 5.1 to 5.4.

Figure 5.1: Required humidity for growth of different organisms (Sterling *et al*., 1985)

Note: To achieve an appropriate water activity in the compost, Hudson (1986) more precisely quantified the range as 65-99.9% RH for fungal growth. Smith and Onions (1983) extend the lower end of the range to 61% for one fungus and imply "low water activity" as being 85% or lower.

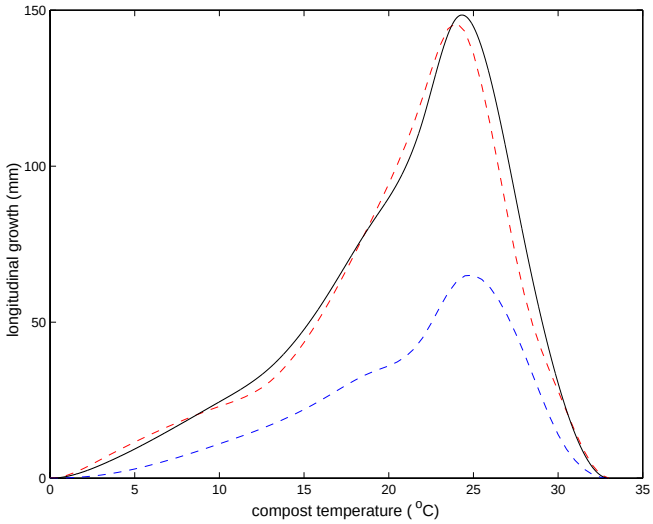

Figure 5.2: Growth rate of *Agaricus albida* as a function of compost temperature (Treschow, 1944), upper dashed line - 30 days growth, lower dashed line - 15 days growth, solid line – normalised.

Note: *Agaricus bisporus* cardinal temperatures: 32°C max., 24°C optimum, 1°C min. (Hedger and Basuki, 1982),
Compare: *Phanerochaete chrysosporium*: 50°C max., 40°C optimum, 10°C min. (Hedger & Basuki, 1982)

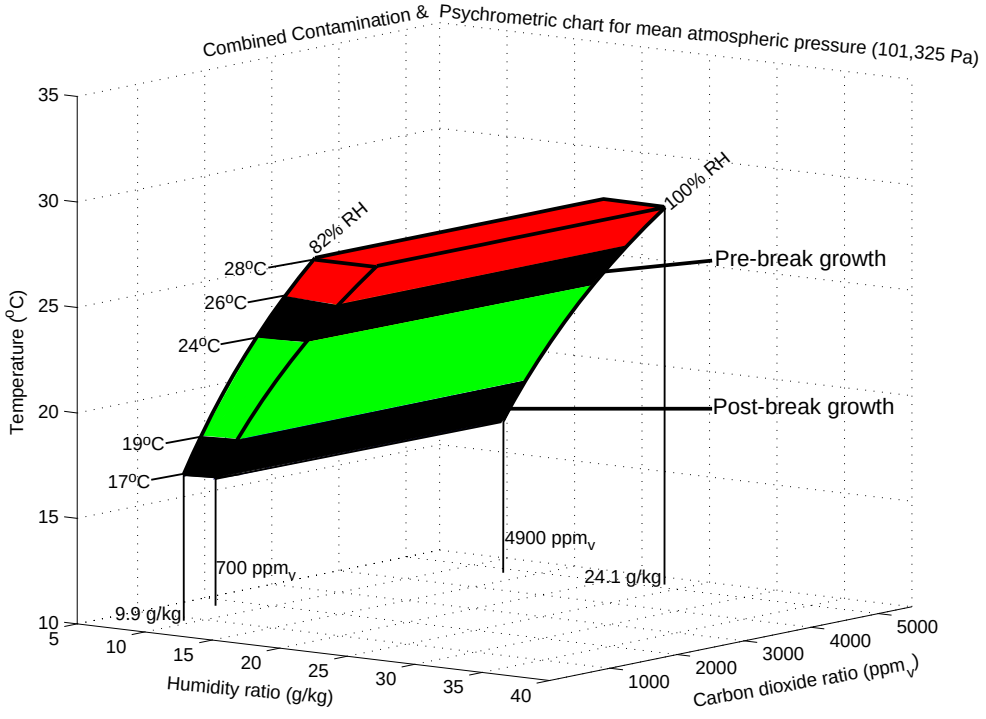

Figure 5.3: Commercial (*Agaricus Bisporus*) climate growth zone
for three most important climate variables

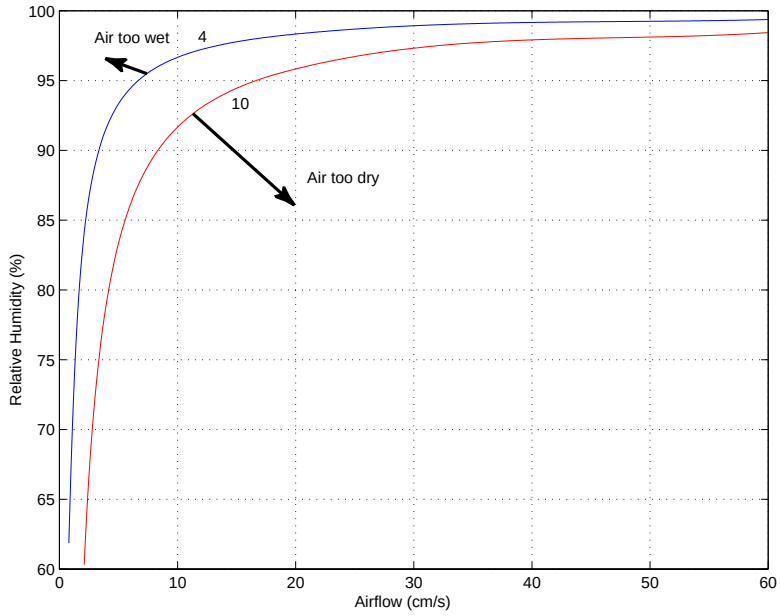

Figure 5.4: Required drying capability, 4 - 10 Pa m^{-1} s^{-1} at 17°C, for healthy growth of *Agaricus* (Edwards, 1979)

6. Air distribution (WP7.3.20)

"Ensuring uniform air movement in a mushroom house is far from easy." (Flegg, 1994)

The simplest form of air distribution system is one where the conditioned air leaving the air handling unit (AHU) is blown directly into the controlled zone, without any consideration for achieving a specified airflow pattern. Perhaps because of its crude simplicity, this type of system is often used for single-zone systems. An example of this type of system is shown in Figure 6.1.

Figure 6.1: Photo of growth chamber air handling/distribution unit: note air vents at top and bottom of AHU

The stainless-steel fronted cabinet, in the right background of the photo shown in Figure 6.1, houses the AHU for this single zone and is supplied by the air that flows into and out of the vents at the bottom and top of the cabinet. High local air velocities, *e.g*., near the vents, are characteristic of such systems. The high air velocities are, however, no guarantee of climate spatial homogeneity in the zone as a whole. Indeed, reports, *e.g*., of stagnant pools and pockets where excessive drying occurs (O'Sullivan, 2001), are quite symptomatic of the system's spatial inhomogeneity. To circumvent such features, a system that meets some specific airflow pattern is required. This can involve a significant leap in terms of air distribution system complexity.

There are two main elements to consider when it is desired to achieve a specified airflow pattern. The first is directional control, via air condition, of the air jet(s) that drive the airflow. The second is also directional control, but in this case, via air containment, usually by perforated ducts, or pipes, and/or by air guidance.

Directional control of an air jet can be effected via air conditioning in order to maintain a target ratio between the momentum and buoyancy forces, *e.g*., as described by the Archimedes number, of the jet with respect to the zone air. Consider the case of a warm jet entering a zone of colder air, where the buoyancy force tends to drive the jet upwards. A jet with the same characteristics, *e.g*., identical air temperature, *etc*., entering a zone of warmer air has a buoyancy force that tends to drive the jet downwards. Clearly this form of directional control only operates in one dimension. The Archimedes number (*A*) has been used (Randall 1975) as an indicator of the path of an air jet leaving an air delivery duct and entering an air space. Equation (6.1) shows one form based on the Etheridge & Sandberg (1996) definition for the case of a non-isothermal horizontal jet supplied horizontally.

$$A_0 = g\,\Delta\rho\,\rho_0^{-1}\,A_0^{0.5}\,U_0^{-2} \qquad (6.1)$$

where,

A_0	=	Archimedes number at the plane of jet entry
g	=	acceleration due to gravity
$\Delta\rho$	=	density difference between jet entry (ρ_0) and the environment
ρ_0	=	jet density at the plane of jet entry
A_0	=	orifice area at the plane of jet entry
U_0	=	jet velocity at the plane of entry

Compared to the type of air distribution system shown in Figure 6.1, the next step up in terms of sophistication is a system that provides an airflow to a particular zone. This can be achieved quite simply by the use of a local fan, as shown in the left part of Figure 6.2, or through the use a fan and air distribution system, as shown in the right part of Figure 6.2. The intent of these systems is to reduce the occurrence of stagnant pools of air. Note that the use of a local fan system creates climate spatial differences within the zone, due to the non-homogenous air velocity distribution within the zone. To reduce the problem of spatial difference, the airflow can be delivered through an air manifold or air distribution system of some sort, as shown in the right part of Figure 6.2.

Figure 6.2: Photo of growth chamber showing air mixing/distribution unit:
Left: (*Shitake*) Oscillating local fan, **Right**: Fan and air manifold (permeable duct)

A manifold system works through physical guidance of the airflow. Physical guidance of the air being distributed can be effected in many different ways, some direct and some indirect. The most common form of direct distribution is via air containment using a duct of some form. Due to their low cost and weight, inflatable ducts are very popular in protected cultivation applications. The design of such ducts for livestock and greenhouse applications have already been addressed, *e.g.*, Wells and Amos (1994). Ducts also have a history of use in mushroom growth applications. Despite their wide use and acceptance, researchers are still experimenting with different duct manifold configurations to establish optimal performance (Lomax, 2001). Alternatively, the physical surfaces of a zone, walls, ceiling, floor, and objects in the zone space can act (indirectly) as guides and/or barriers to the airflow within that zone. For example, a feature of the low-cost Irish growing system is, its use of the walls of the tunnel building and the bags on the floor as guides for the airflow, via the Coanda effect (Tritton, 1977), as shown in Figure 6.3.

Unfortunately in the original design of Irish tunnels, fan power was insufficient to power air circulation at the crop level during periods where heating was full on. This required the retrofit of a boost duct to supplement the air circulation system. Airflows for both single (left) and boost (right) duct systems are shown in Figure 6.3.

The effect of the omission of Archimedes number control in this system, is shown in the left part of Figure 6.3, where the warm airflow floats over the breathing zone of the crop, leaving a stagnant pool of contaminated air hanging over the crop. The effect of the boost duct configuration is to add momentum to the airflow, thus restoring the buoyancy-momentum ratio, which is shown in the right part of Figure 6.3.

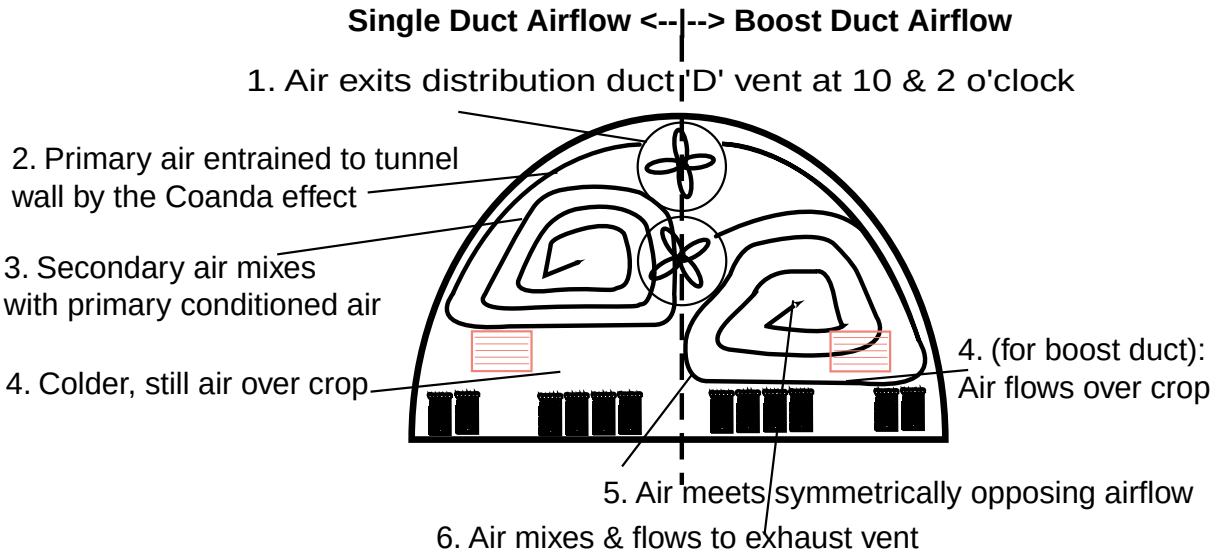

Figure 6.3: Lateral section of tunnel showing airflow field during stratification for standard single-duct tunnel (left part of figure) and corresponding airflow field for boost duct system (right part of figure)

For a tunnel system with racks, additional physical surfaces can be used to guide the air to achieve the desired airflow. A series of blades, or vanes, can be used as deflectors, to interrupt some of the airflow flowing over the internal walls and redirect some air over the racks. Grant (1998) tried such an arrangement very successfully using the deflector configuration shown in Figure 6.4.

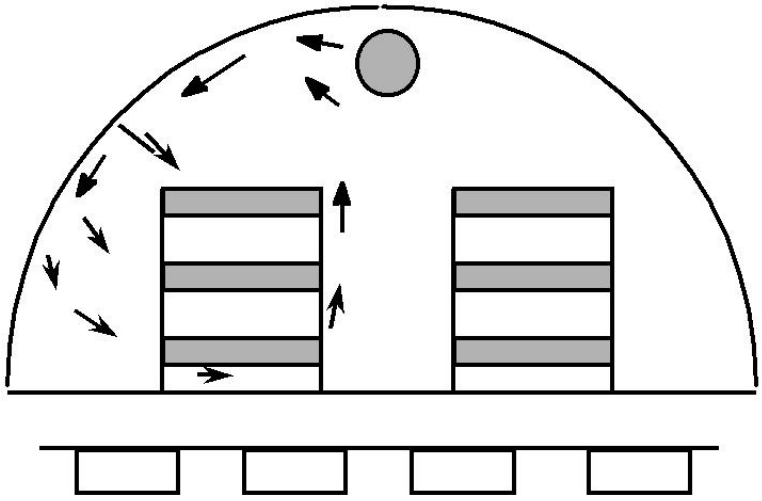

Figure 6.4: Airflow distribution system using blades as deflectors (Grant, 1998)

The Grant deflector configuration shown in Figure 6.4 has several advantages compared to other more established multi-plane horizontal air delivery systems, such as the one shown in Figure 6.5. In the system shown in Figure 6.5, air is sucked in from overhead (right part of figure), ducted down to a hidden manifold, and then blown horizontally through a zone of rectangular cross-section via a perforated supply and return wall. The principal potential advantages of the Grant manifold compared to the hidden manifold and perforated wall are: low-cost and easy access for cleaning/maintenance.

It is possible that the perforated wall may have a more uniform overall climate spatial homogeneity compared to the Grant deflector system, however, it has been shown that the deflector system can deliver a relatively even airflow at multiple desired horizontal breathing zones. Without a comparative study, no

definitive conclusion can be reached as to the two systems relative performance in terms of climate homogeneity.

Figure 6.5: Inside and outside photos of growth chamber with displacement ventilation system: **Left**: Internal perforated supply and return walls (return only shown), **Right**: External overhead ducting

It can be inferred from the works reviewed to-date, that a generally unstated objective of the air distribution system used in mushroom cultivation is to achieve spatially homogenous climate conditions within the bioreactor. Sometimes this objective is indirectly implied, *e.g.*, Flegg and Gandy (1962) introduced "… a small fan for agitating the air inside" (presumably in a manner similar to that shown in the left part of Figure 6.2) and occasionally it is stated explicitly, *e.g.*, Bishop (1979) introduced air distribution "As the reasons for considering air distribution are to achieve evenness of temperature, relative humidity and carbon dioxide concentrations throughout the whole building, …". Note that the intention of agitation or mixing is to create homogenous conditions. However, the rationale for such a (perfectly-mixed) objective has not been observed by the author. One reason could be simplification for subsequent control design. A more likely reason is that if the air is spatially homogenous and of the right condition, then growth climate requirements have been met. It is suggested that (re-)evaluating what the objective of the air distribution system is, may be appropriate in this context. This evaluation is accompanied by a shift in emphasis from spatially homogenous conditions in the zone to conditions in the "breathing zone" of the crop.

