洋菇舍溫濕度及二氧化碳濃度聯控系統設計

A Simultaneous Control System Design of Temperature-Humidity-Carbon Dioxide in a Mushroom Growing House

國立宜蘭農工專校
農機科副教授
廖中明
Chung-Min Liao

國立臺灣大學
農工系副教授
王鼎盛
Tin-Sen Wang

國立臺灣大學
農工所碩士班研究生
吳振甫
Chen-Fu Wu

摘要

由乾空氣，水份及濕空中焓與二氧化碳濃度之聯立物質平衡式可推導出一線性控制模式，用以描述菇舍中溫度濕度與二氧化碳濃度之動態行為。由線性控制模式所模擬之反應結果與現場洋菇舍中量測所得之結果大致吻合。最佳回授控制器之設計，乃是基于現代控制理論中之線性二次調整器。最適性乃基于極小化一特殊積分二次目標函數，此目標函數可將菇舍內溫度，相對濕度及二氧化碳濃度之變異及控制能力極小化。脈衝及階梯式干擾兩者皆納入考慮且最佳回授ＰＩ及ＰＩ控制器也被有效地合成。針對目標函數中控制器之回授增益也提出一靈敏度分析。分析結果指出二氧化碳控制器增益較溫濕度回授增益來得更靈敏。

關鍵詞：洋菇舍，菌絲成長，子實體成長，線性控制模式，現代控制理論。

ABSTRACT

A linear control model which describes the dynamics of temperature, humidity, and carbon dioxide level in a mushroom house has been derived from simultaneous mass balance of dry air, water, enthalpy of moist air, and carbon dioxide levels. The responses from the linear control model are found to compare favorably with that from field measured results. Optimal feedback controllers have been devised from the viewpoint of modern control theory based on the linear quadratic regulators (LQRs). Optimality is based on minimizing indoor temperature, relative humidity, and carbon dioxide variations along with control effort. Both impulse and step disturbances are taken into account and optimal P and PI controllers are synthesized. A sensitivity analysis has been performed to study the sensitivity of the objective function with respect to the controller gains. Feedback gains of carbon dioxide controller has been shown to be far more sensitive as compared with that of temperature and humidity controllers.

Keywords: mushrooms growing house, case running, mushroom production, linear control model, modern control theory.

INTRODUCTION

Mushroom that are housed in confined buildings generally are not at liberty to seek their own prefered environment and, consequently, high levels of management are required to ensure that a suitable environment is provided for them. The economics of the process in optimizing return on investment sometimes have led to conditions which have been perceived as being detrimental to mushroom growing welfare. These perceptions as well as the desire to optimize productivity have led to the need to describe and to define the optimum mushroom environment more precisely.

The use of computer-based environmental control systems for protected crop production has been developed mainly for glasshouses. A number of such systems have been described (Willits et al., 1980a, b; Saffell and Marshall, 1983) or are available commercially. Progress in developing systems for buildings used in mushroom production has been less rapid. Schroeder (1983) has described a microprocessor-based control system for buildings used in the compost pasteurization and conditioning phase of mushroom production. A number of computer-based environmental control systems for buildings used in other phases of mushroom production, including cropping, have recently become available, notable in the Netherlands. Such systems have been on distributed processors using custom built components. Their major disadvantage is their high cost.

The most widely used system of mushroom cultivation in Taiwan is compost filled trays stacked in in a growing house. The growing houses are well insulated and usually have means of heating and ventilation.

The compost which commonly consits of a mixture of wetted straw is processed to kill pests and pathogens and make it both suitable and selective nutritionally for the growth of mushroom mycelium. Mushroom spawn is then mixed with the compost and mycelium is allowed to colonize the compost. A casing layer consisting of a mixture of peat and limestone is then added as a surface layer to the compost and further period of micelial growth allowed until the mycelium colonize the casing layer. Once the mycelium has reached the surface of the casing layer, the mushroom is induced to fruit by a change in environmental conditions, and the mushroom are cropped over a period of several weeks, as they reach a suitable size. The crop is normally terminated by the introduction of steam to the house, i.e., cooking cut, at the end of its economic life.

The period of mushroom cropping can be divided into two distinct stages: (1) the growth of the mycelium throughout the casing, and (2) mushroom production. Each stage has specific environmental requirements. The environmental conditions during the transition between the two stages are also important because these cases purely vegetative growth and stimulate reproduction growth, and mushroom production. Briefly, the environmental requirements for the two stages in the cropping houses have been outlined by Tschierpe (1973) and Vedder (1978):

(1) Mycelium growth with the casing, i.e., case running:

Temperature:	25-29°C in the casing.
Relative humidity:	95-100% in the air.
CO_2 Level:	0.5–2.0% (v/v) in the air.

(2) Mushroom production:

Temperature:	14-18°C in the air.
Relative humidity:	80-95% in the air
CO_2 Level:	0.03–0.15% (v/v) in the air.

During the final stage, when mycelium is growing through the casing, the temperature of the casing rather than of the air is critical. During the second stage, when the mushrooms are being initiated and are growing out of the casing, the air temperature and humidity are most important. It is therefore necessary to control the humidity and the casing or air temperature depending on the growth of the crop.

The layflat polythylene tubing has been used to distribute air in mushroom cropping houses. A typical distribution duct for this purpose is about 200mm in diameter and 20m long, suspended below the ridge. Pairs of holes are punched at intervals along the length of the duct, from which jets of air issue, mixing with and generally stirring the air in the house.

The airflow through the mixing box and circulation ducting is regulated to between 0 and 1500 m^3hr^{-1} by a fan. Air is discharged from the polythylene ducting through 10mm holes spared at 200mm, downwards through a central alley between the stacks of trays.

The dynamic simulation and control of the thermal and atmospheric environment in an agricultural structure have received much attention in recent years. But relatively few studies have appeared in the literature which deal with the modeling and simulation and automatical control of such thermal and atmospheric environment in a mushroom growing house (Kinrus, 1970; Schroeder, 1969; Schroeder et al., 1974; Wuest et al., 1976; Flegg and Smith, 1976; Dawson, 1952). A mushroom growing house involves hydroscopic materials and chemical reactions where temperature, humidity, and CO_2 concentration control must be mandatory if a satisfactory result is to be produced (Cheng and Han, 1977; Flegg, 1972; Tschierepe; 1973; Flegg, 1979; Flegg et al., 1985).

In order to analyze the behavior of a dynamic system, a mathematical representation of the physical phenomena is needed. Modeling of a physical process in a mushroom growing house is a very synthetic activity, requiring the use all the basic principles, such as thermodynamics, transport phenomena, etc. For the design of controllers for physical processes, modeling is a very critical step. In this work, the dynamics of a lumped-parameter model for describing the behavior of temperature-humidity-CO_2 system were used in the development of controllers (Liao, 1990; Liao and Feddes, 1990; Liao et al., 1991a).

The aims of this paper are:

1. To present an analytical procedure to model the dynamic behavior of temperature, humidity, and CO_2 concentration that comprehensively and systematically accounts for these complex physical and transport processes in a mushroom growing house.
2. To present the optimal feedback control synthesis via modern control theory of a temperature-humidity-CO_2 control system in a mushroom growing house.

It is hoped that through this work a thorough investigation of the temperature-humidity-CO_2 control system in a ventilated mushroom growing house can be reported, with a special emphasis on the feedback control system via modern control theory.

SYSTEM CONTROL MODEL

Temperature-Humidity Control Submodel

A pair of nonlinear differential equations which describe the dynamics of temperature and humidity in a confined agricultural environment have been derived from simultaneous mass balances of dry air, water and the enthalpy of moist air (Liao, 1990). The equations take into account of external heat loads internal heat and moisture loads within a confined environment. Since temperature-humidity control systems usually only allow small derivations of temperature and humidity from a desired operating point, a linearization of the above equations within the bounds of small derivations is justified. On using available relations for the specific volume and enthalpy of moist air, the linearized equations further result in a pair of linear uncoupled differential equations:

$$\{\dot{x}\} = [A]\{x\} + [B]\{u\} + [D]\{v\} \qquad (1)$$

where:

$$\{x\} = \{x_1, x_2\}^T = \{\Delta h_r, \Delta T_r\}$$

$$\{u\} = \{u_1, u_2\}^T = \{\Delta h_i, \Delta T_i\}^T$$

$$\{v\} = \{v_1, v_2, v_3, v_4\}^T = \{\Delta h_f, \Delta T_f, \Delta Q_r, \Delta W_r\}^T$$

$$[A] = \begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix} \quad [B] = \begin{bmatrix} b_{11} & 0 \\ b_{12} & b_{22} \end{bmatrix}$$

$$[D] = \begin{bmatrix} d_{11} & 0 & 0 & d_{14} \\ d_{21} & d_{22} & d_{23} & d_{24} \end{bmatrix}$$

where:

$$a_{11} = -[K_1 (F_i + F_f)]_s$$

$$a_{22} = -[K_2 (F_i(1005 + 1884h_i) + F_f(1005 + 1884h_f) - \partial Q_l/\partial T_r + 0.45W_r)]_s$$

$$b_{11} = [K_1 F_i]_s, \; b_{12} = 0,$$

$$b_{22} = [K_2 F_i(1005 + 1884h_i)]_s$$

$$d_{11} = [K_1 F_f]_s$$

$$d_{14} = [K_1]_s, \; d_{21} = [1884K_2F_f (T_f - T_r)]_s$$

$$d_{22} = [K_2 F_f(1005 + 1884h_f)]_s + [K_2 \partial Q_l/\partial T_a]_s$$

$$d_{23} = [K_2]_s,$$

$$d_{24} = [K_2(1884T_r + 4386.3)]_s$$

where:

$$K_1 = \upsilon_r/V = ((0.00283 + 0.00456h_r)(T_r + 273))/V$$

$$K_2 = (\upsilon_r/V)/(\partial H_r/\partial T_r) = K_1/(1005 + 1884h_r)$$

where:

F = air mass flow rate, Kg dry air/min,
H = enthalpy, Btu/Kg dry air,
h = humidity, Kg water/Kg dry air,
T = temperature, °C,
Q_r = internal heat load, Btu/min,
W_r = internal moisture load, Kg water/min.