Simply put, the purpose of the air distribution system is to deliver an appropriate volume, at an appropriate air velocity, of conditioned air to the breathing zone and to remove contaminated air from the breathing zone. Two measures of performance are relevant in this context: ventilation rate and ventilation efficiency. Ventilation rate is most commonly measured in terms of air changes per hour and this has been calculated for a standard tunnel (Martin *et al.*, 1999). Perfect mixing has a ventilation efficiency of 50%, whereas a piston-type flow has a ventilation efficiency of 100% (Etheridge and Sandberg, 1996). The reason for the lower performance for perfect mixing is that, locally, it can remove conditioned air and/or deliver contaminated air, *i.e.*, precisely the reverse of what is desired.

If the rationale for using perfect mixing was to provide spatially homogenous climate conditions for growth, then this can be achieved with short run piston flow systems, at higher ventilation efficiency. An auxiliary benefit in using a (balanced) piston flow system is that analysis of the differential between supply and return air, and hence, can be used to facilitate the indication of the state of metabolic activity, *e.g.*, respiration, in the bioreactor.

Displacement or piston flow systems are used industrially to maintain a clean air zone upstream of the (normally a point) contamination source and control the dispersion of contaminated air downstream of the contamination source, *e.g.*, such as in the biological safety cabinet (BSC) shown in Figure 6.6. Note that climate conditions in a BSC are dependent on ambient room air condition, as its principle function is solely to remove biohazardous (CDC, 1995) particulates from the air. From one perspective the system shown in

Figure 6.6, is the other design extreme to that shown in Figure 6.1 because it incorporates no AHU functionality, whereas that of Figure 6.1 only incorporates AHU functionality.

From a displacement system perspective, a mushroom crop is unusual in that it is normally spatially distributed around a bioreactor. Were the crop to remain spatially distributed in current format, the breathing zone downstream would be more contaminated and less conditioned than that upstream. The challenge in applying a displacement system is, to arrange the crop so that the air supply runs are short enough that supply air is not significantly contaminated or deteriorated in condition, before it is removed from downstream areas within the breathing zone.

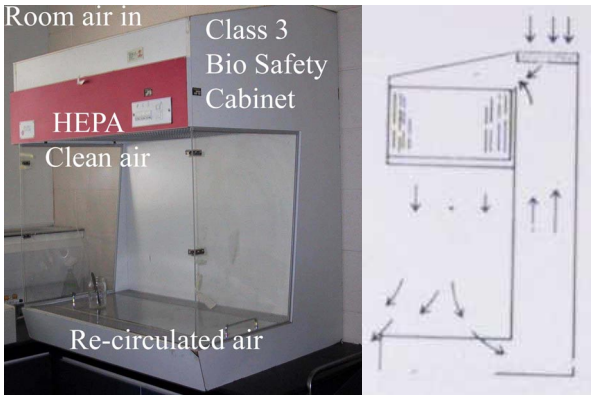

Figure 6.6: **Left**: Layout of a laboratory biological safety cabinet,
Right: Desired airflow of displacement ventilation system

Using existing commercial cultivation systems for comparison, where there is generally a local flow of a displacement form immediately over the crop surface, it would appear that a run of less than 1.5 m would provide crop-level conditions that are comparable to existing systems.

6.1 Bioreactor layout

An air distribution system has to be suitable for the process layout under consideration. Hence, prior to introducing the air distribution system under consideration, it is first necessary to introduce the process layout under consideration itself.

Typically, a gravity fed cylindrical tower design is used as the basis of specialist solid-state reactor layout, such as that of Schuchardt and Zadrazil (1988) for a white-rot fungal cultivation on a straw substrate, or the two stage reactor design of Caro (1988) for an *Aspergillus* fungal cultivation on a beet pulp substrate. Whilst the tower design has energy saving advantages due its inherent gravity fed nature, it has a corresponding disadvantage. The disadvantage is that its vertical orientation induces gravity induced compaction within the substrate and hence decreases porosity, with a consequential increase in resistance to metabolic gas exchange.

For a small energy penalty, the compaction disadvantage can be minimised by simply moving reactor flow throughput from a vertical to a horizontal flow direction, *i.e.*, by laying a tower reactor on its side, which then resembles a drum bioreactor. Furthermore, to facilitate gas exchange, the closed environment of the tower is opened into that of a conveyor. Combined together, these two characteristics, horizontal layout and large surface area for metabolic gas exchange, provide an environment which more closely resembles the natural forest floor that is home to fungi in the wild, than that of the more common tower reactor. This type of reactor layout is similar to the tunnel fermenter class of Weiland (1988) but with a different air distribution system (lateral instead of vertical). Hence, it is envisaged that the degradation process occurs in a tunnel bioreactor such as that shown in Figure 6.7.

The input to the fungi bioreactor shown in Figure 6.7 is the compost, *i.e.*, the mix of solid ligno-cellulose wastes from previous loops. Spawn is mixed with the compost and the mixture is left to run on the conveyor for the duration of time that degrades the lignin to the required degree. The spawn-run time and amount of

degradation required determines the time the mixture is left on the conveyor and hence the conveyor length. Conveyor width is determined by the volume of compost that is required to be degraded, because there is a maximum hyphal tip growth rate. If more than one climate zone is required to optimise tip growth rate, then this can be accommodated by a system of air curtains as shown in Figure 6.8.

The airflow across the fungi bioreactor shown in Figure 6.8 is a piston-type displacement ventilation system using a laminar airflow with a high ventilation efficiency. This is because the air is extracted as soon as it has completed a single pass of the process, instead of undergoing a mixing process (recall Figure 6.3). Sensors positioned at supply and return positions allow calculation of the change in state of the air's condition and thus, indirectly, of the metabolic state of the mycelium.

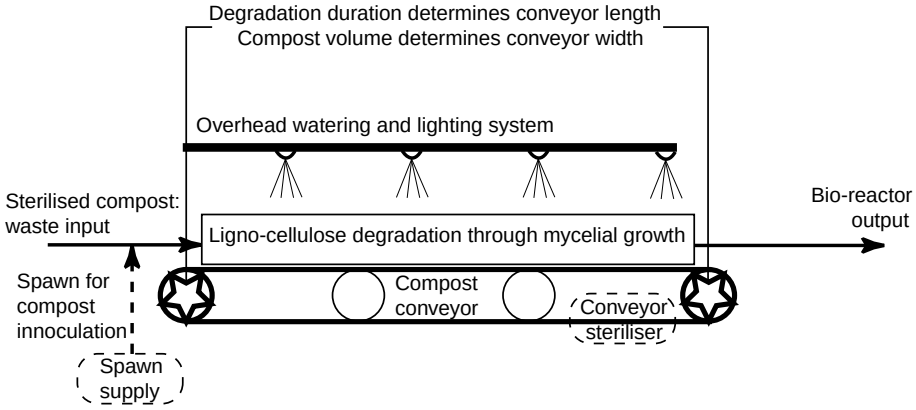

Figure 6.7: Conceptual layout of fungi bioreactor, side-view
(surrounding enclosure, air handling unit (AHU) and air distribution system omitted for clarity)

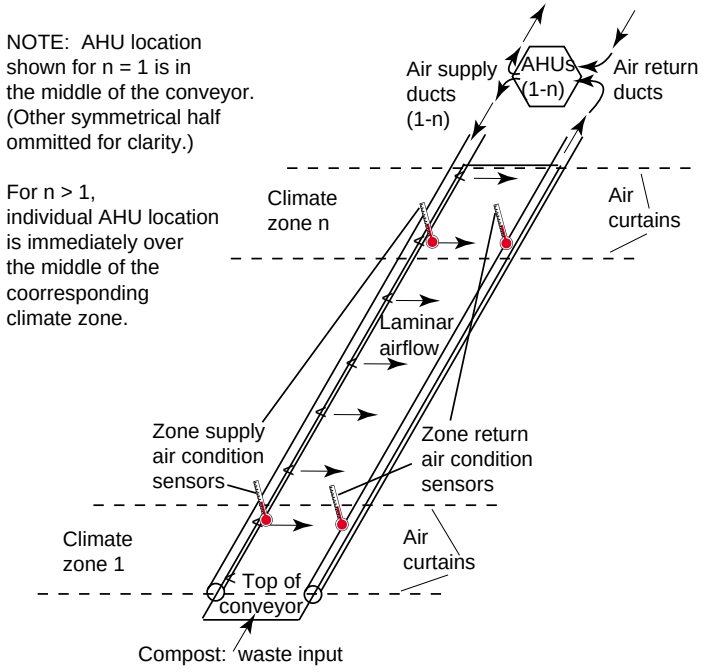

Figure 6.8: Air distribution layout for a multi-zone fungi bioreactor with displacement ventilation system, oblique overhead-view (surrounding enclosure, watering and lighting systems, omitted for clarity)

Selected Air Distribution Literature in a Mushroom Context

Spoelstra (1953) emphasised that there should be equable distribution of fresh air and no unwanted drying up, but made no mention as to how this could be achieved or quantified, other than by showing different distribution systems and observing that air velocity should be no more than 0.1 m/s. Watson (1959)

introduced the chimney effect (*i.e*. natural ventilation) and suggested the use of fabric ducts, by noting their effectiveness at air filtration. Stewart (1967) discussed "Typical ventilation duct arrangements and air distribution patterns in growing houses" by showing a mixing arrangement in the context of a air jet thrown through a nozzle, by example. Although delivery of air "where it is required" was stressed, no quantification of how this could be achieved was introduced. Flegg (1974) suggested a "… general pattern of air movement …" without any indication of how the air flow visualisation was determined, that is similar to that of Grant (1998), shown in Figure 6.4, but without any deflectors or air manifolds and without any discussion of the effect of stratification. Bishop (1979) focussed on the technology of air distribution without discussing any air distribution patterns *per se*.

Bowman (1987) evaluated the effect of placing a duct at the side wall at "half-stack height" on air velocity in an eight high tray house. Later (1989), Bowman commented on the poor ergonomics of this duct position and discussed the introduction of a more ergonomic alternative, including a permeable duct. The objective of achieving uniform environmental conditions was stressed. In 1991, Bowman discussed the use of high-pressure ducts at the side walls in combination with a permeable central overhead duct. An improvement in air velocity variation (7%) compared to a conventional house (30%) was noted. Following from work by Bowman, Grant (1989) showed how the then non-uniform air distribution conditions in a mushroom tunnel could be significantly improved. He proposed several modifications to the existing layout.

1. The incorporation of an air straightener to reduce the swirling motion introduced by an axial fan. Grant used a tube bundle straightener as opposed to a Zanker or Sprenkle straightener, whose recommended (BS 1042) lengths are respectively 4 diameters, 1 diameter, and 2 diameters. Grant found that 1.5 diameters was a reasonable compromise for the tube bundle used.
2. By modifying a duct design development for greenhouses, Grant applied a non-uniform vent distribution along the longitudinal axis of the distribution duct. This development was incorporated to eliminate the non-uniform volumetric delivery of air that resulted if a uniform vent distribution was used.
3. As the airflow used tunnel wall surfaces for guidance, he recommended the repositioning (where possible) or re-orientation of deflecting obstructions (*e.g.* light fittings) from the air delivery path.
4. In a later but independent development to that of Bishop (1979) or NIAE (1980), Grant used a D-shaped vent cut-out with the cut-out hinged out on the downstream side, so that it acted as a vent exit deflector.

Loeffen (1992) noted that indiscriminate use of perforated polyethylene ducts can result in uneven air distribution and suggested an air velocity of 0.15 m/s as being the highest acceptable over the crop. He presented models for free and forced convection, and measured air velocity due to free convection (mean = 0.076 m/s) when the casing was between 1.5-2°C warmer than the air. Then he presented results for a three duct forced convection system but did not provide duct layout details. Flegg (1994) noted the difficulty in attempting to achieve uniform (stirred) conditions in a central duct system with six-o'clock vents coupled with return ducts at the side wall, using smoke for analysis.

As an aid in analysis of the low velocity airflow required in mushroom growth, Lomax *et al*. (1995) introduced lightweight plastic flags as airflow indicators. The flags were much cheaper than an equivalent thermal anemometer measurement solution and were used to show the benefit of adding auxiliary distribution ducts to a house with a central overhead duct. In an experimental house, Lomax *et al*. (1996) constrained airflow over the crop to give a longitudinal air path length of 3 m. Air condition was measured at entry and exit, and two crops, of different strains, were grown at different air velocities (0.3 and 0.15-0.25 m/s). It was found that the timing and location of peak crop harvest varied depending on air velocity. Later, in an attempt to improve air distribution, Lomax (2001) reported that the D-shaped vents promulgated by Grant (1989) "… cause a measurable improvement in direction".

7. Air filtration (WP7.3.19)

"Louis Pasteur's theory of germs is ridiculous fiction."
Pierre Pachet, Professor of Physiology, Toulouse, 1872.

As evidenced by its central role in biological safety cabinets (CDC, 1995), an air filtration system can be considered as the safety system for a bioreactor. This is because the system does not supply any of the necessary nutritional or climatological prerequisites for growth. They are, however, an essential element in reactor design as they prevent the ingress and/or escape of hazardous process particulates.

Air filtration systems, *i.e.*, the entrapment of pollutant(s), are used as a supplement to contaminant source control, *i.e.*, the containment of pollutant(s), in order to minimise the pollutant load in an airspace. Maintenance of human health is the principal reason for the installation of an air pollution control system via source control systems and/or air filtration systems. It is generally accepted (Liddament, 1996) that particles below 30 μm (microns) are inhalable. Human air filtration mechanisms, *i.e.*, the nose and wind pipe, when effective, typically trap particles greater than 10 μm. Particles below this size can enter, lodge in the lung or be transferred to the bloodstream, and possibly initiate the onset of disease.

A particle that initiates disease may be: a passive particle, *e.g.*, asbestos, an active particle, *e.g.*, radon, an (potentially allergic) irritant, *e.g.*, tobacco smoke (dust mite faeces), or it may be an active pathogen. Potential intact pathogens may be: viral (>0.1 μm), bacterial (0.3-30 μm), or fungal (3-30 μm), (note that these figures are approximate). Given these size ranges, it can be seen that if air filtration can be used to trap (especially sub-10 μm) airborne particles, then it is effectively a synthetic supplement to the natural air filtration system of humans. Note that gravity is not very effective at precipitating out very small airborne particles (<3 μm), because they tend to stay suspended in air due to Brownian motion (molecular bombardment). Hence, gravitational deposition is not a significant competitor technology to synthetic air filtration.

Several technologies are used to obtain clean(er) air. The use of: cyclones and air washers/scrubbers for particulate separation, plants/*etc*. as air bio-remediators, and gas filtration/adsorption/*etc*. are just some examples. In a commercial protected cultivation context, note that cyclone separation has been used inadvertently (Martin *et al*., 2001) through the fan, albeit at the cost of reduced fan life-span. Also, note that an air washer has been used in the mushroom school, Horst, the Netherlands, to separate the fine spores released by *Pleurotus*, from the air.

The context for this filtration application is primarily the removal of particulates such as spores, viruses, *etc*. In the space domain, energy use is a constraint, hence, the main focus is on traditional filtration technologies which generally work by entrapment, through one or more of the following mechanisms: sieving, impingement, or electrostatic attraction.

There are two main types of synthetic air filtration mechanisms for the removal of airborne particulates. The most common (Liddament, 1996) means of air filtration is by impingement of airborne particles on a porous membrane (which is often of pleated construction). Less common is the use of an electrostatic filter, which, compared to the membrane type, is notable in that it requires a source of electric power. Regardless of the type of filter(s) used, the design, construction and installation requirements to produce an effective system are summarily outlined by Liddament (1996) and Goodfellow and Tahti (2001).

Note that a concrete air filter recommendation is dependent on the outcome of the Vito investigation into spore characteristics (as identified at the EWC meeting on 2002-04-16).

Membrane Filter
The membrane type of filter has a limit on the size of particle that can be filtered from the air, because particles that are smaller than the mesh size in the membrane can pass through the filter. However, this type of filter can still filter out particles smaller than the mesh size through any or all of the following mechanisms: direct impingement (which is one of the reasons for pleated construction), diffusion/Brownian

motion, reductions in mesh size through clogging, and electrostatic attraction. Although these effects do occur in practice, testing to a particular standard, *e.g.*, EN 779 or EN 1822, does not specifically identify this action.

Therefore, a membrane filter's specification generally reflects its worst case filtration performance, *i.e.*, a membrane filter's filtration performance generally improves with use. Unfortunately, the price for this increased filtration performance is an increase in the resistance offered to airflow through the filter, so, the fan has to work harder to get the same airflow through the filter. Note that membrane filters may be arranged in different shapes: pleated, sheet (also known as panel or plain), bag, *etc*. Examples of pleated and sheet filters are shown in Figure 7.1.

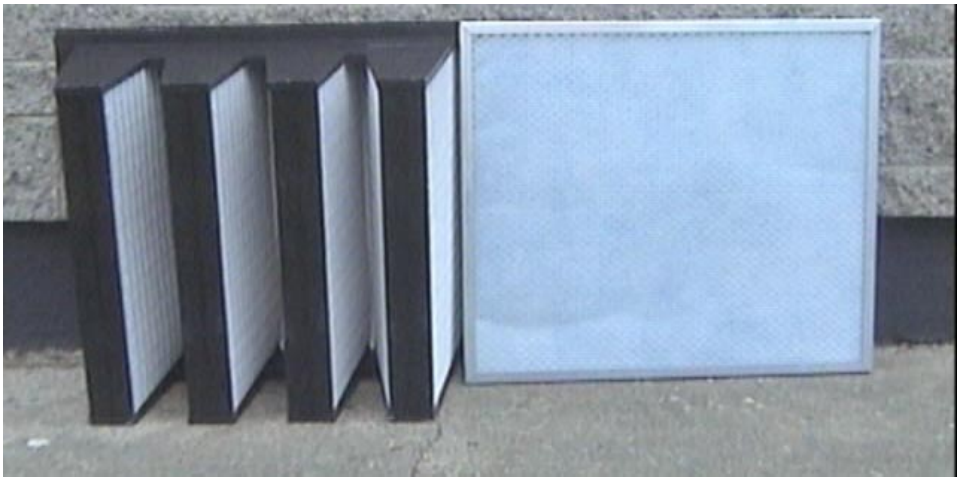

Figure 7.1: Photo showing examples of the construction of a pleated (left) and sheet (right) filter

As noted by Grant (2001), "No filter is perfect.", even when it is of fresh manufacture. Therefore, it is important to understand how filters are rated. There are many specifications that apply to air filters, *e.g.*, dimensions, throughput, *etc*. The three key specifications in terms of filtration performance are: mesh size, efficiency, and effective flow rate.

Mesh size determines the filter's rating in terms of its ability to trap particles of a specified dimension. The mesh size dimension is usually expressed as a figure, in microns, that will trap a particle that is nominally spherical. The efficiency, η, rating normally refers to the proportion of particles, which are greater than the mesh trap size, that are trapped by the filter during one pass of the airflow through the filter. So, a 90% efficiency rating for a 10 μm filter means that, approximately 10% of particulates greater than 10 μm will remain in the airflow after one pass through that filter. Another common form of expressing this aspect of performance is through the use of the term penetration, *P*, which is related to efficiency through Equation (7.1).

$$P = (100 - \eta)\% \tag{7.1}$$

For a one-pass, displacement system in a perfectly sealed zone with no internal particle sources, penetration, *P*, can be used to establish the steady state internal particle concentration, p_i, when the external particle concentration, p_e, is known, through Equation (7.2).

$$p_i = (P/100)\, p_e \tag{7.2}$$

The third key specification is a less reliable measure in the opinion of the author and is more suited to re-circulatory systems. This is the effective flow rate, which is the product of airflow rate and efficiency. This figure is used to suggest that, a filter of 45% efficiency will have the same entrapment of particles as a 90% filter, where the lower efficiency filter's airflow is double that of the higher efficiency filter. This figure is

used in the argument that a low efficiency, multi-pass, or re-circulatory, air filtration system, can have an effective performance that is comparable to high efficiency filters.

From a maintenance perspective, membrane filters are problematical because of the effect of clogging. When one element of the mesh traps a particle, that element and possibly neighbouring elements are no longer available to allow air to flow through the filter. Consequently, the resistance of the filter increases, and the increased resistance causes a greater pressure drop across the filter. Eventually, in dirty conditions, the filter becomes so clogged that the capacity of the fan is inadequate to deliver an adequate airflow through the air distribution system. Hence, a maintenance regime of regular cleaning and/or replacement (Martin *et al.*, 2001) is required.

Pre-filtering the incoming air with a filter of larger mesh size can extend the lifetime of a filter. However, this technique is inappropriate where the dirt particles to be trapped have low dimensional variation, because most of the particles can get through the larger mesh anyway. Hence, application of this technique requires that the characteristics of the filtration load are known. Alternatively, for a given mesh size, increasing the surface area can extend the lifetime of a filter. Compared to a sheet filter this is what a pleated filter achieves. From an air propulsion perspective, a general secondary benefit of increased filter area is a reduction in overall filter resistance.

Filter Classification

Commercial filters are rated by several different systems. The Eurovent (EU) standard has been used in Europe for some time. Since 1979 (Goodfellow and Tahti, 2001) a EU4/5 rating has been the standard filter rating for general use.

A filter of EU4 rating would: probably be of pleated construction, have a pressure drop in the range 50-250 Pa, an efficiency in the range 30-40% at >2 μm, and >90% at >5 μm. High performance membrane filters are known as high efficiency particulate air (HEPA) filters. A HEPA filter of EU11 rating would typically: have a pressure drop in the range 250-650 Pa, and an efficiency in the range 99.95-99.97% at <2 μm.

Alternatives and supplements to the EU classification system exist. Coarse filters G1-G4 of EN 779 rating, correspond to their counterpart EU1-EU4 ratings, as do fine filters F5-F9 (EU5-EU9). Supplementary test standards such as EN 1822 (*c.f.*, Table 1) can then be used to separate HEPA filters H10-H14 from even more efficient ultra low penetration air (ULPA) filters U15-U17. The application of ULPA filters tends to be limited, *e.g.*, as the final stage of filtration in the AHU for a clean room.

Electrostatic Filter

It can be argued that the highest air filtration ratings of all, can be obtained through a hybrid combination of electrostatic and membrane techniques. Electrostatic filters work by using a grid system (one plate of which is similar to the mesh) of alternately charged and grounded electrode plates as the particle trap. Before the particles enter the grid they are charged using a high intensity electric field. The induced charge on the particle attracts it to an electrode plate where it is trapped. Note that electrostatic filters also require a maintenance regime of regular cleaning and/or media replacement, and, additionally, a washing regime. (Note that washing can degrade membrane only types.) Otherwise, as the dirt accumulates on the charged plates, the electric field strength diminishes, thus reducing the efficiency of the filter.

Energy Consumption & Replacement

The energy load presented by a filter, to a flowing air mass, is a function of its pressure drop, Δp. Consider a simple ventilation system: a fan (of efficiency η) supplying air (of volumetric flow q) to a single zone through a filter (for a time t). The energy (E) consumption of this ventilation system can be calculated using the formula (Goodfellow and Tahti, 2001) expressed in Equation (7.3).

$$E = q\,\Delta p\,t / 1000\,\eta \text{ (kW hr)} \tag{7.3}$$

Typically the cost of the energy attributable to using the filter is greater than the cost of a replacement filter after one year. In space applications, the transport cost of a replacement filter is such that extremely long-life

filters are desirable. Long-life in this context generally means with a lifetime greater than estimated mission time-span. Note that due to the space context, rules of thumb regarding filter replacement, *e.g.*, replacement after the end of the "pollen season" and/or after the end of the "winter damp season", are inappropriate.

Filter Position
Normally, filters are positioned in the inlet duct to remove pollutants from external fresh air, and/or they are positioned to filter pollutants from internal re-circulated air, and/or to act as a filter for a local pollutant source. Sometimes it is possible to separate the load placed upon an air filter such that each individual filter can be better specified to handle a smaller specific load.

Consider the air handling unit (AHU) configuration shown in Figure 7.2. In this configuration, it can be argued that the re-circulation filter is subject to a relatively constant internal climate and its associated environment. If the internal pollutant source characteristics, *e.g.*, the spores released by a mushroom crop, are known, then this filter can be dedicated to that particular filtration load, whereas the intake filter has to handle the complete load from the pollution spectrum of local outside air.

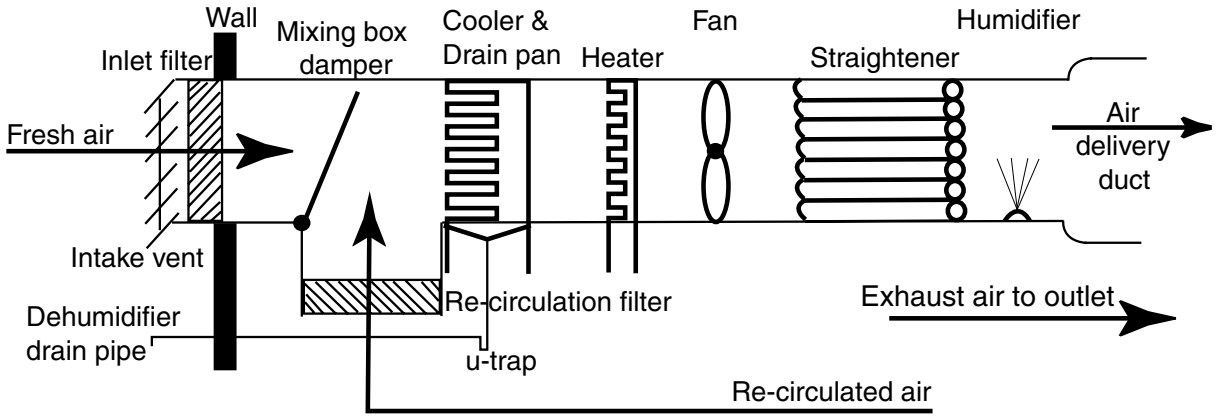

Figure 7.2: Diagram showing principle of filter task separation: separate intake and re-circulation filters

Selected Air Filter Literature in a Mushroom Context
Wenzek (1987) highlighted the role of air filtration in preventing the spread of disease. Although the characteristics of filters meeting Eurovent 4/5 were introduced, the focus was on filter selection for one of three applications: bulk tunnel spawn running, central air handling systems, and individual cell systems. Bamforth (1990) introduced filter selection and testing. He noted the importance of identifying contaminant size to optimise filter selection but gave no concrete recommendation as to what grade of filter should be used. Thompson (1991) separated the filter selection issue into three: bulk tunnel spawn running, central air handling systems, and individual cell systems. Concrete recommendations for each application were provided. Lomax (1997) related air filter efficiency to the pressure drop (energy cost) and highlighted the importance of an appropriate maintenance regime.

Airborne Gas/Pathogen Extraction
Note that no standard air filtration system will extract gases, *e.g.* ethylene, that are mixed in the air. For this, a separate gas scrubber that is typically based on one or more of the following principles is required: absorption, adsorption, condensation, incineration, or biological control (Davis, 2000).

In cases where airborne pathogen, *e.g.* Anthrax, dispersal is of concern, the filtration system can be augmented by a pathogen killer or extermination system. As in the case of filtration systems, it is beneficial to know the spectrum of pathogens that it is desired to remove. Mortality can be achieved using several principles of attack. Two common forms of attack system are based on chemical, *e.g.* free radicals, or radiation, *e.g.* ultra-violet, principles. Chemical attack can occur as a side-effect of air passage through a chemical scrubber. The installation of fluorescent ultra-violet lights at the end of the air handling unit is a known anti-pathogen precaution. Dedicated anti-pathogen units have been improved in the recent past,

triggered by Anthrax and other scares, and at least one uses a combined chemical and radiation attack principle (KES, 2002).

8. Air conditioning (WP7.3.21)

Filtration is the first stage of treatment that the supply air receives in the air handling unit layout shown in Figure 7.2, and was discussed in the previous section. Normally, the second stage of treatment that the supply air receives is the mixing of 'fresh' or outside air with recirculated internal air, which is shown in the mixing box of Figure 7.2. Control of the ratio of internal to external air in the mixed air can be based on several variables, and typically the variable selected is air contamination, using carbon dioxide as a contaminant indicator. Consequently, ventilation requirements are normally met through air mixing. In this application, no mixing of external Martian air with internal air is envisaged in the design of the bioreactor.

Traditionally, the term 'conditioning' is used to describe the air's thermal condition and this is the intended meaning of the term in this section, and is normally the tertiary stage of treatment that the air receives in the air handling unit. The thermal condition of the air can be separated into two components: sensible and latent heat. The latent heat component is normally a function of the air's humidity, hence, in terms of air conditioning systems, air is usually considered as a binary mixture of dry air and water vapour. The study of the mix of these two gases is called psychrometry. Whilst latent heat is a function of the water vapour content and its temperature, sensible heat is a function of temperature only. This is evident from the last, *i.e.*, Equation (8.6), of the equations presented in the following sub-sections.

The measurement of humidity can be expressed in different ways, with different numbers describing the same air conditions. Perhaps the most familiar numbers encountered are those of relative humidity (RH). However, RH is not a unit of measurement, it is a gas pressure ratio, and it is not the only means used to describe humidity. There are a bewildering number of concepts available to describe humidity, and to avoid confusion they are not listed here. However, it is necessary to discuss the simplest SI description – humidity ratio. If humidity ratio is currently an unfamiliar or unknown term, think of it in simple terms, it is the ratio of the mass of water vapour to the mass of dry air.

Calculation of Humidity Ratio

The calculation of humidity ratio (W) requires three measurements: pressure, temperature and some hygrometric indication, usually dew point or relative humidity. Air pressure (p) does not exhibit great variance on the earth's surface, so a mean value of 101,325 Pascals (Pa) for sea level, is often used instead of a pressure measurement. The temperature (T) and relative humidity (e) values can be found using a thermometer and hygrometer. Note that SI notation, *i.e.*, ('degrees') Kelvin, is used for the temperature value. Conversion of a degrees Celsius temperature value to a ('degrees') Kelvin value is done using Equation (8.1).

$$T(\mathrm{K}) = T(^{\circ}\mathrm{C}) + 273.15 \tag{8.1}$$

Humidity ratio can be calculated using Equation (8.2), through the ratio of molecular weights of the two gases. This equation requires a value for the water vapour pressure (p_{wv}), which is provided by Equation (8.3). In turn, Equation (8.3) requires a value for the saturated water vapour pressure, through Equation (8.4).

$$W = 0.62198 \frac{p_{wv}}{p - p_{wv}} \tag{8.2}$$

where,

W is the humidity ratio, kg/kg
p_{wv} is the pressure of water vapour, Pa
p is the pressure of air, Pa

$$p_{wv} = \frac{ep_{swv}}{100} \tag{8.3}$$

where,

p_{wv} is the pressure of water vapour, Pa
e is the relative humidity, %
p_{swv} is the pressure of water vapour in saturated moist air, Pa

$$\ln(p_{swv}) = \sum_{i=-1}^{i=3} (k_i T^i) + k_4 \ln(T) \tag{8.4}$$

where,

k_{-1} = -5.8002206e+03
k_0 = 1.3914993
k_1 = - 4.8640239e-02
k_2 = 4.1764768e-05
k_3 = - 1.4452093e-08
k_4 = 6.5459673
T is the air temperature, K

Equations (8.2) and (8.3) are standard expressions for humidity ratio and relative humidity (reformulated) respectively, provided by several sources, *e.g.*, Goodfellow and Tahti (2001), ASHRAE (1989), *etc*., using the perfect gas equation of state, *i.e*., Equation (8.5). Equation (8.4) is the proposal developed by Hyland and Wexler (1983) for the pressure of water vapour in saturated moist air. Their study was commissioned by ASHRAE and the U.S. National Bureau of Standards, a body that has since become the U.S. National Institute for Science and Technology (NIST). The psychrometric tables generated by Hyland and Wexler only apply at standard barometric pressure. Use of perfect gas relationships results in slight errors, but allows the calculation of psychrometric properties at pressures other than standard. As pressure decreases, so too does the error generated by using perfect gas relationships. For this reason, the perfect gas relations are often used instead of the virial equations determined by Hyland and Wexler.

$$pV = nRT \tag{8.5}$$

where,

p is pressure, Pa
V is volume, m^3
n is the number of moles
R is the universal gas constant
T is the absolute temperature, K

Calculation of Enthalpy

Many people think of temperature as an indicator of thermal energy or enthalpy. For perfectly mixed solids and liquids, temperature is indeed a good indicator of enthalpy status. However, for a mix of gases, *e.g*., wet air, temperature alone is not a sufficient indicator of enthalpy status. This is particularly the case when the different gases are quite different in terms of their contribution to overall enthalpy.

Simply put, enthalpy is the sum of the individual thermal energies of the water vapour and the dry air in an air/water vapour mix. Note that the enthalpy of saturated water vapour has approximately double the enthalpy of dry air, in the temperature range of interest, at the same pressure and volume. This is despite the fact that the heat capacity of water vapour is three orders of magnitude greater, as this is counterbalanced by the fact that its concentration (density) is generally three orders of magnitude lower.

Determining the energy or temperature of two mixed airstreams is easy if both airstreams are dry. In this case the temperature is midway between the two temperatures of the two air masses being mixed. However, when the mix consists of more than one gas, *e.g*., water vapour and dry air, then an understanding of enthalpy is required to determine the mixed energy or temperature.