The subscripts "i", "f", and "r", represent recycled, outdoor freshed, and indoor air, respectively. The "Δ" represents variation between variable and steady state value. The subscript "s" represents the steady state condition.

Also, since the external heat load (Q_l) may be expressed as:

$$Q_l = UA_r(T_a - T_r)$$

where:

U = the overall heat transfer coefficient, Btu/-m^2-°C-hr,
A_r = the heat transfer area, m^2,
T_a = the ambient temperature, °C.

Therefore,

$$a_{22} = [K_2\{F_i(1005 + 1884h_i) + F_f(1005 + 1884h_f) + UA_r + 1884W_r\}]_s$$

$$c_{23} = [K_2 UA_r]_s$$

The response from the linear equation is found to compare very favorably with that from the original nonlinear equations (Liao, 1990).

Carbon Dioxide Control Submodel

A linear control model for describing the dynamic behavior of carbon dioxide concentration at any location within a ventilated airspace has been presented from the standpoint of a lumped-parameter approximation (Liao et al., 1991a). The equation can be represented by a first-order time-invariant vector-matrix differential equation. To assess the accuracy of a lumped-parameter model used in predicting carbon dioxide concentrations in a ventilated airspace, a laboratory project has also been presented. Good agreement was obtained between measured and those predicted by the lumped-parameter model (Liao et al., 1991b). The carbon dioxide control submodel then can be expressed as:

$$\{\dot{C}(t)\} = -[S]\{C(t)\} + [V]^{-1} \tag{2}$$

$$\{m(t)\} + [T]\{C_s(t)\}, \{C(O)\} = \{C_o\}$$

where:

$\{C(t)\}$ = carbon dioxide concentration vector, ppm,
$\{m(t)\}$ = CO_2 generation rate vector, ghr^{-1},
$\{C_s(t)\}$ = supplied air concentration vector, ppm,
$[V]^{-1}$ = inverse of air volume matrix, m^{-3},

Matrices [S] and [T] in equation (18) can be expressed as:

$$[S] = [V]^{-1}[Q] \tag{3a}$$

$$[T] = [V]^{-1}[Q_s] \tag{3b}$$

where:

[Q] = system transport matrix, m^3hr^{-1},
$[Q_s]$ = diagonal supply airflow matrix, m^3hr^{-1}.

Matrix [Q] is a square airflow matrix, consisting of the total flow rates of air between airspaces. The sum of the elements in a row (say No. i) of [Q] is equal to the flow rate of outdoor air entering airspace i. All elements in a column (say No. j) of [Q] is equal to the total flow rate or air transferred directly from airspace j to outdoor. Therefore, [Q] can be expressed as:

$$[Q] = \begin{bmatrix} Q_{11} & -Q_{12} & \cdots & -Q_{1n} \\ -Q_{21} & Q_{22} & \cdots & -Q_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ -Q_{n1} & -Q_{n2} & \cdots & Q_{nn} \end{bmatrix} \tag{4}$$

The airflow matrix also can be represented as (Liao et al., 1990b):

$$[Q] = [\beta]Q \tag{5}$$

where:

$[\beta]$ = square matrix of entrainment ratio function,
Q = total volumetric flow rate of outdoor air supplied to whole system, m^3hr^{-1}. ($Q = (F_i+F_f)v_r$)

The equilibrium carbon dioxide concentration can be given as:

$$\{C(\infty)\} = [Q]^{-1}\{E(\infty)\} \tag{6a}$$

where:

$$\{E(\infty)\} = \{m(\infty)\} + [Q_s]\{C_s(\infty)\} \tag{6b}$$

Linear Control Model

Equations (1) and (2) can be compactly expressed as a temperature-humidity-carbon dioxide system control model:

$$\{\dot{X}(t)\} = [F]\{X(t)\} + [G] \tag{7}$$

$$\{U(t)\} + [L]\{W(t)\}$$

where vectors {X}, {U} and {W}, and matrices [F], [G], and [L] can be partitioned comfortably as:

$$\{X\} = \{\{x\} | \{C\}\}^T, \{U\} = \{\{u\} | \{m\}\}^T,$$

$$\{W\} = \{\{v\} | \{C_s\}\}^T.$$

$$[F] = diag\ [[A] | [S]],$$

$$[G] = diag\ [[B] | [V]^{-1}],$$

$$[L] = diag\ [[D] | [T]].$$

where:

{X} = system state variables vector,
{U} = system control variables vector,
{W} = system disturbances vector.

Vectors {X} and {U} are both (n+2) x 1

dimensional vectors, and {W} are (n+4) x 1, while matrices [F], [G] and [L] are (n+2)x(n+2), (n+2)x(n+2), and n+2)x(n+4) dimensional matrices, respectively.

Equation (7) is the continuous form ordinary employed in modern estimation and control theory. The stability criterion for the solution of a linear dynamic equation (equation (7)) has already been discussed (Liao and Feddes, 1990).

MODEL VERIFICATION

Experimental Procedures and Equipment

Mushroom growing house selected: The measurements are taken in a commercial mushroom house located in Tsao-Twen, Taiwan. The cross-section and the dimension of the house (10.66 x 6 x 4.5m) are shown in Figure 1.

Procedures and equipment: The measurement system is comprised of a potable microcomputer, a data logging system and peripherals, a non-interruptiable power supply (model YYAC-105, Yeatay Co., Taiwan), and various environmental sensors measuring temperatures, humidities, and CO_2 levels (Figure 2). Air and compost temperatures, relative humidity and CO_2 levels are measured on a daily basis throughout the production cycle.

(1) The air and compost temperature sensor: Air and compost temperatures were measured by the thermocouple, model TX-GS. There are 30 sampling points for mushroom data, and 2 points for outside meteorological data.

(2) Air relative humidity sensor: Relative humidity was measured by two humidetectors (model RHD-SD 211, Shinyei Kaisha, Japan) which were located on center support beams. A conventional psychrometer (wet and dry bulb) (Asman, Japan) is taken to measure the air relative humidity to compare the measured results via humidetector. Two sampling points were measured.

(3) Carbon dioxide is measured by two automatic sequencing infrared gas analyzer (model CO-300, Horiba Ltd., Kyota, Japan). Air is drawn through a perforated pipe mounted horizontally 90cm above floor in a central pathway and then through plastic pipes fitted with dust filters to the gas analyzers. Before the carbon dioxide measurement, both two gas analyzers were calibrated with known CO_2 concentrations of 0% and 0.15%, respectively.

(4) Data collections: All the data measured from environmental sensors were read and recorded via a data logger (Fluke 2286A Data Logging system, Fluke, USA) and analyzed via a portable computer.

(5) Ventilation rate measurement: The air entered the mushroom house through a polythylene tubing (20cm in diameter, 20m long) which suspended below the ridge. Pairs of hoes (1cm in diameter) punched at intervals along the length of the duct, from which jets of air issue, mixing with and generally stirring the air in the house. Mushroom house was mechanically ventilated by means of a 1/4 HP motor delivering ventilation air. Ventilation is through an air mixing box (plenum) which gives variable mixing of air from outside the house (fresh air) and inside the house (recirculation air) into an overhead duct. The motor was operated at constant speed to maintain constant air velocity. The ventilation air output (m^3hr^{-1}) was measured near the head of the discharge duct located upstream from the motor via an anemomaster (model 24-611, Kanomar, Japan) in accordance with Jorgenson (1983). Measured result shows ventilation rates used throughout the case running and cropping stages were 1231 m^3hr^{-1}.

Verification Procedures

Equation (7) can be used in temperature-humidity-CO_2 simulation. The growing stage to be considered is mycelium growth with the casing (case running). Following considerations shall be included in model verification.

(1) Input data for temperature-humidity system: (i) Indoor recycled air only. (ii) Fresh air mass flow rate: F_f=0, and ambient temperature (T_a) is assumed to be equal to outside air temperature (T_f). (iii) Steady-state internal load: $Q_{rs} = UA(T_{rs} - T_{as})$ (UA = 410 W/°C) (iv) Steady-state external load: Q_{1s} = 0 (v) Indoor and recycled temperatures and humidities are assumed to be equal ($T_r = T_i, h_r = h_i$).

(2) Input data for carbon dioxide system: The mushroom growing house can be modelled as a 5-lump system to study the variations of carbon dioxide concentrations. The airflow pattern of the 5-lump system is shown in Figure 3. Input