Using the humidity ratio calculated by Equation (8.2) and the corresponding air temperature measurement, the air's thermal energy or enthalpy (h) can be calculated from the sum of the specific heat capacities of dry air and water vapour, as given by Equation (8.6). In this equation, degrees Celsius is used for the temperature value. An arbitrary enthalpy value of 0 kJ/kg is chosen to describe the enthalpy of dry air at 0°C, under standard pressure. Moist air acts as a semi-perfect gas, *i.e.* a gas whose specific heat is a function of temperature only, and for this reason the values of the constants in this equation vary to a small degree, depending on the reference source used. The values used here are those provided by Goodfellow and Tahti (2001).

$$h = 1.006T + W(1.85T + 2501) \tag{8.6}$$

where,

h is the air enthalpy, kJ/kg
T is the air temperature, °C
W is the humidity ratio, kg/kg
1.006 kJ kg^{-1} $°C^{-1}$ is the average specific heat of dry air in the temperature range –10 to +40°C
1.85 kJ kg^{-1} $°C^{-1}$ is the average specific heat of steam in the temperature range –10 to +40°C
2501 kJ kg^{-1} is the latent heat of vaporisation for water at 0°C

Psychrometric Chart or Mollier Diagram

To facilitate understanding of the air's condition and how to manipulate it, a psychrometric chart is used. There are two camps in the psychrometric charting field:

- a continental European convention of using temperature for the vertical axis, or
- an 'imperial', *i.e.*, U.K. & U.S., convention of using temperature for the horizontal axis.

The two forms of presentation look quite similar, as one is a reflection of the other in a mirror at a 45° angle. The European psychrometric chart convention, *i.e.*, humidity is on the horizontal axis, will be used here. In an English language context, note that this chart form is sometimes incorrectly called a Mollier chart, which is actually an entropy-enthalpy chart (Harcourt, 2001). Using this convention means that: moving up the chart the air is getting hotter and moving right on the chart the air is getting wetter, *i.e.*, more humid.

Both relative humidity (in %) and humidity ratio (in g/kg or kg/kg) scales are normally included on a chart. Note that this does not increase the number of dimensions, but does increase the complexity of the shape of a chart, by adding a 'coastline' that indicates the transition to super-saturation. 'Going over the edge' *i.e.*, moving beyond the 100% of the saturation curve on the chart, is a move out of psychrometry, from the gaseous water vapour phase into the super-saturated phase. A sample chart is shown in Figure 8.1. Note that Figure 8.1 shows the position of states 1 and 2 that are used in a later mixing example.

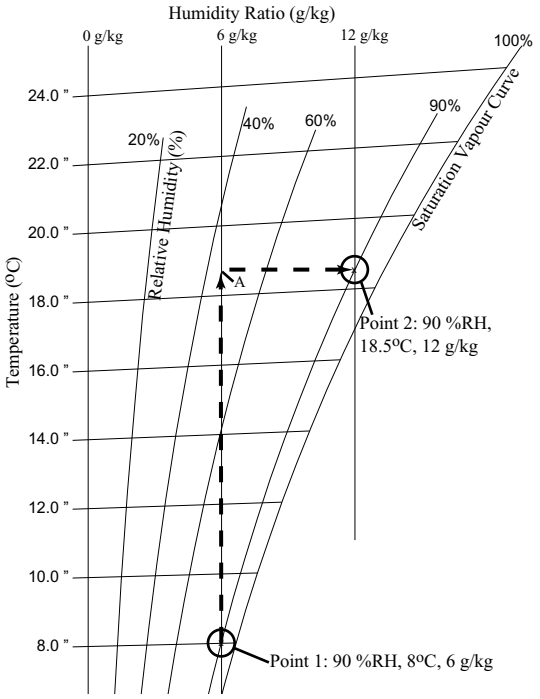

Figure 8.1: Basic psychrometric chart at 101,325 Pa

'Ground zero' or the 0 m for the contour elevation can be taken as mean sea level for an ordinary map, but this '0' mark is arbitrary and it can be raised or lowered as is appropriate for a particular (Martian) site. Correspondingly a change in pressure moves 'ground zero' for a psychrometric chart. Just like a geographic map, measurement at mean sea level is usually taken for what's known as mean atmospheric pressure, 101,325 Pa or 1.013 Bar. In practice what this means is, that a psychrometric chart for someone on a site near the sea uses a different chart than someone on a hill 500 m up, where the air pressure is about 0.9542 Bar. So, first ensure that the psychrometric chart used is appropriate for the (Martian) site elevation or ambient pressure. Note that the pressure *(e.g.*, 101,325 Pa) or height (*e.g.*, 0 m) should be written somewhere on or adjacent on the chart, as shown in the title for Figure 8.1.

Example: Mixing Two Air Masses Together

Now that the concepts of humidity ratio and enthalpy are available, the question of determining the psychrometric properties of mixed air is relatively simple. Consider two bags, each containing one kg of air, with the following properties (RH, temperature, humidity ratio and enthalpy):

1. 90% RH, 8.0°C, 6g/kg, 23 kJ/kg
2. 90% RH, 18.5°C, 12 g/kg, 49 kJ/kg.

Now, connect the two bags together and mix the air up, what are the properties of the resultant mixed air ?

- Is it (90 + 90)/2 = 90% RH
  and (8.0 + 18.5)/2 =13.25°C?
- Or, is it (6 + 12)/2 = 9 g/kg
  and (23 + 49)/2 =36 kJ/kg?

In fact it is 9 g/kg and 36 kJ/kg, and this can be converted to the corresponding values of 97 % RH, 13°C, using a humidity calculator (*e.g.* General Eastern, 1997) or psychrometric chart. If the RH had been 0% in this example, then the mixture would have been dry and the temperature would be as shown in the former calculation, 13.25°C.

It can be seen from this example that there is a big difference in the two RHs calculated (90 and 97%) in this example. This should emphasise the requirement, that when wet air is the subject matter, it is necessary to do calculations using humidity ratio and enthalpy. But where does enthalpy fit in on a psychrometric chart ?

Figure 8.2 shows the chart of Figure 8.1 but with enthalpy data added for the example used, and some lines of constant enthalpy also. These are the parallel diagonal lines of air thermal energy on Figure 8.2 that have been added to the chart shown in Figure 8.1.

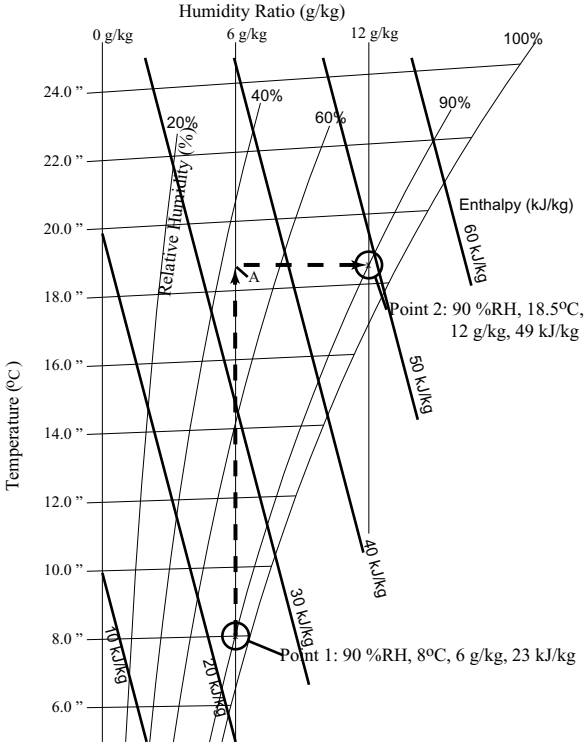

Figure 8.2: Humidity and enthalpy, psychrometric chart at 101,325 Pa

Assuming we can now navigate around a chart, the question now arises as to how we can ‘move’ the air from one point to another. It would seem that some form of ‘engine’ is required to move around the psychrometric chart.

An Air Engine: The Air Handling Unit (AHU)

To affect the state or condition of the humid air that is used for mushroom growth, use is made of the actuators in an air handling unit (AHU). The AHU is like an engine that ‘moves’ air around a psychrometric chart, *i.e.*, it manipulates the heat and moisture of the air.

Normally the effect on air conditioning of the ventilation damper is difficult to define because its effect depends on local outside weather conditions. Mixing of outside (Martian) air with internal air is not currently envisaged in this bioreactor, however, mixing of crew supply air with recirculated or return air from the bioreactor is envisaged. Further discussion of the ventilation damper is described in section 9.

Each actuator in an ideal AHU has one or more ‘services’ that it can provide. These relate to the chart shown in the left part of Figure 8.3.

1. The heater raises air temperature, *i.e.*, getting hotter or moving up the chart.
2. The cooler lowers air temperature, *i.e.*, getting colder or moving down the chart.
3. The humidifier raises air humidity, *i.e.*, getting wetter or moving right on the chart.
4. The dehumidifier lowers air humidity, *i.e.*, getting drier or moving left on the chart.

Using two actuator options together provides a combined service, *e.g.*, heating and humidification makes the air both hotter and wetter. Such combined services are also shown in the left part of Figure 8.3. Unfortunately practical actuator options are such that the ideal desirable range of climate services or vectors is not available. In practice, the vectors shown in the right part of Figure 8.3 more closely represent the services available.

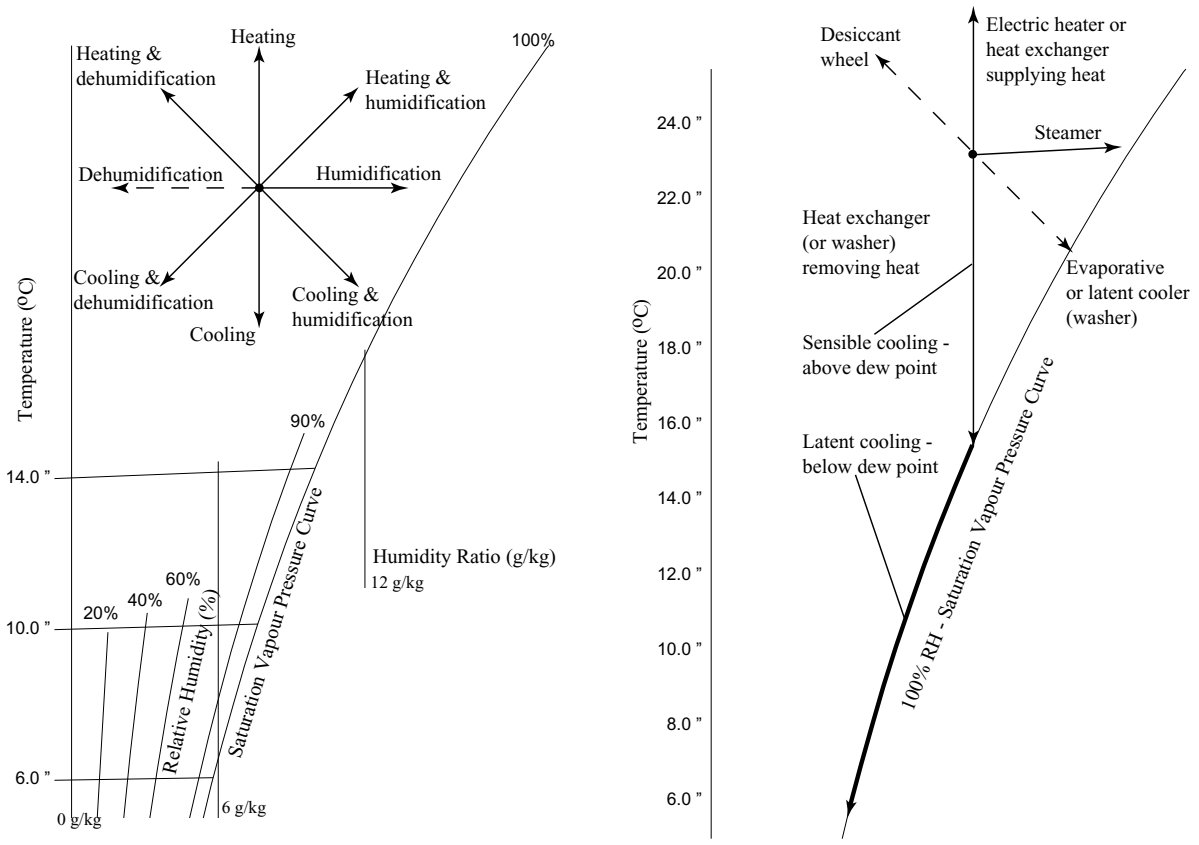

Figure 8.3: Air handling process vectors – **Upper left:** Desired **Right:** Available from actuators

Whilst it would be preferable (from a control perspective) to have an independent means of dehumidification, this is unfortunately "Not practical" (Goodfellow and Tahti, 2001). The generally available actuator options for each of the desired air conditioning processes are listed in Table 8.1.

Table 8.1: Air handling processes and actuator options

Desired conditioning process	**Primary actuator**	**Secondary actuator, requires primary plant**
Humidification only	X	Temperature (T) controlled washer
Dehumidification only	X	X
Heating only	Electric	Heat exchanger (*e.g.* using water or steam)
Cooling only (sensible cooling)	X, see Peltier note below	Heat exchanger (*e.g.* using water or refrigerant) maintained at or above the dew point
Heating and humidification	X	Temperature controlled washer (T >> Tair in) or steamer
Heating and dehumidification	X	Desiccant wheel
Cooling and dehumidification	X, see Peltier note below	Temperature controlled washer (T < Tdew point) or heat exchanger (*e.g.* using water or refrigerant) maintained below the dew point
Cooling and humidification (latent cooling)	X	Temperature controlled washer (T < Tair in)

Note: The Peltier cooling devices generally available are limited to small power capacities, *e.g.* 50 W (ElectraCool, 2002).

It is clear from Table 8.1 that only one service has a primary actuator available and this has implications for control. All other services (and often heating as well) involve a coupling between primary and secondary actuators. For example, to supply heat through a heat exchanger requires a coupling between a heat source, *e.g.* a boiler, and the heat exchanger, each of which typically has a separate control system that may or may not operate in harmony.

Recall from the metabolic equation, Equation (2.1), that the process being controlled is primarily a source of heat, moisture and carbon dioxide. Therefore, for a well sealed reactor, the principal air conditioning services required are the removal of heat and moisture. An evaporative cooler could remove heat from the system but it would unfortunately supply moisture, which is undesirable. Although a desiccant wheel removes moisture it undesirably adds heat. For both these reasons, a cooler (heat exchanger) is a more preferable actuator choice in this application. Furthermore, due to the health implications of poor maintenance (*Legionella*) evaporative coolers are not widely used. In this application, building construction is tight to maintain a closed environment. Hence, an atmospheric sink for the moisture discharge of a desiccant wheel is not readily available and discharge into another compartment is undesirable, due to the increased complexity of inter-compartment coupling. This is also true for other coupling options, *e.g.* "Dry-Kooling" (Drykor, 2001).

Consequently, the air handling unit envisaged is similar to that shown in Figure 8.4, which shows a standard layout for an AHU used in a mushroom tunnel. Note that the AHU shown in Figure 8.4 is non-ideal because the cooler is a multi-function actuator. In addition to cooling the air, it can also dehumidify it through latent cooling.

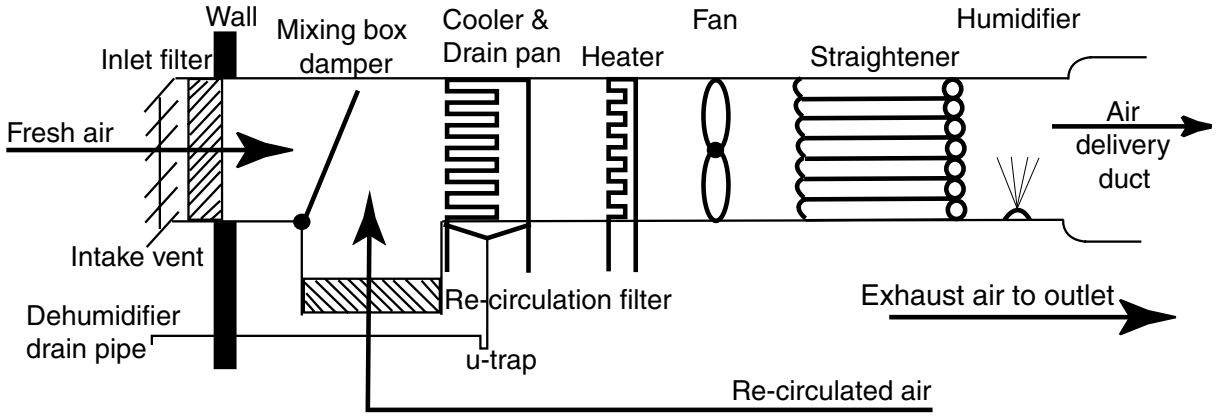

Figure 8.4: Air handling unit layout (also used in Figure 7.2)

9. Ventilation (WP7.3.21)

Compared to air supply for humans, the principal difference required for fungal supply air is the air's condition - it is much wetter. In the Melissa loop, the fungi reactor is planned to co-exist with both higher plant and crew compartments. All of these reactors will require some form of fresh air. In the closed environment of the full loop, fresh air is anticipated as amounting to re-processed air. Re-processed air is foreseen as been oxygenated and cleaned return air, perhaps through some Sabatier and/or scrubbing processes (Davis, 2000).