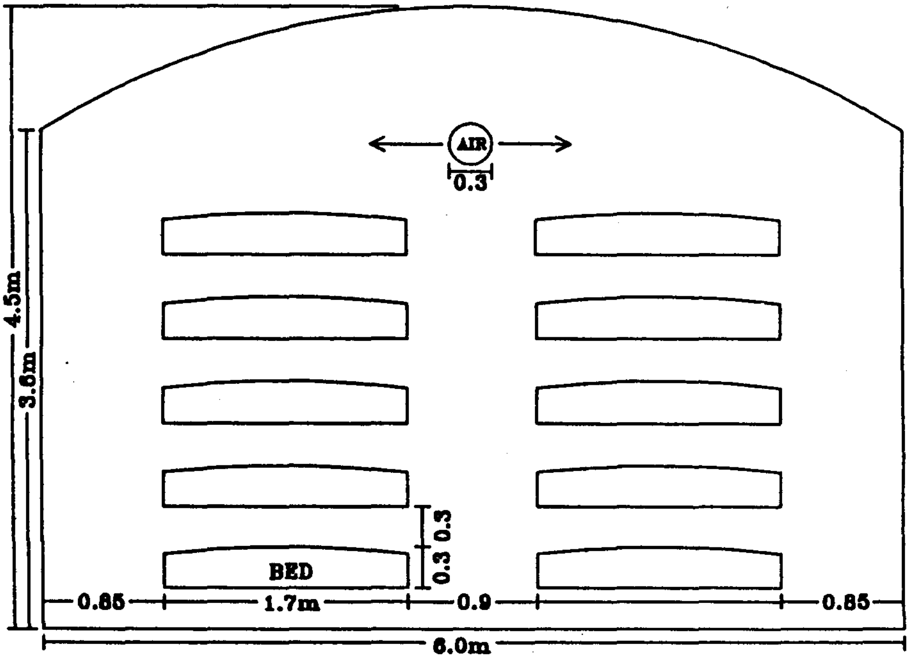

Figure 1. Diagrammatic cross-section of a commercial mushroom growing house

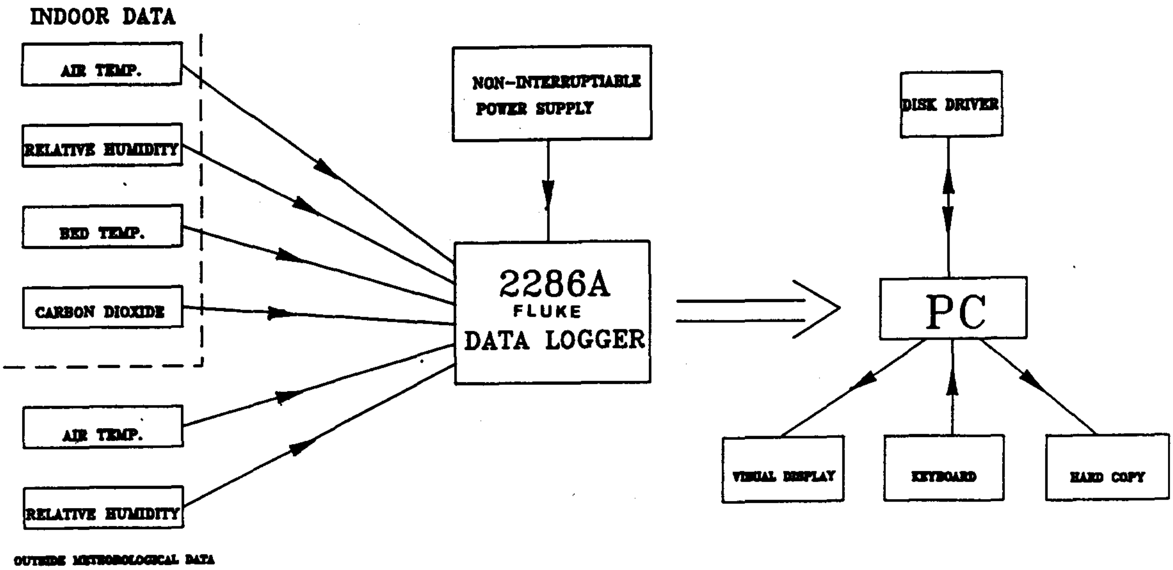

Figure 2. Architecture of the measurement system

data included: (i) Entrainment ratio, β: in order to determine recirculation flow rate, βQ, some estimations of the entrainment ratio is possible on the basis of a simple entrainment concept (Liao et al., 1991b). Therefore, βQ is entirely induced by the primary flow rate, i.e., by the entrainment in the inlet jet, is assumed. For circular jet, the entrainment ratio can be determined by (ASHRAE, 1985): $\beta = \beta Q/Q = 2/K' X/(A_o)^{0.5}$, where x = distance from the outlet (12m), A_o = effective area of the stream at discharge from an open end duct (0.07 m^2), and K' = proportionality constant (approximately 7). Thus, $\beta = 12.96$. (ii) Flow matrix [Q]: flow matrix being a direct sum of the solution of lump flow by 2-D lumped form of control volumes represented the conservation of air mass. (iii) Volume matrix [V]: each lump air volume assumed to be equal (equation (4)). Therefore, $V_i = 57.6\ m^3$, 1 = 1, 2, . . . , 5, based on the volume of $288m^3$. ((iv) Carbon dioxide generation rate vector {m}: carbon dioxide generation rate produced by compost and mycelium is chosen to be 940g CO_2/hr based on the research work done by Lockard and Kneebone (1965). To convert from unit gm^{-3} to ppm (volume), it is assumed that the ideal gas law is accurate under ambient condition (23°C, 1 atm), therefore, the conversion factor for CO_2 from gm^{-3} to ppm is 560.

Figures 4, 5 and 6 show that the responses from the linear control model are found to compare favorably with that from field measured data.

OPTIMAL FEEDBACK CONTROL SYNTHESIS

The equation used to describe the dynamics of temperature, humidity and carbon dioxide concentrations will be the linear multivariable model developed in equation (7). The following system will be analyzed in this work: State variables are indoor absolute humidity (h_r), indoor temperature (T_r), and indoor carbon dioxide concentration (C_r). The feedback variables are indoor relative humidity (ϕ_r), T_r, and C_r. Feedback control is synthesized so that deviations in ϕ_r, T_r, and C_r are minimized.

In order ro derive the optimal feedback control strategy for the system, the linear quadratic regulator (LQR) with state feedback will be considered. The LQR has been well developed for the past two decades. It is not possible or economically feasible to measure all state variables at all locations within a mushroom growing house. Therefore, the problem of obtaining the optimal or suboptimal output feedback control of a time-invariant system is most suitable for the system introduced (Anderson and Moore, 1990).

Practically, however, it is not always possible to have all the state variables available for feedback. Moreover, rather than reconstructing the state variables via Kalman filter (Kalman and Bucy, 1961) or some form of state estimator, the designer may wish to generate the control variables by taking linear combinatins of the available output variables. This is especially true in the case of the temperature-humidity-carbon dioxide system where the state variables are h_r, T_r, C_r. Constructing an optimal feedback controller by measuring these variables may not be very convenient since even though T_f is readily measured, the measurement of h_r is not always straightforward. Rather than measuring h_r, it is far more convenient to measure some output variables such as the dew-point temperature (T_{dp}) or relative humidity (ϕ_r), and to generate the feedback control based on these measurements.

. When the feedback control variables, the so-called output LQR is brought into play wherein the problem of making the components of the output vector small shall be concerned with.

The output vectors of interest to the problems are the following:

$$\{Z\} = [C]\{X\}$$

where:

$$[C] = [N]\ [M]$$

where constant matrices [M] and [N] can be expressed as (Liao, 1992):

$$[M] = \begin{bmatrix} (\partial T_{dp} / \partial h_r)^* & 0 \\ 0 & 1 \end{bmatrix}$$

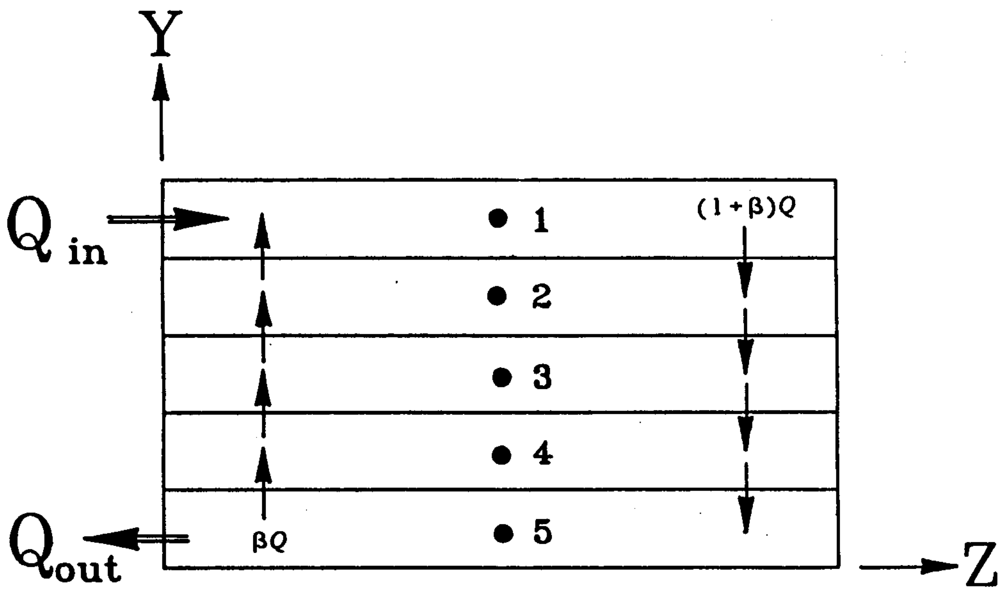

Figure 3. Airflow pattern in 5-lump system for carbon dioxide control submodel simulation

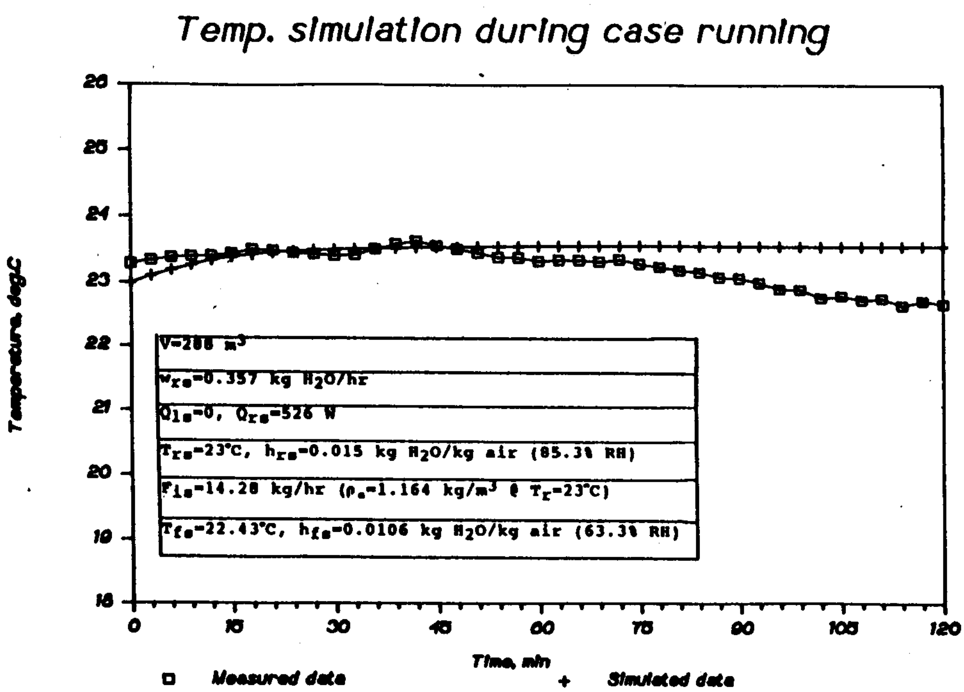

Figure 4. Simulated result of indoor temperature variations during case running

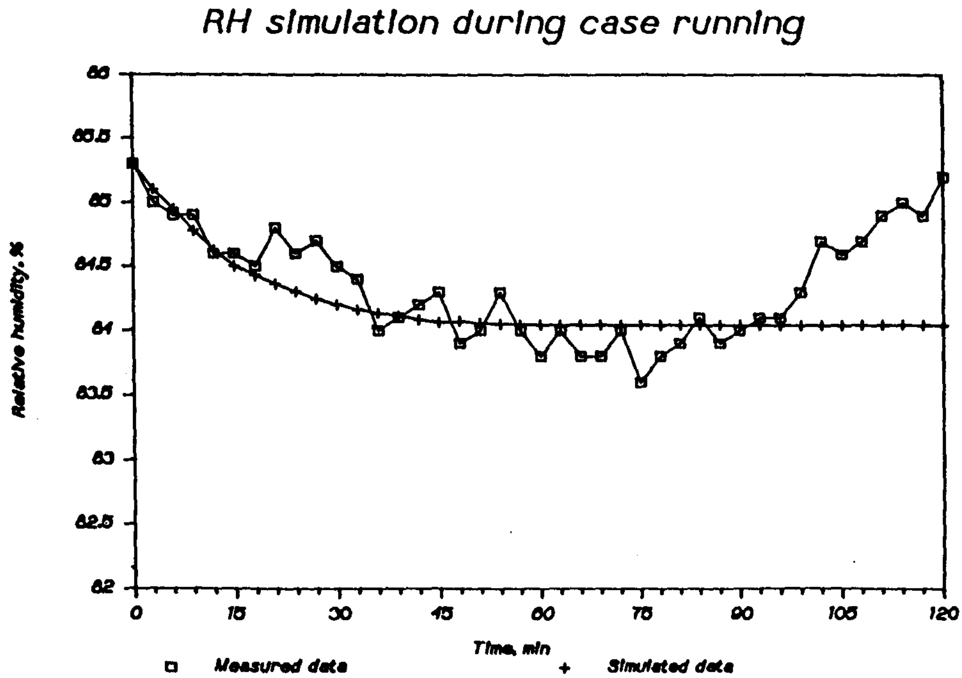

Figure 5. Simulated result of indoor relative humidity variations during case running

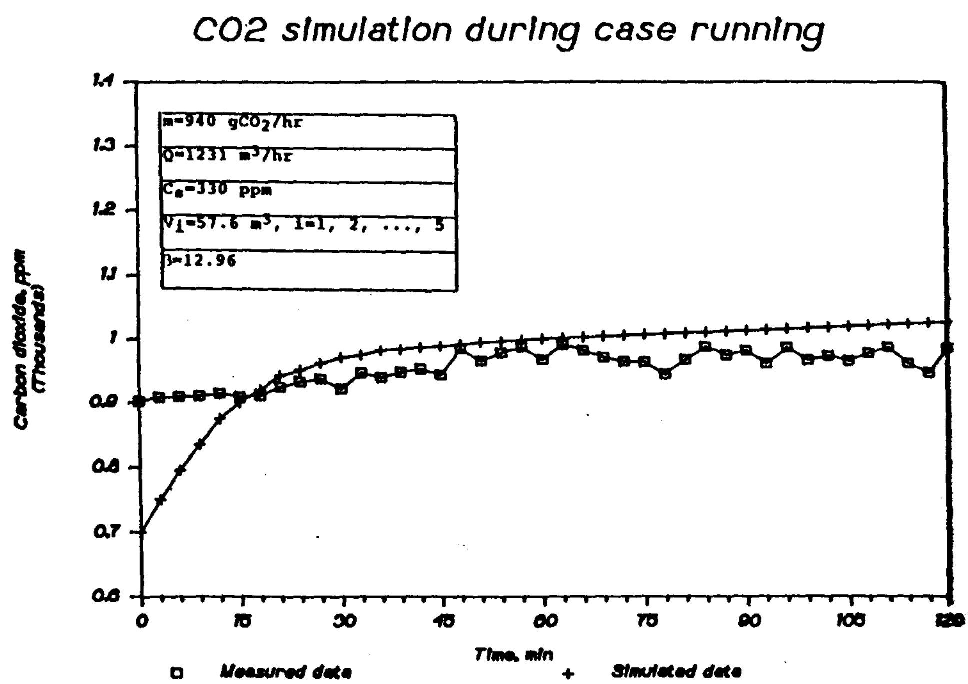

Figure 6. Simulated result of indoor carbon dioxide level variations during case running

where:

$$(\partial T_{dp} / \partial h_r)^* = (T_{dp}^* + 93.02)^2 /$$

$$53100\ (0.271 / (h_r^* (h_r^* + 0.625)))$$

$$[N] = \begin{bmatrix} (\partial \phi_r / \partial T_{dp})^* & (\partial \phi_r / \partial T_r)^* \\ 0 & 1 \end{bmatrix}$$

where:

$$(\partial \phi_r / \partial T_{dp})^* = 1.2x10^5 \phi_r^* /$$

$$(T_{dp}^* + 93.02)^2$$

$$(\partial \phi_r / \partial T_r)^* = -1.2x10^5 \phi_r^* / (T_r^* + 93.02)^2$$

in which T_{dp} is dew-point temperature and "*" represents the set-point value.

And,

$$\{Z\} = \{\{z) \mid \{C\}\}^T$$

where: $\{z\} = \{z_1, z_2\}^T = \{\Delta\phi_r, \Delta T_r\}^T$.

Proportional Control

The aim is to minimize the deviations in indoor relative humidity ($\Delta \phi_r$) and indoor temperature (ΔT_r) (i.e., (z)), using the indoor relative humidity (ϕ_r) and indoor temperature (T_r) as measured output variables:

Consider the system:

$$\{\dot{X}\} = [F]\{X\} + [G]\{U\}, \{X(0)\} = \{X_o\} \quad (8a)$$

$$\{Z\} = [C]\{X\} \quad (8b)$$

the following objective function shall be minimized:

$$J = 1/2 \int_o^{T_f} (\{Z\}^T [Y] \{Z\} + \{U\}^T [R] \{U\})\, dt \quad (9)$$

Now substituting $\{Z\}$ = [C] $\{X\}$ into equation (9) gives:

$$J = 1/2 \int_o^{T_f} (\{X\}^T [C]^T [Y] [C] \{X\} + \{U\}^T [R] \{U\})\, dt \quad (10)$$

It can be shown that $[C]^T[Y]$ $[C]$ is positive semidefinite when [Y] is positive semidefinite, provided that the system in equation (8) is observable. Observability is guaranteed if and only if the matrix:

$$[\ [C]^T \mid [F]^T[C]^T \mid ([F]^T)^2 [C]^T \mid \ldots \mid ([F]^t)^{n+2-1} [C]^T\ ]$$

is rank of (n+2) which is order of vector $\{X\}$ (Anderson and Moore, 1990).

It is, therefore, evident that the output and state LQR have the same form of optimal control except that $[C]^{-1}\{Z\}$ and $[C]^T[Y]$ [C] appear, respectively, wherever $\{X\}$ and [Y] appear in the latter. Hence, the optimal control for system considered (as $T_f \to \infty$) is:

$$\{\hat{U}\} = -[R]^{-1} [G]^T [P_1^*] [C]^{-1} \{\hat{Z}\} \quad (11)$$

where $[P_1^*]$ is the positive definite ans symmetric solution of the algebraic Riccati equation:

$$-[P_1^*] [F]^T [P_1^*] + [P_1^*] [G] [R]^{-1} [G]^T [P_1^*] - [C]^T [Y] [C] = 0 \quad (12)$$

In obtaining equation (11), controllability of the system is assumed. Controllability is satisfied if and only if the matrix:

$$[[G] \mid [F][G] \mid \ldots \mid [F]^{(n+2)-1} [G]]$$

is of rank (n+2) (Anderson and Moore, 1990).

Therefore, equation (11) is the desired P controller for system considered.

Proportional plus Integral Control

Consider the system:

$$\{\dot{X}\} = [F]\{X\} + [G]\{U\} + [L]\{W\}, \quad (13a)$$

$$\{X(O)\} = \{O\}$$

$$\{Z\} = [C]\{X\} \tag{13b}$$

It is desired to obtain an optimal (U) which minimizes (Johnson, 1968):

$$J = 1/2 \int_o^{T_f} (\{Z\}^T [Y]\{Z\} + \{\dot{U}\}[R] \{\dot{U}\})dt \tag{14}$$

Substituting $\{Z\} = [C]\ (X)$ into equation (14) gives:

$$J = 1/2 \int_o^{T_f} (\{X\}^T [C]^T [Y]\ [C]\{X\} + \{\dot{U}\}[R]\{\dot{U}\})dt$$

$$= 1/2 \int_o^{T_f} (\{X\}^T [S]\{X\} + \{\dot{U}\}[R] \{\dot{U}\})dt \tag{15}$$

where: $[S] = [C]^T [Y]\ [C]$.