Therefore, it is assumed that a shared central plant will exist to provide fresh air for both the crew compartments and fungi reactor. Consequently, ventilation for the fungi reactor is assumed to consist of a standard mixing box and damper, as shown in Figure 8.4. However, the intake vent that is normally open to outside air is in this case open to the supply air to the crew compartment. It is also assumed that exhaust air, *i.e.*, return air that is not used as re-circulated air in the mixing box, is returned to the central fresh air plant

(after being filtered for pathogens). The characteristic of the damper(s) in the mixing box is dependent not only on the mixing box itself, but it is also dependent on the complete air handling unit configuration. An example of such a characteristic is provided by Martin *et al*. (2002).

In summary, it is assumed that the function of the air handling unit (AHU) used for the fungi reactor is to condition the air, and that ventilation process requirements are met in a separate central fresh air plant. This assumption is analogous to the situation where a terminal unit is used for individual zone control in a variable air volume (VAV) system.

10. Reactor feedback and climate measurement (WP7.3.23)

Reactor and Metabolic Feedback Option Indicator Summary
The range of climate variables that require to be sensed is summarised in Table 10.1. Note that some variables listed require to be sensed continuously, whereas some are only monitored during commissioning.

Table 10.1: Climate and reactor status variables and feedback indication mechanisms

Climate variable	Direct sensing or measurement	Indirect sensing or calculation
Temperature	Thermometer	
Humidity ratio	X	Hygrometer (dewpoint, RH), Thermometer, Barometer
Enthalpy	X	Hygrometer (dewpoint, RH), Thermometer, Barometer
Density	X	Hygrometer (dewpoint, RH), Thermometer, Barometer
Pressure	Barometer	
Airspeed	Anemometer	
Drying condition	X	As for humidity ratio with addition of airspeed
Archimedes number	X	As for density for both supply and zone air with addition of airspeed
Oxygen	X	Various sensing techniques, *e.g*. paramagnetic, spectrophotometric
Contamination as indicated by carbon dioxide	X	Infra-red spectrophotometer measures absorption of light by gas, often generalised as Infra Red Gas Analyser (IRGA)
Ventilation rate as indicated by tracer gas	X	Differential measurement using IRGA analyser(s) with no spurious sources of tracer gas
Leakage rate as indicated by tracer gas	X	Differential measurement with no spurious sources of tracer (reactor commissioning/maintenance)
Leakage detection external & inter-zonal	Barometers/ smoke	Differential pressure measurement provides indication of infiltration flow direction (reactor commissioning/maintenance)

Reactor Status – Choice of Feedback Variable

Recall the metabolic Equation (2.1), noting that the compost supplies the carbohydrate source, and consider the following three scenarios, shown in Figures 10.1 to 10.3. The first scenario is equivalent to an empty reactor and is useful for instrumentation calibration purposes.

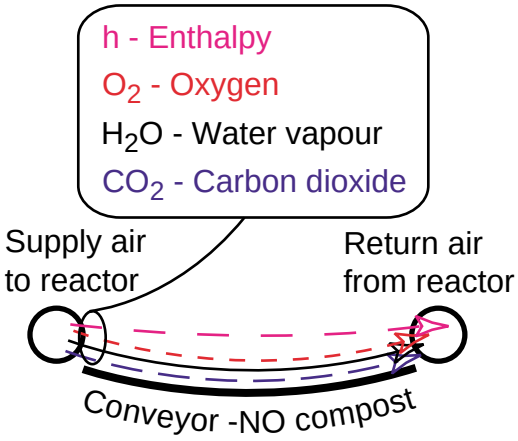

Figure 10.1: Scenario 1, empty reactor in adiabatic steady state with no reactor out-gassing, supply and return air states are equal – useful for calibration of instrumentation

In the second scenario where sterile wet compost is present, note that evaporation changes enthalpy and water vapour state variable status, therefore an alternative indicator to water vapour state, for metabolic activity is required.

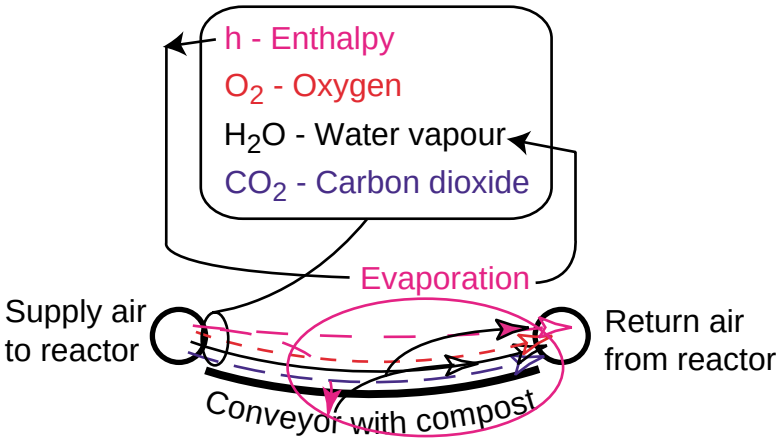

Figure 10.2: Scenario 2, reactor with sterile compost but no fungal metabolism, evaporation of water from compost to air requires a source of thermal energy from supply air and sinks evaporated water vapour into return air

In the third scenario, to prevent metabolism being constrained by oxygen supply an over-abundant supply is recommended, hence the residual oxygen content in the return air biases the change in status of this state variable. As it is assumed that the content of carbon dioxide in the supply or fresh air is low, the bias from the supply air is less in the case of carbon dioxide, which is a by-product of fungal metabolism. Therefore, as the same number of molecules for both oxygen and carbon dioxide are consumed/produced by metabolic activity, carbon dioxide is recommended as an indicator of metabolic activity in the reactor.

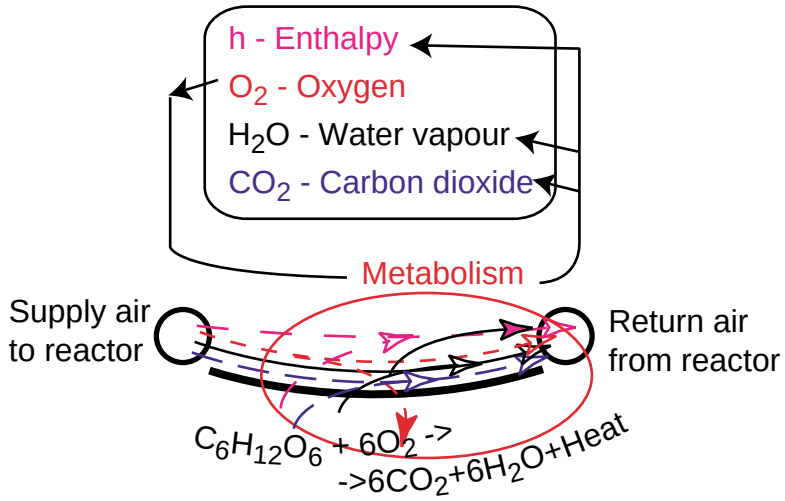

Figure 10.3: Scenario 3, reactor with compost and fungal metabolism, evaporation of water as per scenario 2 (omitted for simplicity), plus fungal metabolism requires oxygen from supply air and sinks metabolised heat, carbon dioxide and water vapour into return air

11. Climate control (WP7.3.21) (WP7.3.22)

As indicated by Equation (2.1), the metabolism of a heterotrophic mushroom fungus more closely resembles that of mammalian respiration or metabolism than that of the autotrophic photosynthesis that is predominant in greenhouses. This resemblance implies that general air conditioning principles used for human building design and modelling are relevant in this application. Also, in the world of indoor or protected intensive cultivation another type of indoor space is of interest, a livestock house. For a well sealed reactor, from an air handling perspective the commonality identified is that the principle functions required are twofold.

- For metabolic inputs, the function of the air handling unit is to provide a source of oxygen.
- For metabolic outputs, the function of the air handling unit is to provide a sink for the heat, moisture and contaminants, principally carbon dioxide.

This metabolic perspective implies that a number of climate variables need to be controlled, namely: oxygen (*O*), temperature (*T*), water vapour (*W*), and contamination (*C*). Furthermore, from an engineering perspective, to ensure that the conditioned air reaches the breathing zone of the fungus in a solid-state reactor, the ratio between the thermal and inertial forces of the supply air, in the form of its Archimedes number (*A*), introduced in the air distribution section, is another climate variable. Finally, and especially if fungal fructification is required, the drying condition of the air needs to be controlled, hence, the air velocity (*U*) in the breathing zone is also a climate variable. In summary, control of the following climate variables is required: ***W A T U C O***.

In a traditional open system, the supply of oxygen and sink of contaminants are related through the ventilation rate by the metabolic reaction. Consequently, control of a single variable, the ventilation rate (*V*), satisfies climate requirements from both these variables, but, in the closed system under discussion, this may not necessarily be the case. Hence, it is recommended that both of these climate variables are retained.

Climate Variable Hierarchy

1. Despite its general lack of use in practice, it is suggested that ensuring that the supply air reaches the breathing zone (***A***) is the most important function of a climate control system, considering that perfect

supply air floating above the breathing zone could lead to low metabolic activity and consequently to reduced enzymatic activity.

2. Widely successfully in practice, it is suggested that ensuring that the supply air is warm enough (***T***) is next most important because of the necessity for a thermal energy supply to support metabolic activity. Equally important from this metabolic input perspective is the supply of metabolic reactant (***O***).

3. Less effectively used in practice, it is suggested that next in priority is ensuring that the supply air is wet enough (***W***). This is because if the air is too wet, drying conditions are poor and condensation can occur, thus facilitating growth conditions for pathogens. Conversely, if the air is too dry then the air's condition may fall outside the range suitable to sustain fungal growth.

4. Although not widely used in practice, it is suggested that next in priority is ensuring that the supply air is dry enough, drying conditions are affected by airspeed (***U***). If drying conditions are poor, condensation can occur, thus facilitating growth conditions for pathogens. If the air is overly dry, then the substrate's condition may fall outside the moisture range suitable to sustain fungal growth.

5. Also widely used in practice, it is suggested that last in priority is ensuring that the supply air is fresh enough (***C***). This is because if contaminant conditions are poor, gas exchange between the substrate and air may be inhibited with a consequential change in enzymatic production. Furthermore, the level of contaminantion affects mushroom morphology.

Review of Climate Models for Control Development

Note that there seems to be a common misconception that climate control and modelling for mushroom growth is similar to that for plant growth in greenhouses. For example, the following quote from Meath (1993) is used to illustrate the potential for climate misunderstanding: "A mushroom growing tunnel is essentially a greenhouse with an insulated, non-transparent cladding. The main processes of heat, moisture, and carbon dioxide transfer between the inside air, the crop, the soil, and the cladding are similar."

In this author's opinion, the details of heat transfer (conduction, convection, and radiation) are quite different in both applications, as are the metabolic reactions of the crop being grown and the ventilation system used in each of the building types. The issues are listed as follows:

1. Conduction: the thermal characteristics of the mushroom tunnel and greenhouse buildings are very dissimilar. A greenhouse has walls and roof of thermally conductive glass, and a floor of thermally conductive soil, whereas a mushroom tunnel has walls and roof of well insulated polyethylene and relatively well insulated concrete, so heat transfer by conduction is dissimilar.

2. Convection: air movement in a greenhouse is generally by natural convection, whereas in a mushroom tunnel air movement is predominantly by forced convection, so heat transfer by convection is dissimilar.

3. Radiation: any internal source of radiation is mainly reflected in a mushroom tunnel, due to the internal white (polyethylene) walls and roof, whereas it can escape (or enter) through the glass of a greenhouse, so heat transfer by radiation is also dissimilar.

4. Crop metabolism: the dominant crop metabolic reactions of concern in a greenhouse are photosynthesis and evapotranspiration, whereas in mushroom growth the metabolic reaction is similar to that of mammalian respiration. Consequently, in greenhouses ventilation is used as a source of carbon dioxide, whereas, in mushroom growth ventilation is used to provide a sink for carbon dioxide.

5. Ventilation system: the main process by which heat, water vapour, and carbon dioxide exchange occur is via the air distribution system. In greenhouses, air circulation is generally by natural ventilation, whereas in mushroom tunnels it is primarily by mechanical ventilation.

The underlying physical principles necessary to formulate a mathematical energy and mass balance model are summarised by Albright in his 1990 text, but this text does not include mushroom growth in its applications domain. Consequently the formulation of available mathematical energy and mass balance models for mushroom growth has generally been a specialised, and often academic, exercise. In the absence (Loeffen, 1999) of appropriate Dutch mushroom climate models, previous Irish models of mushroom climate may be regarded as the rational starting point for any mushroom tunnel climate model development. This is the case for energy and mass balance (white-box) models, grey box (Martin, 2002) and also for black-box models (Martin *et al*.,1997).

Review of Mushroom Climate Control

The years following the Second World War saw the development of the tray system (sometimes the trays were made of old ammunition boxes) of production in the U.K., as opposed to the shelf system which preceded it. It is suggested that the main reason for the move to a higher capital investment system was due to the increased productivity, with approximately 50% more cropping surface on trays than shelves. Along with the increased productivity came a specialisation and division of building functionality, as this appears to have been the era when composting and mushroom growth were separated, *i.e*., prior to this both operations were conducted in the same building. Hence, this would appear to be a good starting point to describe the origin of modern cultivation techniques and the associated climate control requirements, which are quite different for both phases of mushroom growth.

Naturally the shift from the shelf system to the tray system, led to the introduction of new texts, *e.g*., Pinkerton (1954). While his description, quoted at the start of section 3 may be exaggerated, it at least emphasises the relative difficulty of commercial mushroom production, *vis-à-vis* the production of other crops. Perhaps this is because of the problem of disease, the dominant topic of his book, and which is still the dominant topic of mushroom conferences today. Nonetheless, as with other crops, technology has helped increase productivity: Pinkerton's (1954) estimate of "... total time for the crop five to ten months", has shrunk to around five to ten weeks.

As a founder member of the U.K. Mushroom Growers Association, Atkins (1950; 1958; 1974) was well placed to describe the then prevalent climate control technology. However, the control and air handling system described are now outmoded. His observation (1958) "Without this evaporation you should not expect high yields." is still valid today, but to the knowledge of this author it is still the case that no commercial control system either logs or controls evaporation. In acknowledging his predecessors, Atkins (1974) reference to Kligman's (1942) book as the "... best textbook on mushroom growing ever written ..." is in the context of a system that is also outmoded. Also outmoded is Schroeder's (1968) description of the design of an air handling unit to meet conditions in the United States. Similarly dated is Lehman and Schroeder's (1971) description of the evaluation and modelling (using an analog computer) of a proportional controller for composting.

Developments in the period 1972-'79 generally focussed on individual elements of climate control, and the first Dutch mushroom growth reference book (Vedder, 1978) appeared. Coates-Smith (1972) discussed the merits of using mobile cooling and noted its effect on humidity levels. In summer the cooler was used for temperature control, and for autumn, it was used for humidity control. In a fine article, Edwards (1973a; 1973b) assembled the state of the art knowledge of the time. Evaporation is discussed qualitatively but not quantitatively. The importance of filtration is highlighted. The introduction concisely describes the requirements on a climate control system. Schroeder *et al*. (1974) described set-point control of CO_2 by ventilation damper actuation for both a high (spawn-run) and low (pinning) set point. Energy savings by not over-ventilating are noted. Edwards (1976) discussed the economic impact of regulating fresh air by on/off control of the fan rather than by damper control. In Vedder's book (1978) the elements of the air handling unit were discussed but only a passing reference is made to control in the form of thermostatic control of the heater. Van Soest (1979) noted the ventilation requirement for natural cooling as a function of compost temperature (20% increase in air change rate per °C increase in temperature above 16°C). However, no connection is made with external air temperature.

The eighties are notable for the publication of the first U.S. mushroom growth handbook (Wuest and Bengtson, 1982), the finer level of detail expounded in the second Dutch mushroom growth reference book (van Griensven, 1988), attempts at partial integrated control, and a realisation of the complexity of the climate control task in this application.

Wuest and Royse (1982) discussed the primary importance of compost temperature control and noted a relation between heat transfer and compost water content. They cautioned that compost with "less than 63 percent water at spawning is unlikely to be controllable". They noted the three prongs of temperature control used to keep the compost cool: air volume, air temperature, and air humidity (evaporative cooling).

Burrage and Noble (1987) described a BBC-micro based controller and used flow-charts to explain their control algorithm. Control was damper focussed. Good climate regulation was not achieved. Following this, Burrage et al. (1988) used two-stage on/off control for heating and RH control, with proportional band and set limits for CO_2. Control performance was maintained within the established optimal growth limits. Dehumidification was omitted in case the control algorithm became unstable. Carbon dioxide control could be improved by the use of an analyser in each tunnel or a higher sampling rate than that used (12 minutes).