Taking the time derivative of equation (13) yields:

$$\{\ddot{X}\} = [F]\{\dot{X}\} + [G]\{\dot{U}\}, \{X(0)\} = \{0\},$$

$$\{\dot{X}(0)\} = [L]\{W\}$$

$$\{\dot{Z}\} = [C]\{\dot{X}\} \tag{16}$$

and defining:

$$\{\Omega\} \equiv \{\dot{X}\}, \{\Theta\} \equiv \{U\}, \{\boxminus\} \equiv \{\dot{Z}\}$$

equations (13) and (16) can be reduced to the following pair of vector differential equations:

$$\{\dot{X}\} = \{\Omega\}, \{X(0)\} = \{0\}$$

$$\{\dot{\Omega}\} = [F]\{\Omega\} + [G]\{\Theta\}, \{\Omega(0)\} = [L]\{W\}$$

$$\{Z\} = [C]\{X\}$$

$$\{\boxminus\} = [C]\{\Omega\}$$

which can be compactly expressed as:

$$\{\dot{\Omega}\} = [F_a]\{\Omega\} + [G_a]\{\Theta\},$$

$$\{\Omega(0)\} = \{\Omega_i\}$$

$$\{\Lambda\} = [C_a]\{\Omega\} \tag{17}$$

where:

$$F_a = \left[\begin{array}{c|c} [0] & [I] \\ \hline [0] & [F] \end{array}\right] \qquad [G_a] = \left[\begin{array}{c} [0] \\ \hline [G] \end{array}\right]$$

$$\{\Lambda\} = \left[\begin{array}{c} \{Z\} \\ \hline \{\boxminus\} \end{array}\right] \qquad [C_a] = \left[\begin{array}{c|c} [C] & [0] \\ \hline [0] & [C] \end{array}\right]$$

Also in terms of the new variables equation (15) becomes:

$$J = 1/2 \int_o^{T_f} (\{\Omega\}^T [S_a]\{\Omega\} + \{\Theta\}^T [R]\ \{\Theta\})dt \tag{18}$$

where:

$$[S_a] = \left[\begin{array}{c|c} [S] & [0] \\ \hline [0] & [0] \end{array}\right] = \left[\begin{array}{c|c} [C]^T [Y]\ [C] & [0] \\ \hline [0] & [0] \end{array}\right].$$

$[S_a]$ is positive semidefinite since [S] is positive semidefinite. Thus the original output LQR in equations (13) and (14) has been reduced to a state LQR whereby given the system in equation (17) it is desired to find that $\{\Theta\}$ which minimizes equation (18). The optimal control to this problem as $T_f \to \infty$ (assuming controllability and observability is satisfied for the system in equation (13)), is given by:

$$\{\hat{\Theta}\} = -[R]^{-1} [G_a]^T [P_1^*]\{\Omega\}$$

$$= -[R]^{-1} [G_a]^T [P_1^*]\ [C_a]^{-1}\{\hat{\Lambda}\} \tag{19}$$

where $[P_1^*]$ is the positive definite and symmetric solution of the algebraic Riccati equation:

$$-[P_1^*][F_a] - [F_a]^T[P_1^*] + [P_1^*][G_a]$$

$$[R]^{-1}[G_a]^T[P_1^*] - [S_a] = \{0\}$$

Equation (19) can be rewritten as:

$$(U) \quad \left[\begin{array}{c|c} [L_{11}] & [L_{12}] \\ \hline [L_{21}] & [L_{22}] \end{array}\right] \left[\begin{array}{c} \{\hat{Z}\} \\ \hline \{\dot{\hat{Z}}\} \end{array}\right] \qquad (20)$$

where the $[L_{ij}]$ are appropriately partitioned submatrices of the matrix $[-[R]^{-1}[G_a]^T[P^*{}_1]$ $[C_a]^{-1}$. Their final results are:

$$\{U\} = [[L_{12}] + [L_{21}]]\{\hat{Z}\}$$

$$+ [[L_{11}] + [L_{21}]] \int_o^t \{\hat{Z}(\tau)\} dt \qquad (21)$$

This is the optimal feedback controller for system considered with constant disturbance and is also the desired PI controller.

Performance of Implementation

Figure 7 shows the structure of P and PI controllers for system considered. In the case an outdoor disturbance is assumed whereby the outdoor temperature (T_f), outdoor humidity (h_f), and outdoor carbon dioxide concentration (C_f) are supposed to undergo a sudden step change. Specifically, T_f changes from T_{fs} to T_{fs}+10°C, h_f changes from h_{fs} to h_{fs}+0.02 kg H_2O/kg air, and C_f changes from C_{fs} to C_{fs}+1000 ppm. Table 1 gives the steady state summer operating conditions.

The above disturbances are simulated and the corresponding responses of inside temperature (T_r), inside relative humidity (ϕ_r), and inside carbon dioxide concentration (C_r) under the P and PI regulating actions of the optimal feedback controllers are simulated and analyzed graphically. The simulations were done in complied BASIC on a personal computer.

As a first step in the numerical investigation the state and output controllability and observability of the system was verified. Next, the effect of the matrices [Y] and [R] in the objective functions was investigated. Both [Y] and [R] were selected as diagonal matrices, i.e.,

$$[Y] = diag\,[Y_{11}, Y_{22}, Y_{33}],$$

$$[R] = diag\,[R_{11}, R_{22}, R_{33}]$$

The corresponding scalar versions of equations (9) and (14) are:

$$J = 1/2 \int_o^\infty (Y_{11}Z_1^2 + Y_{22}Z_2^2 + Y_{33}Z_3^2 +$$

$$R_{11}U_1^2 + R_{22}U_2^2 + R_{33}U_3^2)\,dt$$

$$J = 1/2 \int_o^\infty (Y_{11}Z_1^2 + Y_{33}Z_2^2 + Y_{33}Z_3^2 +$$

$$R_{11}\dot{U}_1^2 + R_{22}\dot{U}_2^2 + R_{33}\dot{U}_3^2)\,dt$$

respectively, where:

$$\{Z\} = \{Z_1, Z_2, Z_3\}^T, \{U\} = \{U_1, U_2, U_3\}^T,$$

$$\{\dot{U}\} = \{\dot{U}_1, \dot{U}_2, \dot{U}_3\}^T,$$

Since the Y_i, U_i, and $\dot{U}_i$ are of different orders of magnitude some approximate scaling factors need to be used in the selection of Y_{11}, Y_{22}, Y_{33}, R_{11}, R_{22}, and R_{33} (Liao, 1992). These scaling factors are selected so that all terms representing derivations in state variables in the integrands of objective equations are of the same order of magnitude, and, simplicity all terms representing derivations in control variables (or their time derivatives) are of the same order of magnitude. For instance, if $Y_{11}^1 Z_1^2$, $Y_{22}Z_2^2$, and $Y_{33}Z_3^2$ are to be of the same order of magnitude, i.e., $Y_{11}Z_2^1 = Y_{22}Z_2^2 = Y_{33}Z_3^2$, then $Y_{11}/Y_{22} = Y_2^2/Y_1^2$, $Y_{22}/Y_{33} = Y_3^2/Y_2^2$. Now it is estimated that during the transient periods Z_1^2 will be approximately of the order of 10^{-4}, while Z_2^2 and Z_3^2 will be of the order of 1 (Liao, 1990; et al., 1991b), and therefore, $Y_{33} = Y_{22} \cong 10^{-4} Y_{11}$, hence the scaling factor relating Y_{33}, Y_{22} to Y_{11} is 10^{-4}. By similar reasoning it was found that $R_{33} = R_{22} \cong 10^{-6} R_{11}$ (Since no general criterion could be found, U_i^2 and $\dot{U}_i^2$ were assumed to be of the same order of magnitude, namely, $U_1^2 \cong \dot{U}_1^2 \cong 10^{-6}$, and $U_2^2 = U_3^2 = \dot{U}_2^2 \cong 1$).

Thus in the preliminary investigation it is only necessary to adjust Y_{11} and R_{11} while Y_{22},