In the second Dutch book (van Griensven, 1988), Arkenbout drew from previous work (Arkenbout, 1985) and dealt thoroughly with the physics of climate control for mushroom growth on a case study basis with extensive use of Mollier (psychrometric) diagrams and discussed the air handling unit. However, climate control *per se* and control of the air handling unit was omitted in this otherwise extensive treatment. Bowman (1989) discussed means by which air distribution may be improved for the tray system of production using low-level ducts, thus providing a basis of acceptability for using a perfectly stirred tank model for control. In his rework (1989) of Edwards (1978) evaporation study, he mentioned the undesirable effect of on/off temperature fluctuations to emphasise the need for good control. In an energy saving vein, Dean (1989) described the benefits of using a heat pump for environmental control in mushroom growing. It was claimed that the heat pump provided full control of heat, CO_2 and one-way control of RH. Typical U-values were given.

Lamber (1989) noted the passing of a decade of climate computer use in the Netherlands and provided a general discussion of computer benefits in this application. His comment on climate,

"an accurate manual or electronic control is almost impossible"

is perhaps still appropriate today. Although evaporative climate control was introduced as the latest Dutch development, the water mass balance research to facilitate such control remains to be done (Loeffen, 1999).

The decade of 1990-'99 was notable for its absence of significant commercial development, major developments in composting, further research that partially integrated climate control, and Irish progress to satisfy the requirement for integrated climate control.

Robins (1990) described the elements required in the design of a climate controller. Moving from this requirement stage, Burrage (1991), discussed the inter-relatedness of the three control objectives, quantified the effect of variation in temperature control on humidity (0.5°C is approximately a change of 4% RH) and stressed the importance of gradual change.

The major climate control equipment manufacturers have all described their climate control approach, where proportional integral (PI) control is the most complex form of control used, (AEM, 1991; Agrisystems, 1991; (Zentronics) Emmett, 1991; Fancom, 1993). Multivariable control was not discussed. Still in a commercial vein, Lamber (1991) identified the climate components: temperature, humidity, airflow, CO_2, and, oxygen, as determining factors. For climate control; monitoring of air and compost temperature, humidity, CO_2, air volume and ammonia content in exhaust air was considered. It was proposed that control of evaporation is the key to optimal growth, hence accurate air volume and humidity measurement for mass balance calculation is necessary.

In the context of environmental control, Gulliver *et al*. (1991) deals with the control of composting to meet odour emission levels. Composting was also the focus of the work of Harper *et al*. (1992), who described a large-scale environmental chamber and the control of composting experiments, but using a different air handling set-up. The controlled variables were temperature (rapid initial increase) and oxygen (limits combustion/metabolism), controlled indirectly via airflow.

Loeffen (1992; 1993) addressed the issue of air distribution in Dutch houses and measured the rate of leakage, using decay rate measurements of a tracer gas as a function of re-circulation rate, but did not relate air change rate to vent position. Addressing a different form of leakage - that of energy, Carlier and Zwart (1994) included the use of a climate computer as a mushroom energy saving possibility.

Singh et al. (1994) described an integrated control system for temperature and relative humidity control in *Volvariella volvacea* mushroom growth. Air quality and light intensity were deliberately omitted from the integrated control strategy. On/off control was used in the case study of eight climate (temperature and RH only) scenarios. The controller was used in an experimental house in Bangkok. No quantitative control performance results were given. Also in the same geographical region, Hui *et al*. (1998), introduced an unvalidated and unspecified fuzzy controller.

Irish research interest began with the work of Hayes (1991), who presented an initial computer model for control evaluation that agreed closely with the greenhouse climate control approach taken by Udink ten Cate (1983), but presented no control results. A student of Hayes, Meath (1993) presented a simulation of on/off and proportional control strategies of air temperature. Evaporative cooling and condensation were not accounted for in the model. Validation of the model was not extended to the full size tunnel in Teagasc. A summary of the computer model was described by Hayes and Meath (1994) but is expounded in greater detail in the M.Sc. thesis of Meath (1993). Subsequent to this work, Murray's M.Eng. Sc. Thesis (1995) described the environmental control system developed for the experimental tunnels in Teagasc. A detailed model of airflow was not developed. Temperature and humidity time constants were modelled and measured, and found to be slow with the author suggesting a sampling interval of 1-5 minutes as adequate. The model developed (temperature, humidity, and carbon dioxide) was analysed and found to be non-linear.

Murray's (1995) control design assumed that all states are available, *i.e*., sensors are available to measure the states of interest, hence the design problem revolves around the formulation of a control law for the controller in the feedback system, *i.e.*, no state estimator is required in the design. The control law structure that Murray used was that of a regulator. He used optimal control to specify the feedback gains required for the control law matrix. The control design used linearisation around an operating point. An optimal control law was established and then the plant limitations (on/off characteristics) accounted for before the law was adapted and implemented for a digital pulse width modulator (PWM) thermal on/off controller.

Corcoran (Murray's supervisor) and Grant (1997) described the state-space controller of Murray (1995) and noted that: “The difficulty which growers face is that the only automatic control available is thermostat on/off temperature control. The fan, damper and steamer are then manually adjusted to regulate the humidity and carbon dioxide levels”.

In a commercial context the Irish firm Climator (1996) describe patented moving coil technology for a heat pump application in mushroom growth that reduced the air pressure losses associated with the cooler coil when not in use.

Most recently, Martin (2002) developed a model predictive controller (MPC) for contamination control using carbon dioxide as a controlled variable and a hierarchical rule-based controller for the three main climate variables: temperature, humidity and contamination. The MPC controller affected the rate of dilution ventilation via the ventilation damper, whose characteristic was described by Martin *et al*. (2002). Predictive parametric control, which is a variant of predictive functional control, was used to control the non-linear characteristic of the damper.

Brief Review of Other Climate Control Strategies
The author is unaware of any climate control strategies that focus on fungal, as opposed to mushroom, development *per se*, hence no supplement to the review of the previous section is appropriate in this context.

Although dissimilar in climate requirements, the literature for greenhouse climate control is rich in the variety of control strategies that have been attempted. A more thorough review of this subject is available in Martin (2002). Note that one relatively recent summary of the state of the art in plant climate control on earth and in space was provided by Albright *et al*. in 2001. From a control perspective, this review showed that arguably nothing more technically advanced than a MPC strategy was used for climate control.

Despite its popularity as a research objective for both academic and commercial organisations, it would appear that the range of single-zone model and control strategy approaches used is more extensively covered by greenhouse applications than by human building applications. A brief review of this subject is available in Martin (2002). Note that one relatively recent paper indicates the state of the art in this field of commercial climate control applications. The paper of Salisbury (2002) shows that the dominant control strategy used in practice is some variant of proportional-integral (PI) and/or pulse width modulation (PWM) for on/off actuators.

11.1 Climate model used for control development
The following model development is based on an adaptation and extension of the one described in Martin (2002) using the principle of balance in a zone, *i.e*. the change in the energy or mass stored in the zone air is the difference between the energy or mass leaving, and the energy or mass entering the zone.

Note that the dynamics of the reactor air constitute a process. A complex process or system can usually be modelled by an agglomeration of simpler sub-systems. In this case, the sub-systems used to model the process may be divided into two types, those that relate to mass and those that relate to energy. The process sub-systems are discussed individually under these designations, in that order.

Mass Balance Process - Contamination
Figure 11.1 is a diagram of the factors that contribute to the contamination mass balance for the reactor.

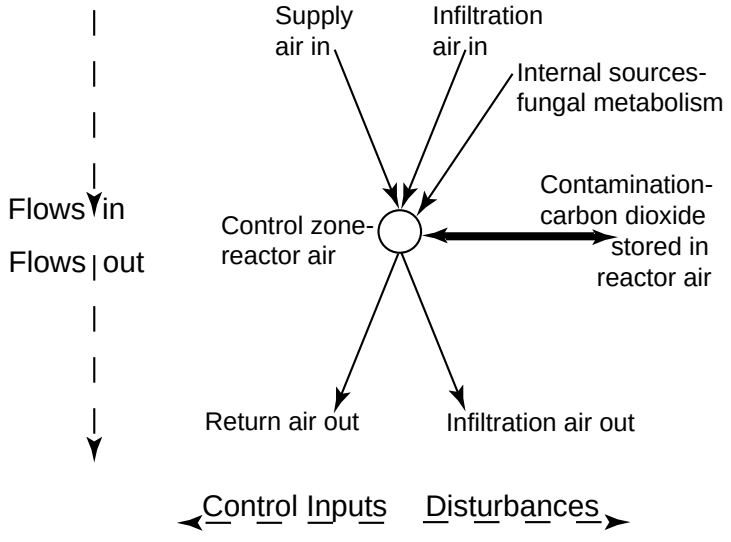

Figure 11.1: Contamination / CO_2 mass flow balance for zone air with fungus in steady state condition

For infiltration and ventilation, a flow of supply air into the reactor dilutes the contaminants inside. Therefore, by displacement, a flow of supply air into the reactor corresponds to a flow of contaminant from the reactor in the return air. From the internal sources, *e.g*., crop metabolism, it is assumed that there is only a flow of contaminant into the reactor. Note that in this diagram, any contaminant flow from other internal sources, *e.g*., occasional crew access, is incorporated with the flow of this source.

Mass Balance Process – Water Vapour

In a similar development to Figure 11.1, it can be seen that Figure 11.2 is a diagram of the factors that contribute to the water vapour mass balance for the reactor, with the addition of evaporation and condensation.

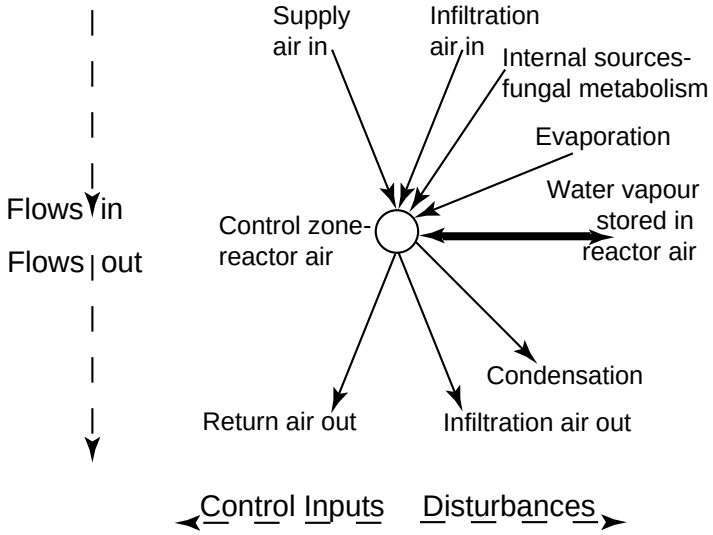

Figure 11.2: Water vapour mass flow balance for zone air with fungus in steady state condition

Mass Balance Process – Oxygen

In a similar development to Figure 11.1, it can be seen that Figure 11.3 is a diagram of the factors that contribute to the oxygen mass balance for the reactor, but in this case metabolism is a sink as opposed to the source in the contamination case.

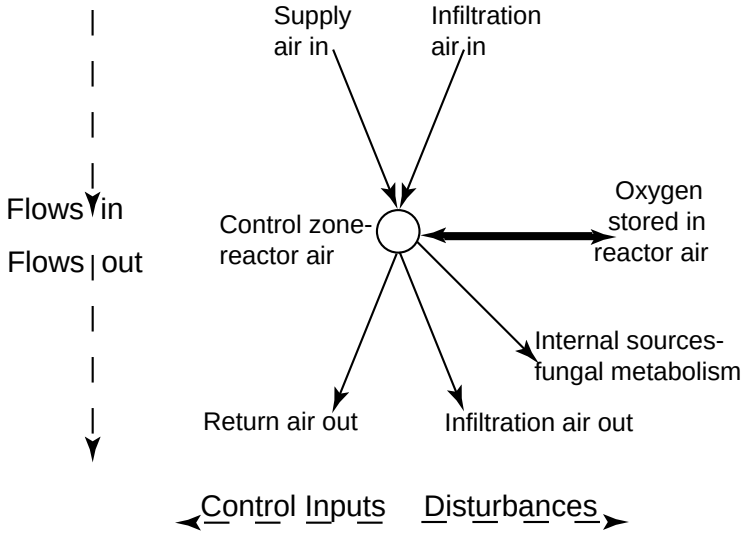

Figure 11.3: Oxygen mass flow balance for zone air with fungus in steady state condition

Energy Balance Process – Thermal

In a similar development to Figure 11.2, it can be seen that Figure 11.4 is a simplified diagram of the factors that contribute to the enthalpy balance for the reactor, with the addition of heat exchange to or from the reactor fabric.

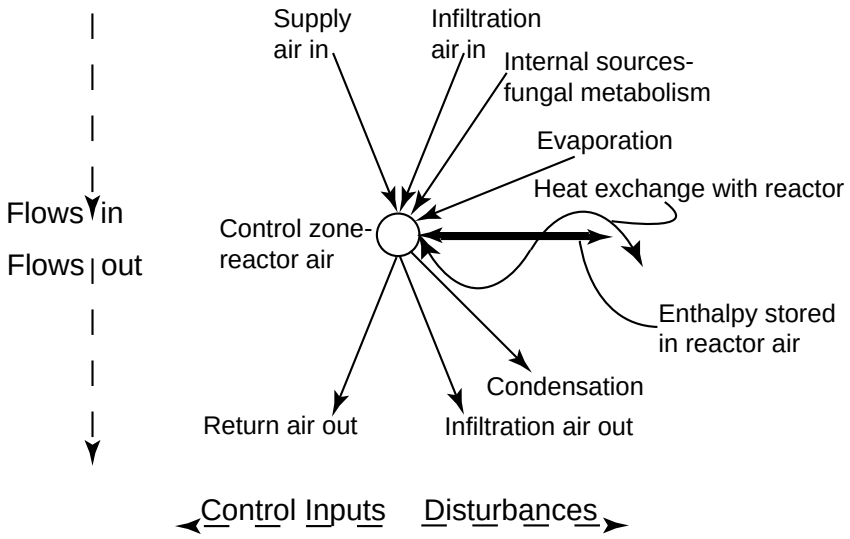

Figure 11.4: Simplified thermal energy flow balance for zone air with fungus in steady state condition

Energy Balance Process – Kinetic/Buoyancy

The preceding energy and mass balance processes use an assumption that the air in the reactor can be characterised using lumped parameters, *i.e.*, there is no significant spatial variation in the air's climate. For anything other than a very small space, this assumption is invalid in the case of the effect of kinetic and buoyancy forces.

It can be seen from the flow lines shown in Figure 11.5 that the supply air will float up, following a curved trajectory (Etheridge and Sandberg, 1996), if its density is lower than that of the reactor's zone air. Conversely, if the supply air's density is greater than that of the reactor's zone air, the supply air will sink, again following a curved trajectory.

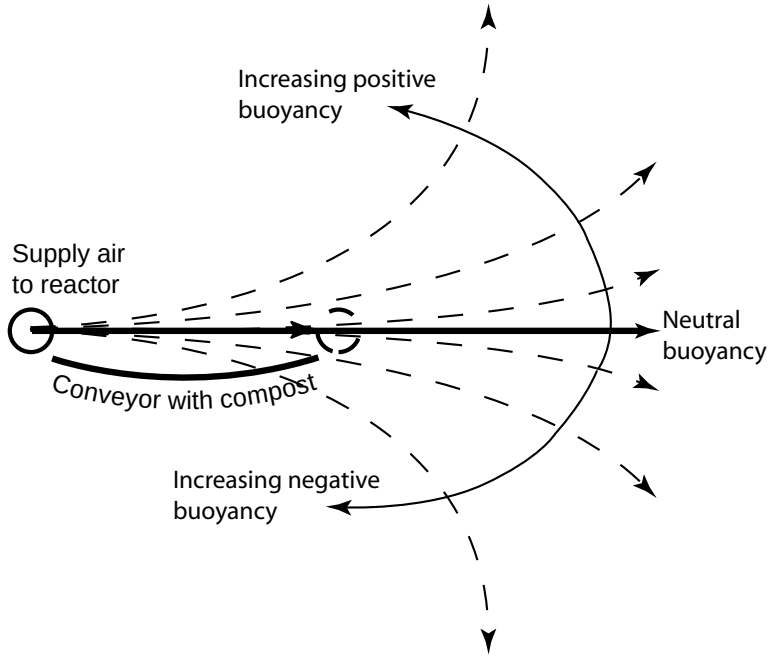

Figure 11.5: Potential trajectories for a range of kinetic/buoyancy energy balances; simplified for an infinite zone by omitting the effect of mixing, turbulence, physical fixtures and the Coanda effect

The neutral, float, or sink trajectory followed by the supply air is dependent on the ratio of inertia to buoyancy forces. For supply air delivered to an infinite zone, the case where the inertia is fixed and

buoyancy varies is shown in Figure 11.5, but simplified to omit the effect of mixing, turbulence, and physical fixtures, *etc.* If the Reynold's number is low enough, the supply airflow can be considered as laminar and turbulence can be ignored, and this is the assumption used here. Under these conditions the only other major consideration is the effect of physical fixtures and this requires an understanding of the Coanda effect (Tritton, 1977).