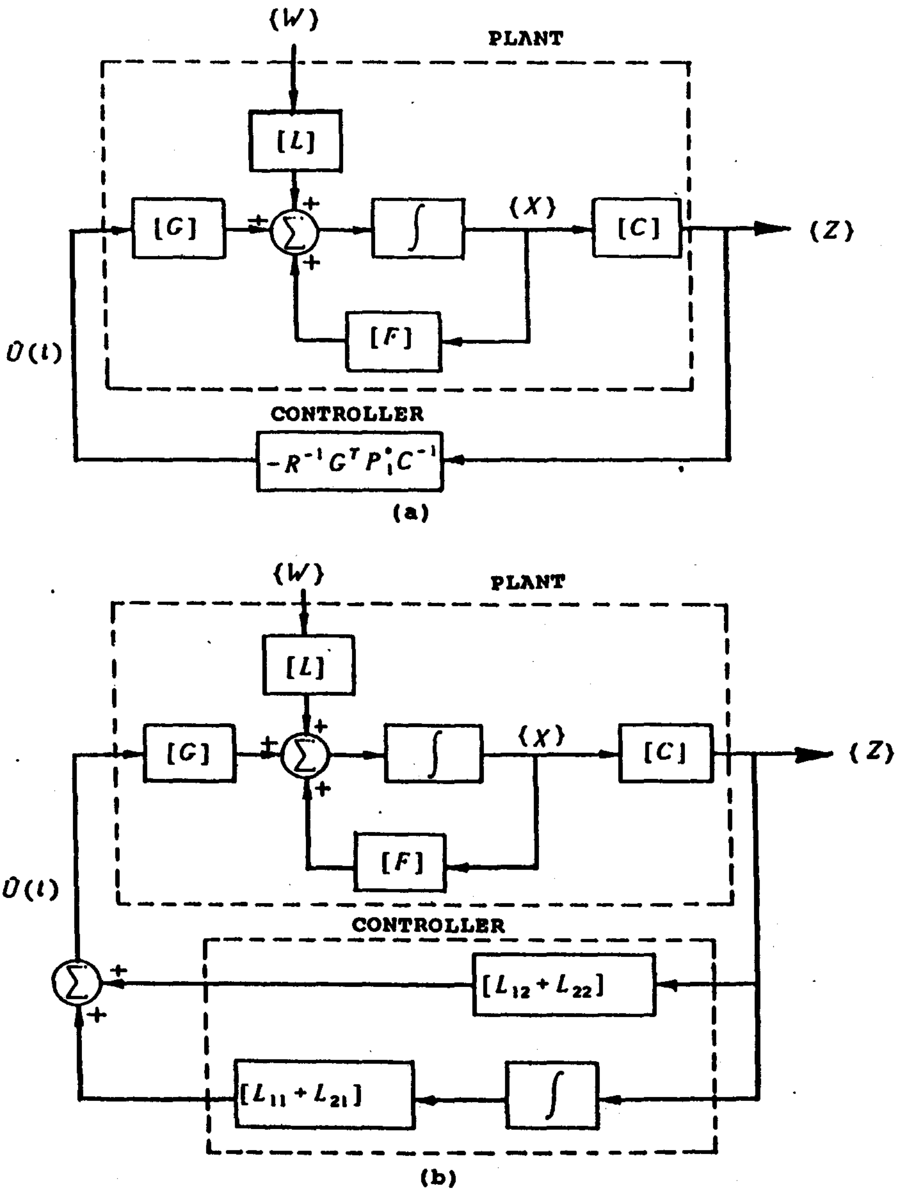

Figure 7. Structure of control system (a) optimal P control (b) optimal PI control

Y_{33}, and R_{22}, R_{33} are fixed by the above scaling factors. In this work R_{11} is kept constant at 1, and only Y_{11} is varied.

Figures 8-13 show the responses of T_r, ϕ_r, and C_r under the relating action of the P and PI modes of control respectively. In Figures 8-13, Y_{11} is the parameter and it is rather obvious from these figures that by changing the value of Y_{11} it is possible to obtain almost any desired response for T_r, ϕ_r, and C_r. If necessary, the above scaling factors could be adjusted to achieve the desired responses. This illustrates that an indirect form of state and/or control constraints may be included by a proper selection of the weighting matrices. In comparing figures 8-13, it is evident that the P control does result in a steady-state offset althoug it is possible to reduce the offset by increasing Y_{11}, while the PI mode results in a damped response with no overshoot or steady-state offset. Therefore, in employing P control there is a trade-off between the range of acceptance steady-state offset and an upper bound on Y_{11} dictated by design and/or economical limits.

Sensitivity in Optimal Control System

After having designed a control system, the designer cannot expect to duplicate precisely the nominal performance characteristics of system components or parameters. The reasons for this are the ever present uncertainties and nonidealities of the real world. Basic system parameters change with operating condition and environmental effects such as temperature, shock, and atmospheric conditions. Then there are always manufacturing tolerances in the components used to construct the controllers. One way to obtain confidence in the analytical design is to determine the consequence of change in the basic parameters. Such an analysis is called sensitivity and is essential in evaluating theoretical results.

There are two ways in which the inaccuracy or variation in components or parameters can affect the objective function: (1) variation in the controller parameters, and (2) variation in the parameters of the controlled system. The main objective in this work is to determine sensitivity with regard to controller parameters, here it is assumed that the system parameters are not subject to any variation. Therefore, it shall deal solely with the first subject and the development will follow that of Pagurek (1965).

One of the goals of a sensitivity is to assign accuracy requirements for system parameters consistent with sensitivity significance in a system model. Now it can use the development of the work done by Pagurek (1965) to analyze the sensitivity of the feedback gains of the optimal P and PI controllers. Based on the result of such analysis, to obtain some insight as to the accuracy requirements of the various feedback gains during the actual design of the individual controllers can be obtained.

Equation (11) is valid for the optimal P control,

$$\{\hat{U}\} = -[R]^{-1}[G]^T[P^*]\ [C]^{-1}\{\hat{Z}\}$$
$$= [K]_o\{\hat{Z}\} \tag{22}$$

which may be rewritten as:

$$\begin{bmatrix} U_1(t) \\ U_2(t) \\ U_3(t) \end{bmatrix} \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \begin{bmatrix} \hat{Z}_1(t) \\ \hat{Z}_2(t) \\ \hat{Z}_3(t) \end{bmatrix}$$

The controller parameters shall be concentrated on are the nine feedback gains $K_{11}, K_{12}, \ldots, K_{33}$, which, for simplicity, will be redesignated as $K_1, K_2, \ldots, K_9$, respectively. In the case of the PI control, equation (21) is valid. Equation (21) which on integration with respect to time yields:

$$\{\hat{U}(t)\} = [K]_o \begin{bmatrix} \int_o^t \{\hat{Z}(\tau)\}\, d\tau \\ \{\hat{Z}(t)\} \end{bmatrix}$$

which may be written as:

$$\begin{bmatrix} \hat{U}_1(t) \\ \hat{U}_2(t) \\ \hat{U}_3(t) \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} & K_{15} & K_{16} \\ K_{21} & K_{22} & K_{23} & K_{24} & K_{25} & K_{26} \\ K_{31} & K_{32} & K_{33} & K_{34} & K_{35} & K_{36} \end{bmatrix}$$

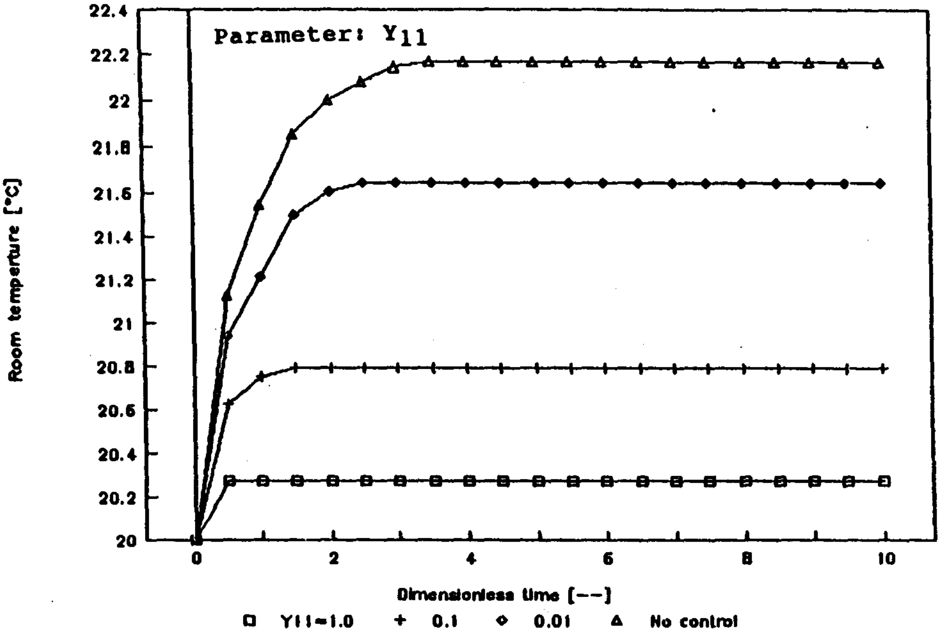

Figure 8. Responses of indoor temperature under optimal P controller

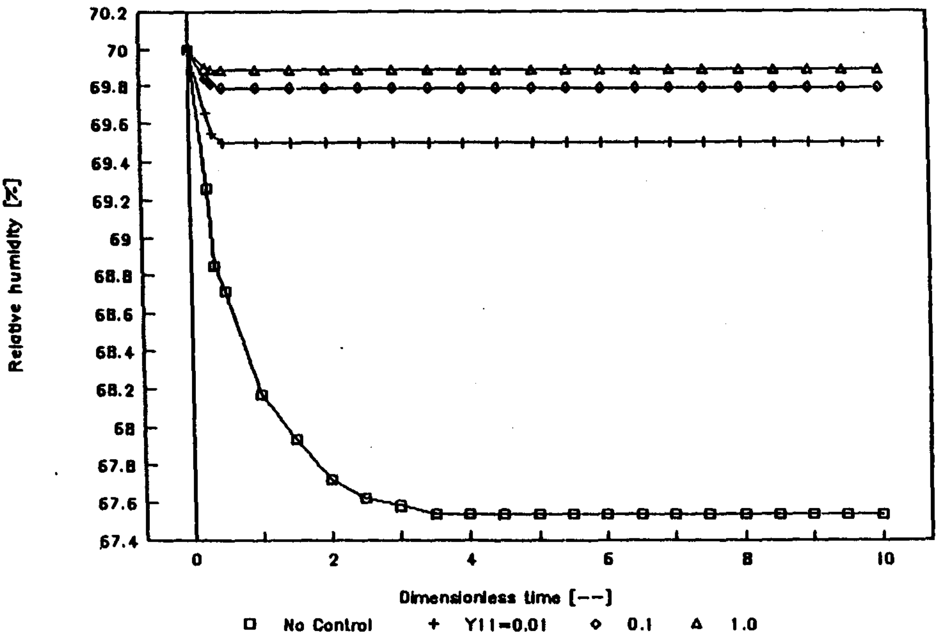

Figure 9. Responses of indoor relative humidity under optimal P controller

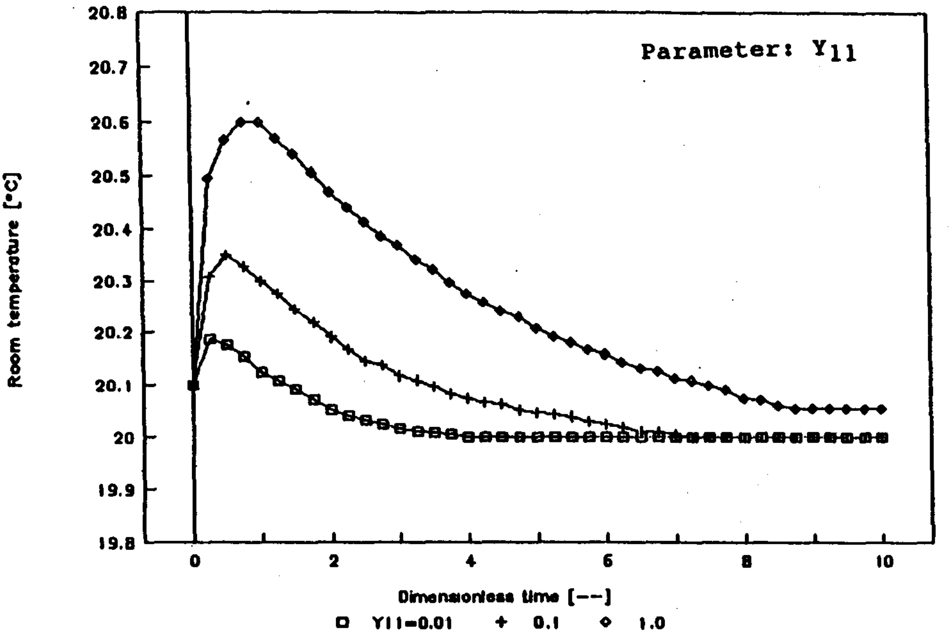

Figure 10. Responses of indoor temperature under optimal PI controller

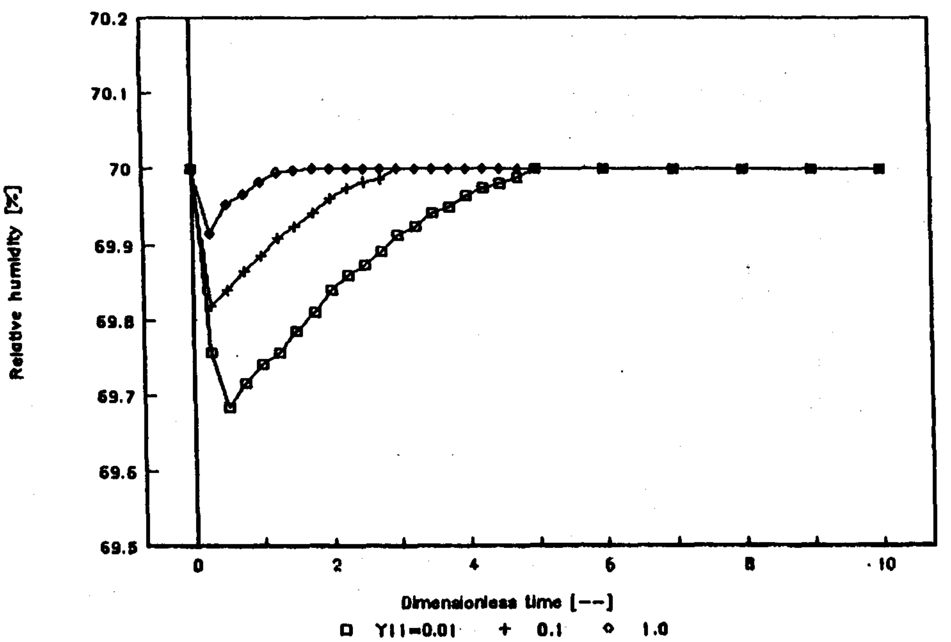

Figure 11. Responses of indoor relative humidity under optimal PI controller

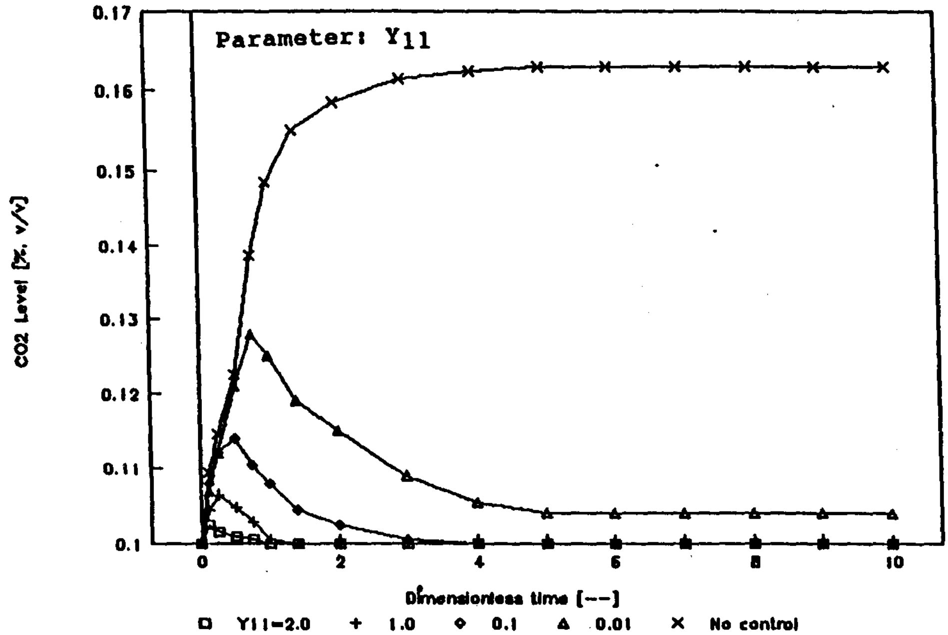

Figure 12. Responses of carbon dioxide level under optimal PI controller

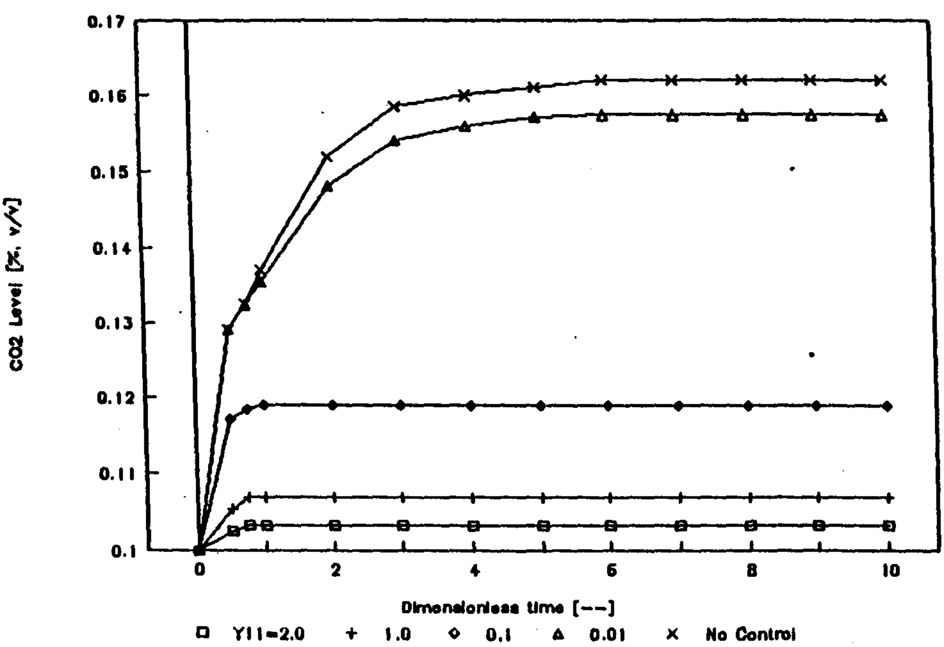

Figure 13. Responses of carbon dioxide level under optimal P controller

$$\begin{bmatrix} \int_o^t \hat{Z}_1(\tau)\,d\tau \\ \int_o^t \hat{Z}_2(\tau)\,d\tau \\ \int_o^t \hat{Z}_3(\tau)\,d\tau \\ \hat{Z}_1(t) \\ \hat{Z}_2(t) \\ \hat{Z}_3(t) \end{bmatrix} .$$

It can be seen that equation above is indeed equation (21). The controller parameters shall be concentrated on are the eighteen feedback gains K_{14}, K_{15}, K_{16}, K_{11}, K_{12}, K_{13}, . . . , K_{36}, K_{31}, K_{32}, K_{33}, which will be redesignated as K_1, K_2,. . . , K_{18}, respectively.

Tables 2 and 3 respectively summarize the results of the sensitivity analysis of the optimal P and PI controllers. The cases (Y_{11} = 1.0, 0.01) discussed earlier are analyzed. The nominal values of the K_i shown are the optimal values determined via the developments of feedback control synthesis for system considered. The sensitivity of the objective function with respect to the feedback gains is shown as the magnitude of a symmetry matrix, $[M_{ii}]$. Matrix $[M_{ii}]$ may be referred to as a relative sensitivity coefficient matrix. The magnitude of $[M_{ii}]$, however, can be defined by the maximum eigenvalue of $[M_{ii}]$; i.e., $\|[M_{ii}]\|$ = max ($|\lambda_1$, $|\lambda_2|$, ... $|\lambda_{(n+2)}|$) where λ_1, λ_2. . . , are the eigenvalues of $[M_{ii}]$. The $[M_{ii}]$ and $\|[M_{ii}]\|$ are determined according to Pagurek (1965).

Both Tables 2 and 3 show that the objective function is 10^6 times more sensitive to the feedback gains associated with U_3 (the inside carbon dioxide generation rate, (m_i)) than that to those associated with U_1 (the inlet control temperature, (ΔT_i)) and U_2 (the inlet control humidity, (Δh_i)). This indicates that great care has to be emphasized in maintaining the feedback gains of the carbon dioxide controller at their nominal values since the optimal performance of the overall control scheme depends more on these nominal values than those of the temperature and humidity controllers.

One observation that is immediate from Tables 2 and 3 is that as Y_{11} increases, the sensitivities with respect to the integral gains increase. Individual case studies may have to be undertaken to study the effects of weighting factors on gain sensitivities, since the above results are only those of a particular study. In designing a control system, however, the designer cannot treat all the parameters (gains) of the control system with equal importance, for of all the possible parameter (gain) variations, some are much more critical than others in determining whether the complete system can be expected to meet given specifications. Therefore, special attention must be paid to these critical parameters (gains).