When a fluid impacts a solid surface there are conditions when the fluid will attach to the surface as opposed to rebounding from it (recall the example of a water jet from a tap being moved by the back of a spoon). The Coanda effect describes the conditions where a jet of fluid is attached to a surface. Note that a jet can become detached from a surface when it encounters a physical fixture, but that it could then re-attach to the surface at another point or be re-directed elsewhere. Such form of re-direction is exactly the desired effect of using the blade deflectors shown in Figure 6.4.

Minimisation of the use of ducting is important from a de-contamination perspective. The Coanda effect can be used to great benefit in minimising the use of ducting. This is important in reactor design due to the potential for an outbreak of disease. It is difficult to speculate as to potential sources of disease in the Melissa loop, but it is suggested that a design that facilitates de-contamination after a disease outbreak is to be favoured compared to one where de-contamination is difficult. (In this context it may be appropriate to recall the de-contamination difficulties encountered in many countries in the 1970-80's after outbreaks of sick-building-syndrome.) Consequently, open surfaces are to be preferred to closed ducts. This suggests using the compost as a carrier surface for the airflow across it, as shown in Figure 11.6.

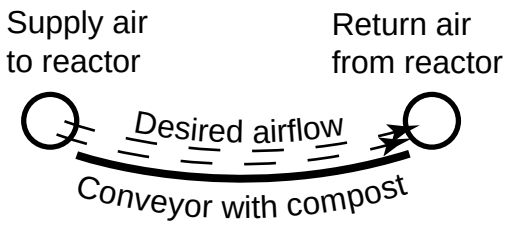

Figure 11.6: Desired airflow path using the Coanda effect

11.2 Climate model equation format

The following model equation is based on the one described in Martin (2002), expanded in more detail in Appendix A, using the illustrative models introduced previously, using contamination/carbon dioxide as an example for mass balance. Similar forms for: oxygen, humidity ratio and enthalpy (simplified to omit heat exchange with the reactor) can be obtained by an appropriate substitution of variables.

$$\frac{dc_z}{dt} = v\left(\frac{\rho_z}{\rho_s}c_s - c_z\right) + \frac{\Phi_z}{V_z\rho_z} \tag{11.1}$$

where,

c_z is the zone air's contamination/carbon dioxide, kg/kg
v is the ventilation, or air change, rate, s^{-1}
ρ_z is the zone air's density, kg/m^3
ρ_s is the supply air's density, kg/m^3
c_s is the supply air's contamination/carbon dioxide, kg/kg
Φ_z is the zone source rate of contamination/carbon dioxide, kg/s
V_z is the zone air's volume, m^3

11.3 Climate control equation format

The following control equation summary is based on the development described in Martin (2002) using Equation (11.1) as a model for contamination as an example. Just as is the case with terrestrial applications,

it is assumed that the contamination level in the supply air is not capable of being altered using the reactor's air handling unit. Therefore, the only variable that can be controlled in Equation (11.1) is the ventilation rate, *v*. Controlling this variable affects the amount of fresh air used to dilute the contaminants in the reactor zone's air, thus indirectly affecting the desired controlled variable, the zone air's contamination, c_z.

Unfortunately because the system's time constant, τ, is related to the reciprocal of the ventilation rate, *v*, any control scheme that affects this variable also affects the structure of the system. Such a form of control is unusual, as normally it is a state of the system that is controlled. A model predictive control scheme, parametric predictive control (PPC), was developed by Richalet (1997) for precisely this application. Unfortunately, when used by itself this control scheme introduces a bias. The bias can be removed by the use of a standard predictive functional controller (PFC) in cascade with the PPC. A block diagram showing such a cascaded control loop architecture is shown in Figure 11.7

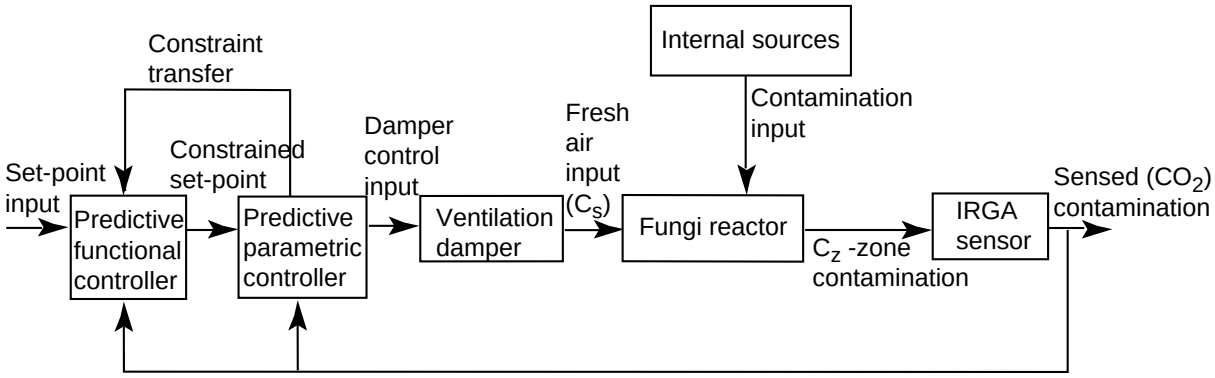

Figure 11.7: Block diagram of contamination control system, showing cascaded control loop structure

The following PPC control Equations (11.2)-(11.4) are based on the development described in Martin (2002), for the contamination model introduced in the previous section, as an example.

$$\tau = \frac{-t_s}{\ln \alpha(n)} \tag{11.2}$$

where,

τ is the time constant of the system, s
t is the sampling time interval of the control system, s
α is a parameter affecting the system's inertia, calculated using Equation (11.3)
n is (now) the current calculation under iteration by the algorithm

$$\alpha(n) = \frac{(c_{csp}(n) - c_z(n))(1 - \lambda_{ppc}) + c_z(n) - U_c(n)}{c_z(n) - U_c(n)} \tag{11.3}$$

where,

α is a parameter affecting the system's inertia, used in Equation (11.2)
c_{csp} is the zone air's contamination/carbon dioxide constrained set point, kg/kg
c_z is the zone air's contamination/carbon dioxide, kg/kg
λ_{ppc} is the controller's "aggressiveness"
U_c is a parameter describing the system's contamination input (both supply and internal sources), calculated using Equation (11.4)
n is (now) the current calculation under iteration by the algorithm

$$U_c(n) = \frac{\rho_s(n)}{\rho_z(n)} c_s \tag{11.4}$$

where,

U_c is a parameter describing the system's contamination input (both supply and internal sources), used in Equation (11.3)
ρ_s is the supply air's density, kg/m^3
ρ_z is the zone air's density, kg/m^3
c_s is the supply air's contamination/carbon dioxide, kg/kg
n is (now) the current calculation under iteration by the algorithm

Note that Equation (11.3) is subject to three constraints:

1. $c_z(n) > U_c(n)$
2. $(c_{csp}(n) - c_z(n))(1 - \lambda_{ppc}) + c_z(n) - U_c(n) > 0$
3. $(c_{csp}(n) - c_z(n))(1 - \lambda_{ppc}) + c_z(n) - U_c(n) < c_z(n) - U_c(n)$

The first constraint expresses the statement that no ventilation should occur if the supply air is more contaminated than the zone air. The second constraint avoids a zero or negative numerator, and the third constraint limits the range of α to lie between 0 and 1. The constrained set point, c_{csp}, that is derived using these constraints is then passed to the PFC controller, after the PPC has completed its iteration, where it is used to maintain alignment between the PFC's model of the system and its expected status.

The following predictive functional control (PFC) control Equation (11.5) is based on the development described in Martin (2002), for the contamination model introduced in the previous section, as an example.

$$c_{csp}(n) = \frac{(c_{sp}(n) - c_z(n))(1 - \lambda_{pfc}) + c_{mpfc}(n)(1 - \alpha_{mpfc})}{k(1 - \alpha_{mpfc})} \tag{11.5}$$

where,

c_{csp} is the zone air's contamination/carbon dioxide PPC constrained set point, kg/kg
c_{sp} is the zone air's contamination/carbon dioxide set point, kg/kg
c_z is the zone air's contamination/carbon dioxide, kg/kg
λ_{pfc} is the controller's "aggressiveness"
c_{mpfc} is a parameter describing the system's modelled contamination/carbon dioxide, kg/kg,
α_{mpfc} is a parameter affecting the system's modelled inertia,
k is a parameter describing the system's gain
n is (now) the current calculation under iteration by the algorithm

12. Overall reactor summary, size and scaling issues (WP7.3.23)

The default standard configuration for a solid-state fermenter has generally been a tower or stirred tank reactor, and these configurations have been applied to many specific problems. For example, construction details of a stirred tank fermenter for filamentous fungi have been available since at least 1978 (Kristiansen and Sinclair, 1980). The requirement to facilitate oxygen transfer through enhanced gas exchange has been recognised since the mid-1970's. In this regard, Kristiansen and Sinclair (1980) provide a brief review of "new fermenter configurations" to promote gas exchange, including: thin channel, tubular loop, film, circular ring, and rotating disc types. In a lignin-degradation context, Zadrazil (2000) provides a summary review of reactor research status and the issue of reactor scale-up, and concludes that further research is required on several process aspects, particularly air conditioning control. Conversely, Soares and Correia (2000) address the issue of scale-down, to micro-chip levels "Bioreactor-on-a-chip", in the context of process sampling. However, none of these reviews make explicit the implicit design objective inherent in "new" designs, namely a configuration that has a **high surface to volume ratio**.

The belt configuration shown in Figure 6.7 falls into the high surface to volume configuration category. Essentially, the configuration shown in Figure 6.7 is the linear counterpart to a rotating table configuration.

Alternatively the configuration shown in Figure 6.7 could be considered as a moving film configuration. In either case, a major benefit of the configuration shown in Figure 6.7 is that it facilitates the **provision of multiple climate zones**.

Although auxiliary variables, such as pH, are sometimes used as controlled variables in fungal bio-reactors (*e.g*. brewing), a distinguishing feature of the reactor proposed here is that it is intended for use with a solid-state substrate. Consequently, except for indirect thermal control of the substrate, it is foreseen that the **physio-chemical state of the substrate is not directly controlled**.

The climate control requirements for a reactor are highly dependent on whether the function of the reactor is to grow mushrooms or to grow a fungus. For example, the growth of mushrooms requires the provision of multiple climate zones, whereas this requirement has not been identified as being essential for fungal growth. Furthermore, the control requirements for mushroom growth are more extensive and difficult to achieve in practice than that for fungal growth alone. Therefore, if the primary objective is lignin degradation, then it is recommended that a dedicated fungal reactor design is selected. For a sealed impermeable reactor, this limits the control requirements to ventilation rate and temperature control. As these variables can be separately adjusted, this enables the **use of independent climate control loops**. It is suggested that under these independent control loop conditions a simple **standard negative feedback PI control** system can be used.

The belt configuration shown in Figure 6.7 is designed to be scalable. In practice, its use has tended to in a discontinuous time frame, and it has been applied to both medium, *i.e*. commercial rack growth systems, and large, *i.e*. compost production systems. No problems are foreseen in applying the belt system to a smaller scale process.

As introduced in section 6.1, the precise size of the bioreactor is a function of the degradation characteristics of the selected fungus. As a final fungal selection has not yet been confirmed, the corresponding degradation characteristics are unquantified. Consequently, it would be premature at this stage to initiate the calculations necessary to estimate the reactor's size.

13. Open questions

1. Batch and/or continuous (daily batch) process operation ?
    - Critical point that determines reactor layout and design.
    - If the reactor is not operational during flight, storage of waste must be managed.
        - This implies that there is at least one batch to be processed upon arrival.
        - Fungal or bacterial pre-processing could occur during the in-flight storage phase.
2. Single or multiple stages of fungal species ?
    - Could use a sequence of species to increase overall degradation efficiency.
        - For example a soft rot and/or brown rot fungi (where lignin removal is absent/slow/partial) may be used to pre-digest the compost and facilitate lignin availability for increased degradation efficiency ?
    - Different species may have differing climate requirements.
        - Some white rot species have an improved efficiency in a high oxygen atmosphere (Rayner and Boddy, 1988).
        - If the selected species is/are photosensitive then a lighting system is required.
3. Full range of fungal growth phases required or limited to one phase (spawn run) ?
    - May require multi-zone control and/or multiple reactors.
4. What are the appropriate, fungal dependent, climate variable requirements ?
5. Energy use limitations ?
    - Dehumidification is typically four times more expensive (in energy terms) than heating.
6. Pest/competitive growth control ?

- Use of chemicals or filtration/clean-room approach or pasteurisation ("cook-out").

7. Treatment of air supply to remove anti-fungal volatile organic compounds that may be of internal or external origin, *e.g*., from the higher plant growth chamber ?
   - As part of their growth cycle, many plants release anti-fungal gases such as aldehydes, terpenes, nonanol, hexanol, *etc*., (Stutte and Wheeler, 1997).
8. Possibilities for enhancing performance ?
   - Ultrasonic bioreactor (*e.g*. Schlager, 1998).
9. Trapped by orthodox mushroom AHU thinking?
   - Given that the crew compartment needs its own AHU, there is no need to replicate in the fungi reactor, AHU services that are available from a central crew AHU, *e.g.* dehumidification. Relative sizing between crew and fungi requirements may be an issue here, but proportionality should exist between the two, under steady state conditions.
   - If mushrooms are not a growth requirement, then there is no rationale for carbon dioxide control (only monitoring as an indicator of metabolism), because carbon dioxide is completely miscible with air. Therefore oxygen control is required to ensure a supply for metabolic activity, to replace the surrogate oxygen supply control that carbon dioxide control provides in existing design practice. Existing fungi bioreactors are generally not controlled for oxygen, see point 2 and note van Geffen's (1998) approach.
   - The reactor design requirement question is then, what is the range over which to regulate the oxygen supply. If the 'cheap, earthly' approach is appropriate, *i.e*., limiting the maximum range of oxygen control to the crew compartment supply level, by solely using crew compartment supply air as fresh air input to the fungi reactor, then orthodox mushroom AHU design thinking is appropriate.
   - If the maximum of the oxygen control range is high or even 100% then a new AHU and reactor design approach is necessary. This might consist of a hermetically sealed reactor with makeup oxygen injected into the supply air and 'overpressure' air removed from the return air. Thermal management would still be required due to the metabolic source of heat.
   - By abandoning a requirement to keep air RH below 100%, the reactor (sauna) itself can be used as a dehumidifier through the saturation vapour pressure effect. The curve describing the effect would presumably have to be (re)characterised for fungi reactor gas (dry oxygen ?) instead of standard dry air (Hyland and Wexler, 1983), if the fungi reactor gas varies significantly from dry air.

14. Conclusions

As the requirements for a mushroom bioreactor are significantly more numerous and more complex than those for a fungal bioreactor, and because mushrooms are not a crew dietary requirement, it is concluded that a fungal bioreactor is sufficient for lignin degradation. Consequently, although the belt design presented and shown in Figures 6.7 and 6.8 is capable of having a limited range of distinct climate zones suitable for mushroom growth, this capability is not required.

To facilitate fungal metabolic gas exchange, it is concluded that a high surface to volume reactor is required. Hence, it is recommended that a belt configuration, *e.g*. similar to that shown in Figures 6.7 and 6.8, is used.

A displacement ventilation system can be provided by suitable location of the supply and return ducts, in conjunction with full use of the Coanda effect across the top of the compost on the belt conveyor in the reactor. The benefits of the high ventilation efficiencies associated with such a system are such that a displacement system, such as the one shown in Figure 6.8, is recommended. It is important to note that positioning of the vents in the ducts is critical to obtaining full benefit from the Coanda effect.

Electrostatic air filtration systems have a high maintenance cost, are more complex and require a power supply for operation, compared to membrane types. The marginal benefit in terms of fan energy use can be negated to some extent by using an extremely large area for a comparable membrane type. For these reasons a membrane type air filter is recommended.

In both the selection of actuators and instrumentation systems, the use of direct primary systems, as opposed to secondary or indirect systems, is recommended.

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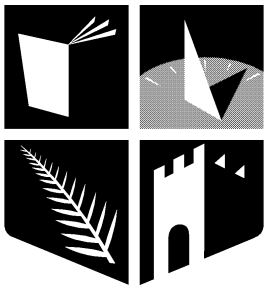

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ESA contract 15689/01/NL/ND

TECHNICAL NOTE TN 71.6.4a, Appendix A

Final Report on Fungi Compartment Studies:
Solid State Fungi Reactor - Initial Concept,
Climate Model Development

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1. Climate model development

Ventilation model

When first order models are used in a control system analysis, three commonly accepted key structural parameters of such models are: the system's gain, *k*, the system's time constant, τ, and the system's time delay, t_d. These three parameters are often abbreviated as *ktd*.