Therefore, the results of sensitivity analysis suggested that the control of the ventilator can be based on two factors: the carbon dioxide level and the temperature with the cropping control unit. The ventilator required for optimal carbon dioxide control is calculated first, the algorithm depending on whether an upper or lower limit for the carbon dioxide has been selected.

SUMMARY AND CONCLUSIONS

The ability to exert precise environmental control becomes increasingly important as hybrid strains of high-yielding mushroom, which require precise environmental control, if their potential is to be realized, come into commercial use. Furthermore, good environmental control allows the grower to exploit techniques such as controlled timing of mushroom flushes, enabling a better market price to be obtained for the produce.

The aim of proviging integrated control of casing or air temperature, relative humidity and carbon dioxide level to obtain optimum conditions for growth in mushroom growing houses was achieved by developing a simultaneous temperature-humidity-carbon dioxide control via modern control theory.

Future refinement of the theoretical control systems presented in this paper need to further develop the system hardware. It is strongly recommended that any further work on this project be proceeded by the development of a low-cost microcomputer-based environmental control system.

Table 1. Steady state operating conditions

$V = 288\ m^3$	$W_{rs} = 0.357$ kg water/min
$Q_{ls} = 0$ W	$Q_{rs} = 526$ W

A. Summer operating conditions

Indoors: $T_{rs} = 20°C$, $h_{rs} = 0.010$kg water/kg air (70% RH)

Outdoors: $T_{fs} = 30°C$, $h_{fs} = 0.02105$ kg water/kg air (80% RH)

Recycled air: $T_{is} = 10°C$, $h_{is} = 0.0085$ kg water/kg air RH = 80%

Fresh air mass flow rate $F_{fs} = 12$ kg air/min

Recycled air mass flow rate $F_{is} = 24$ kg air/min

Total volumetric airflow rate in the house: $Q = 1231\ m^3/hr$

Table 2. Results of sensitivity analysis of P controller

Y_{11}	Nominal value, K_0
0.01	$K_9 = -0.079$ (3515.4)[a]
	$K_8 = -0.0008$ (15106.8)
	$K_7 = -0.000095$ (167078.5)
	$K_6 = 22.76$ (0.0004)
	$K_5 = 1.87$ (0.0035)
	$K_4 = -0.33$ (0.15)
	$K_3 = 33.46$ (0.0002)
	$K_2 = -0.96$ (0.09)
	$K_1 = -0.02$ (0.107)
1.0	$K_9 = -0.95$ (358.4)
	$K_8 = -0.08$ (3366.9)
	$K_7 = -0.002$ (34796.5)
	$K_6 = 250.3$ (0.004)
	$K_5 = 105.6$ (0.00036)
	$K_4 = -8.5$ (0.033)
	$K_3 = 160.8$ (0.0008)
	$K_2 = 95.6$ (0.007)
	$K_1 = -5.6$ (0.0005)

[a] Magnitude of $[M_{ii}]$.

Table 3. Results of sensitivity analysis of PI controller

Y_{11}	Nominal value, K_0
0.01	$K_{18} = -0.09$ (8830.7)[a]
	$K_{17} = -0.003$ (115971.5)
	$K_{16} = -0.0002$ (1678046.3)
	$K_{15} = -0.14$ (2217.3)
	$K_{14} = -0.08$ (16086.4)
	$K_{13} = -0.05$ (170100.6)
	$K_{12} = 24.91$ (0.0082)
	$K_{11} = 10.86$ (0.076)
	$K_{10} = -0.96$ (1.12)
	$K_9 = 26.62$ (0.0009)
	$K_8 = 9.7$ (0.085)
	$K_7 = -0.85$ (1.62)
	$K_6 = 30.67$ (0.0007)
	$K_5 = 15.68$ (0.0054)
	$K_4 = -0.54$ (1.65)
	$K_3 = 40.56$ (0.0002)
	$K_2 = 9.96$ (0.074)
	$K_1 = -0.08$ (2.004)
1.0	$K_{18} = -0.306$ (4127.14)
	$K_{17} = -0.00079$ (290237)
	$K_{16} = -0.00005$ (3014518.6)
	$K_{15} = -0.26$ (3147.5)
	$K_{14} = -0.0016$ (120810.8)
	$K_{13} = -0.00032$ (1100967.7)
	$K_{12} = 79.009$ (0.004)
	$K_{11} = -3.055$ (0.29)
	$K_{10} = -2.65$ (1.65)
	$K_9 = 47.75$ (0.003)
	$K_8 = -5.42$ (0.121)
	$K_7 = -0.98$ (6.4)
	$K_6 = 250.4$ (0.002)
	$K_5 = -9.68$ (0.095)
	$K_4 = -4.46$ (0.76)
	$K_3 = 84.96$ (0.0056)
	$K_2 = -10.46$ (0.147)
	$K_1 = -5.45$ (5.06)

[a] Magnitude of $[M_{ii}]$.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of the National Science Council of R.O.C. under grant NSC-80-0409-B-197-03.

REFERENCES

Anderson, B. O. D., and J. B. Moore, 1990. Optimal control, linear quadratic methods. Prentice-Hall Inc., New Jersey.

ASHRAE Handbook of Fundamentals. 1985 American Society of Heating, Regrigrating, and Air Conditioning Engineers, New York.

Cheng, S., and Y. S. Han. 1977. Study on the effect of environmental factors on development of abalone mushroom. Taiwan Mushrooms 1(1): 2-10.

Dawson, H. 1952. Heating systems. M.G.A. Bull. 32: 227-243.

Flegg, P. B. 1972. Response of the cultivated mushroom to temperature with particular reference to the control of cropping. Mushroom Sci. VIII: 75-84.

Flegg, P. B., and J. F. Smith. 1976. Controlled-environment facilities for mushroom research at the Glasshouse Crops Research Institute. Annual Report of Glasshouse Crops Research Institute. Pp. 555-62.

Flegg, P. B. 1979. Effect of temperature on sporophore initiation and development in Agaricus bisporus. Mushroom Sci. 10 (part 1): 595-602.

Flegg, P. B., D. M. Spenser, and D. A. Wood. 1985. (ed.) The biology and technology of the cultivated mushroom. John Wiley & Sons, New York.

Johnson, C. D. 1968. Optimal control of the linear regulator with constant disturbance. IEEE Trans. Automatic Control, AC-B:416-412.

Jorgenson, R. 1983. Fan Engineering (8th ed.). Buffalo Forge Company. Buffalo, NY.

Kalman, R. E., and R. S. Bucy. 1961. New results in linear filtering and prediction theory. Trans. ASME, J. Basic Engng. 83: 95-106.

Kinrus, A. 1970. Ventilation of mushroom production houses. Mushroom News 18(2): 4-10.

Liao, C. M. 1990. Analysis of the dynamic behavior of temperature and humidity in confined agricultural environments. J. Chinese Agric. Engng. 36(4): 39-49.

Liao, C. M., and J. J. R. Feddes. 1990. Mathematical analysis of a lumped-parameter model describing the behavior of airborne dust in animal housing. Applied Math. Modelling 14(5): 248-157.

Liao, C. M., T. S. Wang, and C. M. Liu. 1991a. A lumped-parameter model describing the behavior of carbon dioxide concentration in a slot-veltilated airspace (I) modeling and mathematical analysis. J. Society of Agric. Structures, Japan 22(1): 9-16.

Liao, C. M., T. S. Wang, and C. M. Liu. 1991b. A lumped-parameter model describing the behavior of carbon dioxide concentration in a slot-ventilated airspace (II) model verification. J. Society of Agric. Structures, Japan 22(1): 17-23.

Liao, C. M. 1992. Design of an optimal temperature-humidity control system in confined agricultural environments. J. Chinese Agric. Engng. 38(1): 43-53.

Lockard, J. D. and L. R. Kneebone. 1965. Investigation of the metabolic gases produced by Agricus bisporus (Leg)sing. Mush. Sci. 6: 281-289.

Pagurek, B. 1965. Sensitivity of the performance of optimal linear control systems to parameter variation. Int. J. Control 1: 33-45.

Saffell, R. A., and B. Marshal. 1983. Computer control of air temperature in a glasshouse. J. Agric. Eng. Res. 28: 469-477.

Schroeder, M. E. 1969. Forced ventilation with proportional control for the standard double mushroom house. Mushroom Sci. VII: 421-428.

Schroeder, M. E., L. C. Schisler, R. Snetsinger, V. E. Crowley and W. L. Barr. 1974. Automatical control of mushroom ventilation after casing and through production by sampling carbon dioxide. Mushroom Sci. IX (part 1): 269-278.

Schroeder, M. E. 1983. Programmable digital microprocessor control system for thermophilic composting in mushroom culture. *In*: Agricultural Electronics-1983 and beyond, Vol. I. American Society of Agricultural Engineers. St. Joseph, MI, Pp. 396-401.

Tschierpe, J. J. 1973. Environmental factors and mushroom growing. Part II. Mushroom J.

2: 77-94.

Vedder, P. J. C. 1978. Modern mushroom growing. Stanley Thornes, Cheltenham, 420 pp.

Willits, D. H., T. K. Karnoski, and W. F. McClure. 1980a. A microprocessor-based control system for greenhouse research-Part I hardware. Trans. ASAE 23: 688-698.

Willits, D. H., T. K. Karnoski, and E. H. Wiser. 1980b. A microporcessor system for greenhouse research-Part II software. Trans. ASAE 23: 693-698.

Wuest, P. J., L. C. Schisler, and M. E. Schroeder. 1976. A unitized forced-air ventilated system for mushroom growing. Mushroom News 24(1, 2): 70-78.

收稿日期：民國81年6月16日
修正日期：民國81年7月8日
接受日期：民國81年7月13日