In ventilation system analysis, a commonly accepted key parameter is the system's air change rate (ACR), which is used here synonymously with ventilation rate. In ventilation system terminology, ACR is taken to mean the number of times the air in a zone is changed per unit time (usually an hour). Ventilation systems can have many different configurations with a wide variety of ventilation efficiencies. Using the definitions provided by Etheridge and Sandberg (1996), a ventilation system of 100% ventilation efficiency ($\eta = 1.0$) is interpreted as one with a pure piston flow regime, and a ventilation system of 50% ventilation efficiency ($\eta = 0.5$) is interpreted as one with a pure mixing regime. Ventilation efficiencies below 50% are taken as indicative of ventilation systems with some degree of short-circuiting, and ventilation efficiencies between 50% and 100% are taken as some mix of a mixing/piston flow regime. It is intended that the ventilation efficiency of the system shown in Figure 11.6 is as close as possible to 100%.

Consider a zone of air of volume, V_z, being supplied by a flow of air, q_s. Equation (A.1) then gives the nominal ACR or ventilation rate, v_n.

$$v_n = \frac{q_s}{V_z} \tag{A.1}$$

where,

v_n is the nominal ventilation, or air change, rate, s^{-1}
V_z is the zone air's volume, m^3
q_s is the supply air's volumetric flow rate, m^3/s

The nominal ventilation rate given by Equation (A.1) only applies for a ventilation system of 100% efficiency. To relate the nominal ventilation rate to the actual ventilation rate, Equation (A.2) is used.

$$v_a = \eta v_n \tag{A.2}$$

where,

v_a is the actual ventilation, or air change, rate, s^{-1}
v_n is the nominal ventilation, or air change, rate, s^{-1}
η is the ventilation system's ventilation efficiency, lying in the range 0-1

To relate the actual ventilation rate to the system's time constant, Equation (A.3) is used. It should be clear that the higher the ventilation rate, the shorter the system's time constant.

$$\tau = \frac{0.63}{v_a} \tag{A.3}$$

where,

τ is the system's time constant, s
v_a is the actual ventilation, or air change, rate, s^{-1}

Mass balance model

For a closed air zone with all internal surfaces made of impermeable materials, *i.e.*, no absorption or emission of gases to or from internal solids or liquids, the expression of a dynamic gaseous mass balance is:

the rate of change of mass stored in the zone air is equal to the sum of the mass flows for that zone. In general the mass flows for a zone are:

1. the mass flow supplied to the zone (input), Φ_s,
2. the mass flow returned from the zone (output), Φ_r,
3. the mass flow generated in the zone (internal sources), Φ_z.

This is expressed by Equation (A.4):

$$\frac{d}{dt} M_z = \Phi_s - \Phi_r + \Phi_z \qquad \text{(A.4)}$$

where,

M_z is the mass stored in the zone, kg
Φ_s is the mass source rate supplied to the zone, kg/s
Φ_r is the mass source rate returned from the zone, kg/s
Φ_z is the mass source rate generated in the zone, kg/s

Water vapour mass balance model

For water vapour, the preferred physical SI mass measurement unit for a mass balance model is the total mass of water vapour present in the zone air. However, to facilitate inter-system comparison, and for psychrometric calculations, this mass measurement is usually normalised into the form of one of a number of different dimensionless mixing ratios. One such form of the mixing ratio is the proportion of water vapour per unit dry air by mass, which is expressed by Equation (A.5a) for the zone air. This ratio is a psychrometric calculation that is known as the humidity ratio.

$$W_z = \frac{M_{Wz}}{M_{daz}} \qquad \text{(A.5a)}$$

where,

W_z is the zone air's humidity ratio, kg/kg
M_{Wz} is the mass of water vapour stored in the zone, kg
M_{daz} is the mass of dry air stored in the zone, kg

Humidity ratio can be calculated via measurements of air temperature, humidity and pressure through a psychrometric calculator. Different calculators can return different values for humidity ratio using the same measurement values, depending on the empirical expression used for determining saturated water vapour in air, and the physical values, *e.g.* specific heat capacity, used in the calculation for the measurement range of interest.

In a similar form to Equation (A.5a) a less common form of water vapour mixing ratio unit is the proportion of water vapour per unit moist mixed air, which is expressed by Equation (A.5b). This unit of humidity expression is known as the specific humidity.

$$x_z = \frac{M_{Wz}}{M_{az}} \qquad \text{(A.5b)}$$

where,

x_z is the zone air's specific humidity, kg/kg
M_{Wz} is the mass of water vapour stored in the zone, kg
M_{az} is the mass of moist air stored in the zone, kg

For the case of completely dry air, *i.e.*, no water vapour content, a value of zero applies to both humidity ratio and specific humidity. Confusion between the units can easily arise because the two units are

numerically close and use the same dimensionless mass ratio unit of expression. Hence, it is important to note that because of their pre-mixed and post-mixed perspectives respectively, the two units mean different things. The relation between the two units is given by Equations (A.5c) and (A.5d).

$$x_z = \frac{W_z}{1+W_z} \tag{A.5c}$$

$$W_z = \frac{x_z}{1-x_z} \tag{A.5d}$$

For example, a one kilogram mass of dry air that is mixed with 15 grams of water vapour has a humidity ratio of 0.015 kg/kg and has a total mixed mass of 1.015 kg. However, a one kilogram mass of mixed air that contains 15 grams of water vapour has a specific humidity of 0.015 kg/kg and has a total mixed mass of 1.000 kg. So both ratio are numerically the same, but the total masses are different. Although humidity ratio is a preferred form of psychrometric expression, using specific humidity as the humidity variable of interest facilitates model development because air density is a property of mixed air.

Rearranging Equation (A.5b) and by noting that the mass of zone air is the product of its density and volume, Equation (A.6) can be used to establish the total mass of water vapour in the zone, *i.e.*, in the form of the preferred physical SI measurement unit.

$$M_{Wz} = x_z \rho_{az} V_z \tag{A.6}$$

where,

M_{Wz} is the total mass of water vapour stored in the zone, kg
x_z is the zone air's specific humidity, kg/kg
ρ_{az} is the density of air in the zone, kg/m^3
V_z is the zone air's volume, m^3

Using Equation (A.4) to express the mass balance in the zone and substituting Equation (A.6) on the left hand side yields Equation (A.7).

$$\frac{d}{dt} x_z \rho_{az} V_z = \Phi_{ws} - \Phi_{wr} + \Phi_{wz} \tag{A.7}$$

where,

x_z is the zone air's specific humidity, kg/kg
ρ_{az} is the density of air in the zone, kg/m^3
V_z is the zone air's volume, m^3
Φ_{ws} is the water vapour mass source rate supplied to the zone, kg/s
Φ_{wr} is the water vapour mass source rate returned from the zone, kg/s
Φ_{wz} is the water vapour mass source rate generated in the zone, kg/s

The water vapour mass source rate supplied to the zone, is the product of the specific humidity of the supply air and the mass source rate of supply air. The mixing ratio form of Equation (A.5b) is used to express the mass ratio in the supply air. The mass source rate of supply air is the product of the volumetric supply rate and the density of the supply air. Equation (A.8) expresses this relation.

$$\Phi_{ws} = x_s q_s \rho_{as} \tag{A.8}$$

where,

Φ_{ws} is the water vapour mass source rate supplied to the zone, kg/s

x_s is the supply air's specific humidity, kg/kg
q_s is the volumetric flow rate of air supplied to the zone, m^3/s
ρ_{as} is the density of air supplied to the zone, kg/m^3

Rearranging the form of Equation (A.1) for q_s and substituting into Equation (A.8) yields Equation (A.9).

$$\Phi_{ws} = x_s v V_z \rho_{as} \tag{A.9}$$

where,
Φ_{ws} is the water vapour mass source rate supplied to the zone, kg/s
x_s is the supply air's specific humidity, kg/kg
v is the ventilation rate of air supplied to the zone, s^{-1}
ρ_{as} is the density of air supplied to the zone, kg/m^3

Under steady state conditions the supply air displaces the zone air, hence the flow rate of return air is equal to the flow rate of supply air. Hence, the form of Equation (A.9) can be used to express the mass flow rate of air returned from the tunnel, but noting that the air's specific humidity and density are now that of the zone air. This yields Equation (A.10).

$$\Phi_{wr} = x_z v V_z \rho_{az} \tag{A.10}$$

where,
Φ_{wr} is the contamination mass source rate returned from the zone, kg/s
x_z is the return air's specific humidity (assumed to be the same as that of the zone), kg/kg
v is the ventilation rate of air returned from the zone, s^{-1}
ρ_{az} is the density of air in the zone, kg/m^3

Substituting Equation (A.9) and Equation (A.10) into Equation (A.7) yields Equation (A.11).

$$\frac{d}{dt} x_z \rho_{az} V_z = x_s v V_z \rho_{as} - x_z v V_z \rho_{az} + \Phi_{wz} \tag{A.11}$$

The volume of air in the zone is fixed and hence may be taken outside the differential. Assuming near-isothermal and near-isohumid conditions, *i.e.*, the density of air in the zone changes slowly compared to the timescale of interest, allows the assumption that the zone air density is fixed and hence, it may also be taken outside the differential. Dividing across by both these terms re-presents Equation (A.11) as Equation (A.12), which is the dynamic water vapour model for the zone air.

$$\frac{d}{dt} x_z = v\left(\frac{\rho_{as}}{\rho_{az}} x_s - x_z\right) + \frac{\Phi_{wz}}{\rho_{az} V_z} \tag{A.12}$$

where,
x_z is the zone air's specific humidity, kg/kg
v is the ventilation, or air change, rate, s^{-1}
ρ_{as} is the supply air's density, kg/m^3
ρ_{az} is the zone air's density, kg/m^3
x_s is the supply air's specific humidity, kg/kg
Φ_{wz} is the zone source rate of water vapour, kg/s
V_z is the zone air's volume, m^3

Combined ventilation and contamination mass balance model

By substituting Equation (A.3) into Equation (A.12), and simplifying for the case where there are no internal sources, *i.e.*, $\Phi_{wz} = 0$, Equation (A.13) is formed.

$$\frac{d}{dt}x_z = \frac{0.63}{\tau}\left(\frac{\rho_{as}}{\rho_{az}}x_s - x_z\right) \tag{A.13}$$

Multiplying across and gathering x_z terms yields Equation (A.14).

$$\left(1+\frac{\tau}{0.63}\frac{d}{dt}\right)x_z = \frac{\rho_{as}}{\rho_{az}}x_s \tag{A.14}$$

Note the density ratio term (ρ_{as}/ρ_{az}) in Equation (A.14) and recall the gain (k) concept from a first order model. This density ratio term is the gain of such a ventilation model. The time constant (t) has already been identified in Equation (A.3). The time delay (d) of the system, which has been omitted so far to simplify this analysis, is the time taken from operation of the actuator until a change in the zone air occurs and is composed of two parts. The first part is the time taken for actuator operation itself. The second part is pure transport delay through the ducting, *etc*., and this is approximately the product of the reciprocal of airspeed and distance from the actuator in the air handling unit to the supply vent. For control system analysis, these (ktd) terms are commonly shown using the Laplace domain control systems transfer function model form in Equation (A.15), simplified for the case where there are no internal sources, *i.e.*, Equation (A.14).

$$x_z(s) = \frac{ke^{-ds}}{1+ts}x_s \tag{A.15}$$

To relate Equation (A.15) to (A.14) note:

$k = \rho_{as}/\rho_{az}$
$d = 0$ for the ideal case
$t = \tau/0.63$

This simplified analysis to relate the ventilation and mass balance models, has ignored the internal sources within the zone. However, they can be incorporated into this model as an additional disturbance term, through a development from Equation (A.12) to give Equation (A.16). Note that no delay is appropriate for this disturbance term as it operates within the zone and hence is assumed to have an instantaneous response, as opposed to the supply air, which is delivered through ducting to the zone.

$$x_z(s) = \frac{ke^{-ds}}{1+ts}x_s + \frac{t\dfrac{\Phi_{wz}}{\rho_{az}V_z}}{1+ts} \tag{A.16}$$

where,

x_z is the zone air's specific humidity, kg/kg
$k = \rho_{as}/\rho_{az}$
$d = 0$ for the ideal case
$t = \tau/0.63$
ρ_{as} is the supply air's density, kg/m^3
ρ_{az} is the zone air's density, kg/m^3
x_s is the supply air's specific humidity, kg/kg
Φ_{wz} is the zone source rate of water vapour, kg/s
V_z is the zone air's volume, m^3

By using a steady state analysis, *i.e.*, $s = 0$, Equation (A.16) can be checked for consistency and correctness using four intuitive scenarios. Note that each scenario is bounded by the constraints discussed in the following section.

1. Internal sources, Φ_{wz} are zero. In this case the second term is zero. By examining the first term, it is clear that zone air will tend to the state of the supply air.
2. Internal sources, Φ_{wz} are non-zero, but the ventilation rate is infinity, hence, through Equation (A.3), t is zero. In this case the second term is zero. By examining the first term, it is clear that zone air will tend to the state of the supply air.
3. Internal sources, Φ_{wz} are non-zero, and the ventilation rate is zero, hence, through Equation (A.3), t is infinite. In this case the second term is infinite (for the case of perfect sealing !) and consequently the total of both terms is also infinite.
4. Internal sources, Φ_{wz} are non-zero, and the ventilation rate is between zero and infinity, hence, through Equation (A.3), t is positive and finite. In this case the second term is positive and finite. Hence, it is clear that zone air will tend to some value greater than that of the supply air.

Constraints on water vapour mass balance model

The amount of water vapour that can be mixed with dry air is a non-linear function of temperature. When air reaches this condition, it is said to be saturated. If the air is cooled, and/or further water vapour is mixed with the air, condensation will occur. Hence, each water vapour term in the model has to be constrained to lie within its appropriate range as expressed in Equations (A.17 and A.18). Consequently, the model itself is dependent on a temperature model for each water vapour term.

$$x_z \leq x_{zSat} \tag{A.17}$$

$$x_s \leq x_{sSat} \tag{A.18}$$

where,

x_z is the zone air's specific humidity, kg/kg
x_{zSat} is the zone air's saturated specific humidity, kg/kg
x_s is the supply air's specific humidity, kg/kg
x_{sSat} is the supply air's saturated specific humidity, kg/kg

Enthalpy balance model

Clearly a temperature model is more complex than the mass balance model developed here, because the assumption of impermeable surfaces for all supply and zone materials does not hold in the case of heat transfer. However, a simple temperature model can be generated by assuming adiabatic conditions, *i.e.* a perfectly insulated reactor. In this case, the enthalpy in the zone can be modelled by a substitution of variable into Equation (A.16) to give Equation (A.19).

$$h_z(s) = \frac{ke^{-ds}}{1+ts} h_s + \frac{t\dfrac{\Phi_{hz}}{\rho_{az} V_z}}{1+ts} \tag{A.19}$$

where,

h_z is the zone air's enthalpy, kJ/kg
$k = \rho_{as}/\rho_{az}$
$d = 0$ for the ideal case
$t = \tau/0.63$
ρ_{as} is the supply air's density, kg/m^3
ρ_{az} is the zone air's density, kg/m^3
h_s is the supply air's enthalpy, kJ/kg
Φ_{hz} is the zone source rate of thermal energy, kJ/s

V_z is the zone air's volume, m^3

Temperature model
Then a temperature model can be established by solving the enthalpy psychrometric Equation (8.6) for temperature, as expressed in Equation (A.20).

$$T = \frac{h - 2501W}{1.006 + 1.85W} \tag{A.20}$$

where,
h is the air enthalpy, kJ/kg
T is the air temperature, °C
W is the humidity ratio, kg/kg
1.006 kJ kg^{-1} $°C^{-1}$ is the average specific heat of dry air in the temperature range –10 to +40°C
1.85 kJ kg^{-1} $°C^{-1}$ is the average specific heat of steam in the temperature range –10 to +40°C
2501 kJ kg^{-1} is the latent heat of vaporisation for water at 0°C

Carbon dioxide mass balance model
The mass balance model for contamination/carbon dioxide is a simpler version of the water vapour model because there is no constraint on miscibility. In this case, the contamination in the zone can be modelled by a substitution of variable into Equation (A.16) to give Equation (A.21).

$$c_z(s) = \frac{ke^{-ds}}{1+ts} c_s + \frac{t\dfrac{\Phi_{cz}}{\rho_{az} V_z}}{1+ts} \tag{A.21}$$

where,
c_z is the zone air's contamination, kg/kg
$k = \rho_{as}/\rho_{az}$
$d = 0$ for the ideal case
$t = \tau/0.63$
ρ_{as} is the supply air's density, kg/m^3
ρ_{az} is the zone air's density, kg/m^3
c_s is the supply air's contamination, kg/kg
Φ_{cz} is the zone source rate of mass emission, kg/s

2. References

Etheridge, D.W. and Sandberg, M., 1996. *Building ventilation: theory and measurement*. Chichester: John Wiley.